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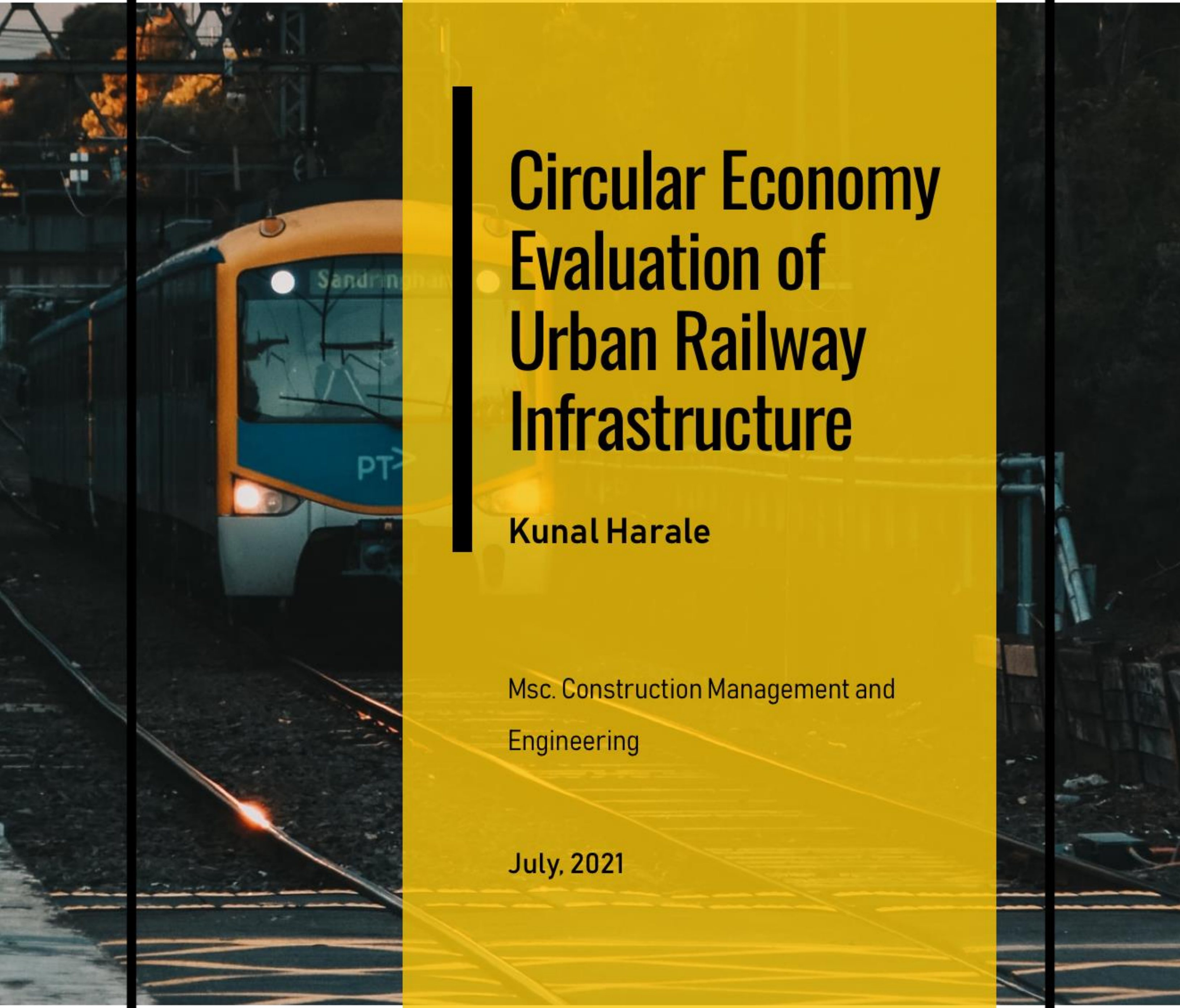

Circular Economy Evaluation of Urban Railway Infrastructure

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Circular Economy Evaluation of Urban Railway Infrastructure

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by,

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Preface

This report is a culmination of an exciting and challenging research into the topic of circular economy that has been conducted over the last several months. This research was performed in collaboration with Mott MacDonald, a global engineering, management and development consultancy. With this thesis, I conclude my Masters in Construction Management and Engineering, at the Delft University of Technology.

This thesis would not have been completed without the contribution of numerous people, to whom I owe my sincere gratitude. Firstly, I would like to thank my chair, Professor dr. Paul W. Chan for his inputs during the formal meetings that provided a unique and a well-rounded perspective. Moreover, I would also like to express my gratitude to Dr. Francesco Di Maio for his constant support and guidance. I would also like to thank Sander Willer, Ricks Schalk and Xinju Liu for keeping up with my progress every week and being actively involved in my work. Your comprehensive feedback and guidance were of great help and pushed me to achieve better results.

I would also like to thank Joost Bolck and everyone at Mott MacDonald for allowing me to conduct my work in this organisation and for their continued support. Furthermore, I would like to thank all my colleagues and interviewees for the enthusiastic discussions, their time, and good advice. I am humbled that so many people that I have never met, took time out of their busy schedules to contribute and coordinate across 3 countries and time zones.

I would like to thank my parents for always believing in me and for their unconditional love. I would not have been able to do this without them. Neeraj, Nupur, Suchit and Sanjay for providing the warmth of a home and being my pillars of strength in times of need. I would also like to thank my friends from back home and the ones I made in Delft. Sally, Mikhail, Daniella, Pooja, Sanne, Raymond, Juan and Sam, thank you for keeping me sane and serving a calming force during the tense moments along this journey. My housemate Sander, thank you for patiently helping me every time I was in distress and providing insightful ideas to tackle my problems. Brainstorming with you was always fruitful. I would also like to thank Simran, for meticulously and patiently helping me with the report and for her words of encouragement throughout this journey.

My years in Delft have brought me experience, knowledge, and discipline, but even more, it has brought me friends, fun and memories. These experiences and friendships have taught me the most, and therefore I thank everyone that I met along this journey. Lastly, I would like to dedicate this work to my late uncle Rajesh, who we lost during the pandemic this year.

Enjoy the read!

Kunal Harale
29th July 2021
Delft.

Executive Summary

Introduction

The European construction sector is responsible for the consumption of almost 32% of total raw material for realizing its projects (Benachio, Freitas, & Tavares , 2020). On a national level, this amount results to almost 50% for the Dutch construction industry (Nellssen, et al., 2018). The ever-growing population stresses the need for sufficient infrastructure and services which only results in an increase in demand and eventually an increase in resource consumption. The current trend of linear model, wherein the virgin raw materials are used to construct end products and eventually discarded at its end of life, poses a major threat for raw material extinction and adds to the problem of excessive resource consumption.

A viable solution for this problem is the introduction of circular economy concepts that aim at closing the raw material loops by considering all the current and future life cycle phases of a product in the initial development stages. Since the launch of the Ellen MacArthur Foundation (EMF) in 2010, circular economy (CE) has gained considerable attention. EMF defines circular economy as "*a regenerative system that aims to keep materials in a closed loop at their highest value*" (Foundation, Cities in the circular economy: An initial exploration , 2017, page 7). CE focuses on much more than reduction of waste through recycling and aims at reducing the consumption of raw materials, designing products such that they can easily be disassembled and reused (eco-design, Design for disassembly) and extending product lifespan through maintenance and repair. CE differentiates the gradation options that help keep the materials and components within the loop by options such as refuse, reduce, reuse, repair, etc (Buren, Demmers , Heijden, & Witlox , 2016).

So far the Dutch industry prides itself in being 97% recyclable for its construction wastes (Nellssen, et al., 2018). Though this feat is remarkable from the aspect of sustainability, the circular economy deems recycling as the least favourable option. This is mainly due to the fact that recycling causes loss of initial value of products that it was orignally designed for. Recycling also utilises additional energy for the realisation of new products and is therefore less favourable than reuse or refurbish. The difference between the recycling economy and circular economy lies in the fact that the former still involves the input of raw materials and generation of wastes, whereas in CE the loops are closed (Buren, Demmers , Heijden, & Witlox , 2016).

Legislative efforts to curb the effects of such global construction practices have resulted in the formation of various international and national policies. One such important policy is the Paris Agreement that aims at limiting the global average temperature rise below 2 degrees. On a national level for the Dutch construction industry, the government has set its vision on becoming 50% circular by 2030 and 100% by 2050 (Nellssen, et al., 2018). In order to achieve these goals, it is necessary to transit and accelerate all aspects of the construction industry with the circular economy model, including the building sector and the infrastructure sector. Review of past studies depict that the transition of the building sector to the circular model is significantly greater as compared to that of the infrastructure sector (Sande L. v., 2019). Therefore, to reach national and international goals, it is also important to transition towards the circular model and ideologies within the infrastructure sector.

Although railways are the most sustainable form of transport, railway infrastructure is far from being circular in terms of material consumption patterns and closing resource loops. These projects are still driven by cost, time and safety parameters, thus assigning lesser importance towards circularity principles. For instance, in the U.K., the construction and maintenance of railways generate approximately 2 million tonnes of waste each year. 68% of the raw materials used within the Dutch construction sector are imported from other countries. The Dutch rail industry exports 90% of their rails to Asia or Turkey once they reach their end of life cycle (Dijksma & Kamp, 2016; Exchange, 2019). This shows the additional benefit of CE in reducing the dependence of raw materials and the potential that can be harvested from these material flows (Exchange, 2019).

Although the research field is progressing at a considerable pace with a strong level of awareness, the actual implementation of CE concepts in the construction industry is still very low (Benachio, Freitas, & Tavares, 2020). This can be attributed to the fact that the stakeholders are lacking practical ways which can guide them to understand and implement such concepts for the construction industry. Even though the first mention of CE dates back to the 1980s, the varied and vast interests in this concept has led to different perceptions and definitions of it. One important study analysis 114 different definitions of circular economy, showing its vivid perspectives (Kirchherr, Reike, & Hekkert, 2017). Therefore, to better understand and to evolve the concept even further, there exists a need to reach a shared understanding and common language (Saidani, Yannou, Leroy, Cluzel, & Kendall, 2019). One way to achieve this commonality goal is by the use of assessment methods that employ the use of indicators. Measurement tools are not only essential to assess the extent of CE implementations but also aid in monitoring the effects of CE implementations. Indicators can provide a standardized language to simplify information exchange and understanding, and thus ease this transition.

Objective

The aim of this research is therefore to develop a framework that would aid the assessment of railway infrastructure components in terms of circular economy principles for three different life cycle phases of the project. This goal is achieved by dividing the research into smaller objectives which begin with developing a clear understanding of CE and its principles. The ambiguity of the topic as already discussed needs to be clarified. Apart from understanding the concepts, it is also essential to understand the existing assessment frameworks and methods, so as to develop a framework that is acceptable and applicable. This objective will also help understand the barriers of the existing frameworks which can be avoided in the new framework. The final objective is to generate and develop indicators for the railway infrastructure components from practice and literature since their absence hinders the implementation and smooth transition towards CE. Based on the above objectives, the following main research question is formulated:

"How can urban railway infrastructure components be assessed in terms of circular economy principles?"

Research approach

To answer the main research question satisfactorily, the research is divided into 4 sub-research questions. Each sub part focuses on analysing the different aspects that are encapsulated in this study, which collectively aid in answering the main research question. The research begins with analysing the theoretical background on circular economy, its principles and ideologies by means of extensive review of previous studies. Multiple definitions from literature are analysed and a suitable definition that could form the basis of this research is selected. The current status of CE in the railway industry is unknown, therefore it is essential to understand the extent of CE for such projects and simultaneously grasp the barriers for its implementation. To understand these points, online interviews with experts were conducted from the Netherlands and abroad.

To further develop a framework which helps in overcoming the barriers within the industry, it is also necessary to understand the current frameworks and thus, some existing frameworks are analysed through an extensive review of previous studies and efforts are made to overcome the existing drawbacks in the new framework. Some frameworks are also reviewed in interviews to see their applicability and the problems faced by users.

Due to the lack of implementation of CE in the rail sector, review of previous studies was not sufficient to develop indicators for the new framework. Therefore, interviews with experts from the field are conducted to gather indicators and at the same time analyse these and check their ability to measure CE. Overall, the major source of inputs for this research are interviews with experts and review of past studies which helped in achieving the final goal.

Results

Based on the analysis conducted during the study, the barriers for CE implementation that were discussed in the interviews depicted the lack of awareness of circularity in the industry. Some stakeholders were aware of the concept of circularity while some thought of it to be more focused on recycling of materials and components. Clients perceived their requirements for projects to be inclusive of circularity principles which was not the case after detailed scrutiny. Specifications often focused on carbon and greenhouse gas emissions, and seldom on closing the material loops. Contractors, on the other hand, were unknowingly implementing circular solutions but due to their lack of awareness, these solutions were labelled sustainable. Though CE falls under the umbrella concept of sustainability, unclear promotion of such solutions can hinder the transition towards CE and also portrays a false image of the preparedness of the market.

Another aspect that hindered CE implementation was the lack of collaboration, and insufficient room to design and implement innovative solutions. Contractors suggested that the client's requirements were often detailed and did not consider CE principles during the procurement and tender phase. Technical requirements make it difficult to deviate to more circular and innovative solutions and therefore specifying more functional solutions is necessary. But due to lack of awareness of the topic given its infancy for the rail sector, knowledge partners can also aid client organizations to adequately include functional requirements in the initial stages.

To create a framework, analysing existing frameworks to overcome their shortcomings is essential. This study aimed at analysing 3 existing frameworks which are currently being used in practice. The Material Circularity Indicator (MCI), DuboCalc, Platform CB'23 was chosen from the plethora of assessment frameworks due to their high usage in practice. Analysis of these frameworks showed the lack of focus on the different Rs from the R framework other than reuse and recycling. Design for disassembly is helpful in determining the suitability of components and materials for the secondary use which was also not assessed in these frameworks. Apart from these drawbacks, Platform CB'23 is currently still in development and lacks methods to weigh the indicators into a final score.

The procurement phase framework consists of a list of 23 qualitative indicators that have been validated by an expert panel and ranked according to their relative importance. These indicators can assess projects and can also be used as a guideline to develop specification requirements for new projects.

The design phase framework consists of two modules - the material input module and design for disassembly module. The former module aims at assessing the components on the origin of the materials/components used. It provides a higher score for components that are reused as compared to recycled and virgin materials. The design for disassembly module assesses the modularity of components in terms of connection tools, accessibility and separation damage. This helps in assessing the condition of the component at the end of its life in order to judge its suitability for use in further lives.

The end of life framework consists of a material output module that assesses the outflow of components and materials at the end of their life on a modified R framework, which is different from the ones used in the design phase.

During the interviews it was also observed that different stakeholders considered different lifecycle phases slightly more important than the rest and capturing this essence in the final framework was necessary. This was done by interviewing a certain set of experts and conducting the analytical hierarchy process to determine weights for each phase based on different perspectives. Thus, the final framework not only distinguished the different life cycle phases, also provided a quantative distinction among them. The components of rail infrastructure that were defined in the scope of this study, also had varying importance as compared to each other based on their carbon footprint, lifespan and amount of material used. In order to correctly gauge this relative importance, annual greenhouse gas emissions for each component were determined, which helped in determining the individual contribution of each component to the overall emissions of the system. Finally, this individual contribution provided a numerical weight to distinguish the components with higher impact and potential to the overall circularity score.

Case study

Two case studies were performed at the end of this study which not only helped in validating the findings but also helped in determining the applicability and usability of this framework. The first case study was performed on the Uithoorn line which is an extension of a current tram line from Amstelveen to Uithoorn, Netherlands. This project is still in the early phase of design and was therefore analysed for the procurement phase. It was observed that the Uithoorn line scores low on circularity for the procurement phase as CE principles were not a crucial factor for the project. Less attention was given to closing the material loops as well.

The second case study performed was on the Uithof line in Utrecht, Netherlands, which was brought into operation in late 2019. This project was therefore analysed for all the lifecycle phases, based on the documents provided and multiple interviews conducted with the project manager. The procurement phase of the project was analysed by studying the requirement specifications. It was observed that for the procurement phase, only one indicator was satisfied and resulted in a score lower than that of the Uithoorn line. The design phase of the project did not have much focus on circularity and material loops either. The entire project was constructed using virgin raw materials and no specifications were described for the end of life scenarios as well. This shows the lack of attention given to closing the material loops and thereby for circularity. Assessing the design for disassembly module from the provided documents proved to be a challenge. Hence, it was completed by interviewing the project manager. Some components were designed well for modularity as they should have been, since modularity was the only indicator that was prescribed in the requirements. The results of the case studies were validated by confirming the final results and conclusions with the respective experts that were involved in the project.

Conclusion

Initial analysis of previous studies highlighted the dominance of traditional linear consumption patterns in the construction industry. The impacts of such practices are long term and in order to provide a habitable environment for the future generations, it is necessary to rethink such practices. Circular economy can provide a vital solution to the problems faced due to the effects and consequences of the linear model. Therefore, to successfully transition to a CE, it is necessary to understand its concepts and principles. Literature consists of a vast knowledge base for CE which can pose a better understanding of the topic at hand, but at same time also gives rise to multiple perspectives. To overcome the barrier of lack of awareness, it is essential to first understand these different perspectives and their underlying fundamentals in order to grasp the entirety of the concept. Barriers faced by stakeholders are often rooted in this unclarity of the topic.

The final framework, which bases its outline on the R model and the design for disassembly aspects, tries to encapsulate the main principles of CE. Drawbacks analysed in existing assessment frameworks relating to the absence of the more extensive R models were overcome by including the most suitable Rs in the new framework for the design and EoL phase. Apart from the material flow aspect, the principle of designing out waste was captured in the design for disassembly module. This aspect was also absent in the existing frameworks and efforts were made to include such aspects that would sufficiently evaluate the modularity of the components involved.

The complexity and uniqueness of every railway project makes it difficult to generate detailed indicators for the procurement phase since each project has a different set of boundary conditions and prerequisites. To keep a broad range of applicability of this framework, the indicators developed for the procurement phase were therefore kept generalized and qualitative.

The final framework thus is an integrated framework of multiple CE aspects which can be used by clients and contractors. It can be useful in assessing the current projects or as a guideline to draft new requirements specifications. The design framework can also be used by designers to evaluate multiple design alternatives and then choose the most suitable solution.

Recommendations for practice

During interviews and case studies, it was observed that stakeholders are often unaware of the exact extent and principles of CE. To overcome most barriers discussed in this research, it is necessary for organisations to garner sufficient knowledge regarding CE. To offer circular solutions, it is necessary for organisations to completely understand the far-reaching impacts and opportunities of CE before diving into the technical intricacies.

Large infrastructure projects are often complex and require the coordination and coherence of multiple stakeholders and organisations. In order to successfully implement circular solutions, early involvement of different stakeholders and contractors from the initial phases is necessary. Circular solutions are not the responsibility or the capacity of an individual stakeholder, but rather a collective effort. The current tendering and procurement processes lack the required involvement of different stakeholders which hampers innovative and circular solutions. Modifications to such processes by early involvement of different stakeholders and knowledge partners can help with better formulation of the requirements that will encompass more circular principles than current practice.

Changes to design methods and formation of the design documents is also necessary to sufficiently design modular solutions and transfer information for future life cycles. While analysing the documents for the case studies, specifically for the design phase, it was observed that little attention was given to specifying the details about connections and joints. In order to assess the design for the disassembly aspect, change in formulating such documents is also necessary. Aspects such as separation damage, connection tool, etc if incorporated in these documents can accelerate the assessment and at the same time provide sufficient data for future projects. If such details of components are known, this data can be reflected upon to check the applicability of these components for and while designing new projects, based on the current disassembled condition of the component. Therefore, DfD details are essential to be incorporated in the project documents which can also aid in the easier formation of material passports.

Limitations and recommendations for further research

During the course of the research, efforts were made to encapsulate most of the CE principles but due to the time constraints, certain choices were necessary. One of many such instances occurred in the early phases of the study, wherein a choice was made to focus only on the technical cycles of components. Biological cycles as depicted by the Ellen MacArthur Foundation (EMF) were decided to be excluded. These were the cycles that referred to biological materials wherein the materials could be streamed out into the environment without any additional processes. Including this aspect in the later modifications of the framework can be an interesting addition.

The extent of complexity of a railway infrastructure project was faced with during the case studies. Like many concepts, theory portrays a simplistic image of the different types of tracks and their categories but the vivid nature and combinations were observed while analysing the multiple types of tracks implemented in the Uithof line. The scope of the research in terms of the components analysed can thus be extended to include more aspects such as the top layer finishing and signalling and communication systems, etc. Since concrete and steel components contribute heavily to GHG emissions, addition of such new components in the scope can provide more opportunities to implement circular components.

While determining the relative importance of the different components, the results were determined based on an old database for the carbon emission factors. Though it was observed that the newer versions included more emission factors while the factors for the old components remained the same, it can be interesting to see the deviation of the scores according to the new database, or even a completely different source.

Some major aspects of this research, such as relative importance of procurement phase indicators or the importance of different life cycle phases, were determined based on expert inputs. Since the concept of CE is relatively new, it was difficult to acquire a large panel who expertise in CE. Inclusion of more such experts in the near future can be an interesting addition to observe the variations that can occur based on an increased size of expert panel.

Contents

List of figures

List of tables

List of abbreviations

CE	Circular Economy
EoL	End of Life
EMF	Ellen MacArthur Foundation
PP	Public procurement
GPP	Green Public Procurement
SPP	Sustainable Public Procurement
CPP	Circular Public Procurement
CDW	Construction and Demolition Waste
DfD	Design for Disassembly

1. INTRODUCTION

This chapter briefly introduces the concept of Circular Economy and its importance in today's world along, with the importance of urban railway infrastructure. It also establishes the research gap and the formulation of the problem statements along with the main and sub research questions.

1.1 THE NEED FOR CIRCULAR ECONOMY

The fast development of countries resulting from the technological and industrial advancements around the globe has put immense pressure on the existing natural resources. In the last century, there has been a drastic increase in the demand for raw materials. According to Anastasiades et. al (2018), since 1960, when countries started to urbanize and economies showed signs of prosperity, the increased consumption of raw materials became prominent. Majority of the industries, especially the construction sector, are heavily dependent on virgin raw materials to produce the necessary goods. These requirements arise due to the exploding population growth on the demand side. Estimates predict, the increase in the middle classes will rise from 1.8 to 4.9 billion people by 2030 which will eventually increase the stress on demand for all commodities (Towards the circular economy, 2013). The ever-growing stress on global resources is increasing as the demand for these resources are growing at an exponential rate whereas their replenishing capacity is very slow. If the current trends of mining raw material continues, it will result in around 180 billion tons of raw materials mined annually by 2050 (Anastasiades, Van Hul, Audenaert, & Blom, 2020) which will lead to resources to soon be extinguished.

The consumption of such large amounts of virgin raw materials also leads to the problem of waste generation in large quantities, which according to the current practices is eventually disposed. The European Commission found that the construction industry is responsible for 32% of the total consumption of natural resources and as much as 25-30% of all waste generated in the EU is Construction and Demolition Waste (CDW) (Benachio, Freitas, & Tavares, 2020). Out of these wastes, it was found that multiple materials that are currently being disposed have a high potential of being recycled and reused. This potential that such wastes inherit, led to the identification of CDW as a priority waste stream by the European Union (European Commission, 2018).

The production of such large amounts of waste contributes to major global problems such as global warming and climate change. These problems are currently the frontrunners of a global crisis and need immediate attention. The construction industry is responsible for 25-40% of energy consumption and 40% of CO_2 emission out of which the production of cement alone is responsible for 5% of the worlds' total CO_2-emission (Leendertse, Hendriksen, & Kerkhofs, 2018). To curb such problems in the construction industry, international agreements and policies have been signed. The Paris Agreement, which focuses on keeping the global average temperature rise below 2° C was signed by 174 countries and the European Union, and promotes the inclusion of environment friendly policies in national and international activities. To reach the goals of such agreements and policies, the traditional construction processes and methods that make use of the linear economy of "Take – Make – Dispose" need adjustments. These traditional methods employ material extraction from the earth that are then used to construct the final product. After the end of its life cycle, these products are eventually disposed. These practices are the main reason for the high demand of virgin raw materials and for the large amount of waste produced. The global population is headed for an overshoot and the policies and efforts to curb the overconsumption problems over the past 30 years have been insufficient (Verberne, 2016).

Replacing this ideology by transitioning towards a circular and closed process is one of the main solutions to the aforementioned problems. Implementation of the circularity principles and ideologies are emerging as the main catalysts to achieve sustainability goals. The Ellen MacArthur Foundation (EMF) defines circular economy (CE) as an economy which is *"restorative and regenerative by design, and aims to keep products, components, and materials at their highest utility and value at all times"* (Foundation, Cities in the circular economy: An initial exploration , 2017, page 7). It focuses on optimizing resource yields by circulating components and materials at their highest utility and value (Lesmes, 2020). The influence of CE can be made in material input, design, production, consumption and end of life (EoL) phase. In a CE, the EoL phase is connected to the material input phase which helps in minimizing waste streams as well as the required feedstock for new production (Arntzenius, 2020). For projects within the construction sector, the process is usually divided into different life cycle phases. For public projects such as the construction of a new railway line, it usually begins with the procurement of goods and services, followed by the detailed structural design phase. The construction and use phases are then followed by the EoL phase wherein the components are incapable to perform their intended function and thus, are replaced and discarded.

it is estimated that if CE ideologies are implemented, the savings in terms of materials costs will be of USD 630 billion for medium-lived complex goods in the EU and USD 706 billion for fast-moving consumer goods globally (Foundation, Circularity Indicators: An approach to measuring circularity , 2019). Implementation of CE not only provides economic and environmental benefits on a global level but also gives companies the possibilities to mitigate risks, as these are no longer dependent on virgin raw materials that are subjected to material price volatility and material supply. Closing the material loops will also reduce the dependance on virgin raw materials and help tackling the problem of material extinction. Simultaneously, since materials are kept in the loop, reduction in the waste streams and emissions from the production of new materials will also reduce the stress on the global environment. A more detailed understanding of CE is provided in chapter 3 of this study.

Even though the first mention of CE dates back to 1980s, the varied and vast interests in this concept have led to different perceptions and its definitions. One important study analyzes 114 different definitions of circular economy showing its multiple perspectives (Kirchherr, Reike, & Hekkert, 2017). Therefore to better understand and to evolve the concept even further, there exists a need to reach a shared understanding and a common language (Saidani, Yannou, Leroy, Cluzel, & Kendall, 2019). Assessment and measurement of these CE principles are equally important, as they help to determine the extent of circularity of any project. Since the concept of CE has gained traction, many assessment tools have also been developed simultaneously which help in the assessment of projects based on their circularity. In the study conducted by Sassanelli, Rosa, Rocca, & Terzi (2019), various frameworks and concepts that aid CE implementation are described, such as Life Cycle Analysis (LCA), MFA (Material Flow Analysis), DfX (Design for X). Even though these tools are frequently used, they still possess a few limitations such as their inability to encompass all the environmental impacts. The use of LCA can also be enhanced by complimenting its methods by incorporating more CE concepts in these analyses. Also, the MFA only provides information about the quantity of material but lacks means to provide similar information regarding its quality (Elia, Gnoni, & Tornese, 2017). The Material Circularity Indicator (MCI) proposed by EMF tries to provide a solution to this problem by making an attempt to include the loss of materials and quality level by utilizing a re-use potential indicator in the framework (Elia et al., 2017; The Ellen MacArthur Foundation, 2015a). The MCI provides a useful set of indicators but for its computation a detailed material passport is required, which forms the basis of each of the frameworks (Verbruggen, 2019).

1.2 CE IN THE CONSTRUCTION SECTOR

The construction industry accounts for the world's largest consumption of virgin raw materials. It encompasses the production of almost 50% of steel globally and is also responsible for the consumption of more than 3 billion tonnes of raw materials per year (Zimmann, O'Brien, Hargrave, & Morrell, 2016; Benachio, Freitas, & Tavares , 2020). The construction industry is also accountable for CO_2 emissions of about 25-40% (Pomponi & Moncaster, 2017).

It has been observed that despite the concept of CE has been introduced for some years, its implementation in the construction sector has been largely limited (Duan, 2019). From the figures of material consumption and emissions mentioned above, there is a large scope for improvement to minimize the resource intake and reduce the negative environmental effects within construction industry. Though these problems have been in existence for years, the current trends only focus on reducing these ill effects by intervening the energy consumption patterns and carbon emissions (Pomponi & Moncaster, 2017). Even with these interventions, the CO_2 emissions are still on the rise and are expected to double by 2050 (Pomponi & Moncaster, 2017). Implementation of CE strategies in this sector will not only help in eventually reducing these effects but will also reduce the waste production and resource consumption.

Though CE has a high potential within the construction industry, implementation of such changes is difficult due to the peculiar characteristics of the projects. Each building or infrastructure project is unique with varying circumstances and parameters. The project duration and the life cycle is also usually much larger than the projects or products of other industries, and their design choices are also heavily influenced by economic motives (Coenen, 2019). Due to these hinderances, the introduction of CE concepts in the construction industry are slow (Benachio, Freitas, & Tavares , 2020) and researchers have also studied that the slow diffusion also exists due to the absence of standards and lack of government involvement (Benachio, Freitas, & Tavares , 2020).

1.3 CE IN THE DUTCH CONSTRUCTION SECTOR

In the Netherlands, the construction industry is responsible for producing approximately 25 million tonnes of waste flows per year, which is almost three times as much as household wastes (Nellssen, et al., 2018). It is also estimated that the construction processes in the Netherlands result in a raw material consumption of 50%, total energy consumption of 40% and total water consumption of 30%. All these processes also lead to CO_2 emissions of 35% (Nellssen, et al., 2018; Sande L. v., 2019). Apart from the global climatic effects of the linear model, the Netherlands is heavily dependent on other countries for their supply of raw materials and it is estimated that 68% of the raw materials are imported. This dependency also leads to geopolitical tensions which influences the raw material prices and eventually the stability of the Dutch economy (Dijksma & Kamp, 2016).

Despite these significant impacts, the Dutch construction industry only focuses on recycling majority of its waste streams and recycles approximately 97% waste (Nellssen, et al., 2018). This leads to the misconception that the industry is circular and sustainable (Figure 1). Only 3% of the recycled material in the construction sector returns to its original function and the rest is often used as a road base or filler material (Nellssen, et al., 2018). This depicts the loss of initial value of products that they were initially designed for. Recycling also utilises additional energy for the realisation of new products and is therefore less favourable than reuse or refurbish. The difference between the recycling economy and circular economy lies in the fact that the former still involves the input of raw materials and generation of wastes, continuing the demand of raw materials, whereas in CE the loops are closed (Buren, Demmers , Heijden, & Witlox , 2016).

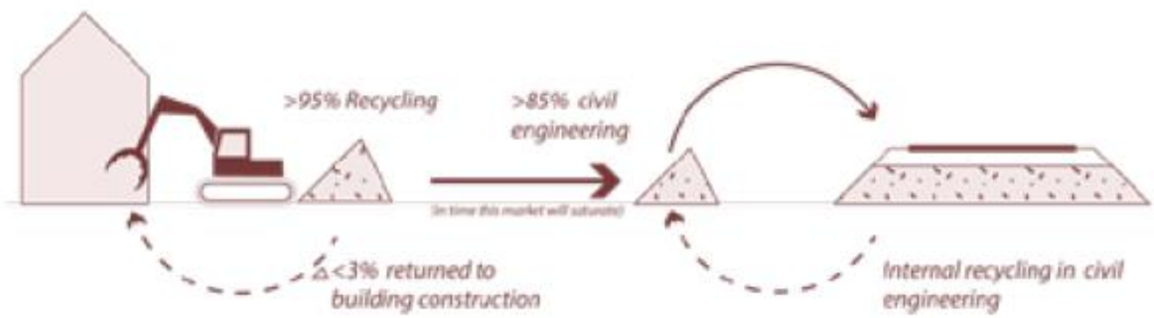

Figure 1: Flow of Construction and Demolition waste in the Dutch Construction industry. (Source: (Nellssen, et al., 2018))

In order to reach the main goals of CE, the Dutch government has set its targets to reach 50% circularity by 2030 and completely circular by 2050 (Dijksma & Kamp, 2016; Nellssen, et al., 2018). According to the report from Rijkswaterstraat (Nellssen, et al., 2018), to achieve the set goals, a few spearheads that will aid the developments in the right direction, some of which are stated below:

- All government procurement to be circular by 2030
- Reduce the CO_2 emissions by 50% by 2030 and 100% by 2050
- Grants for circular business and earnings models
- Development of uniform measurement method for circularity
- Establishment of a knowledge base institute for Circular buildings

The government of the Netherlands has understood the problems of the linear economy and has developed goals to transition towards a more sustainable and circular development. The CE model if implemented successfully is also estimated to generate an additional turnover of 7.3 billion euros and account for 54,000 jobs in the Netherlands. It can also lead to a GDP growth ranging from 1.5 billion euros to 8.4 billion euros (Dijksma & Kamp, 2016). On a larger scale, sustainable efforts are being made to transition to a more renewable source of energy (green electricity) and simultaneously produce as much as 0.4 million kWh electricity by means of solar panels (ProRail, 2016).

1.4 IMPORTANCE OF RAILWAY INFRASTRUCTURE

Transport infrastructure is of major importance for most of the developed and developing countries, as it accounts for the largest proportion of the budget of any public-works program (Polyzos & Tsiotas, 2020). Investments in transport infrastructure affects economic activity of the associated regions and can also be beneficial to the societies of these regions. Railways have connected people, places and opportunities and have the ability to drive economic growth and revitalize communities. These are often considered as a generator of economic growth and also a growth factor for the prosperity of the population (Pietrzak, Pietrzak, & Montwill, 2021). In the Netherlands, 4.5 million daily trips are made by trams and metros (Public Transport in the Netherlands, 2010). The popularity of public transport networks can be attributed to its higher density, complimented by the numerous problems associated with car travel such as congestions, insufficient parking spaces, etc (Public Transport in the Netherlands, 2010).

Railways have a considerable contribution not only in developing transport infrastructure but also in the economy and help reduce the traffic load on other means due to their superior carrying capacity. For different sections of society (eg. Students and senior citizens), railways have a reduced fare which makes travelling cheaper and quicker (Profillidis, 2014). Urban areas also consist of new neighbourhoods, business parks and facility centres which increase the demand for a high quality public transport network system (Public Transport in the Netherlands, 2010).

Before the rise in population, the initial public transport systems such as trams, were considered to be an obstacle for the car traffic (Topp, 1999). With time, the urban traffic and transport policies have taken a different shape. In large cities, car traffic is forced to retreat and the surface is being given back to pedestrians, trams, buses and light rails as these are considered to satisfy the growing public demands in a much better manner with respect to orientation, usage, distance to stops, urban experience and public awareness (Topp, 1999).

Keeping in mind the importance of railways, it is also essential to focus on the downside of constructing such projects which adversely affect the natural environment and material resources. The negative effects of such projects can be observed in the greenfield developments. These projects entail construction of new projects and often lead to large land consumption (Pietrzak, Pietrzak, & Montwill, 2021). The 'brownfield' projects are thus more desirable as these are the redevelopment projects that add new developments to the city without taking away green areas (Wilde, 2006).

The increasing population scenarios pose a big threat not only on infrastructure rehabilitation in the urban areas but also on the demand for infrastructure development (Sahely, Kennedy, & Adams, 2005). Studies show that more than 55% of the human population lives in urbanized areas and by 2030 this value is estimated to increase to 61% and to 70% in 2050 (Pietrzak, Pietrzak, & Montwill, 2021). Eventually these numbers will lead to an increased demand for transport services, and combined with a lack of actions to protect quality of life and the environment, and will lead to increased adverse environmental problems.

In 2015, railways were responsible for approximately 1350 Terajoules of energy consumption, which if compared to an average Dutch household was equivalent to 19000 households (ProRail, 2016). The increasing threat from climate change and sea level rise results in designing and constructing resilient railways to account for the new and expensive vulnerabilities (ARUP, 2020). Along with these insecurities, in order to reduce the impacts of the railways on the climate, it is also necessary to consider new and efficient ways to build these systems. Basis of the selection criteria for tenders is majorly based on economic value. Along with a tradeoff between quality, costs still play a major role in selecting tenders (Economically most advantageous tender (EMAT) criteria). Material costs are approximated to account for almost 22% of the total budget for a railway project. Focusing on such costs based on the principles of CE can help reduce these to a large extent. The tracks and substructure along with the civil engineering structures (bridges and tunnels) account for 58% of the total maintenance costs. A general breakdown for the annual costs shows that, from the entire budget, depreciation costs accounts for 47%, traffic disruption costs for 33% and maintenance costs for 20%. It is important to note here that the depreciation costs are the highest which makes it important to extend the life span of these components of the railway infrastructure as a small extension in lifespan, can result in significant cost savings (Lichtberger, 2005).

1.5 CIRCULAR TRENDS AND POTENTIAL WITHIN THE DUTCH RAILWAYS

Majority of the rails that are used in the Dutch rail network are produced and transported from Austria (Exchange, 2019). ProRail is responsible for the maintenance and extension of the Dutch railway infrastructure and on an average, it replaces between 200 and 300 km of railway tracks annually. Out of these replaced rails, in the current scenario, around 90% of the tracks at their end of life are exported to Asia or Turkey whereas very few are reused in the Netherlands at locations with lower functional requirements (Exchange, 2019).

Pilot projects by organisations such as ARUP show that railway tracks have the potential to be reused in buildings as construction beams, or as functional support structures in the Amsterdam canals. As of 2019, the scrap cost of railway tracks was €0.14/kg which results in a value of €7900/km (Exchange, 2019). Reflecting on the total replacement of rails within the Dutch network as mentioned before, this estimates in a second hand value of rails to be around €1,975,000. If these secondhand rails are instead used for functions such as construction beams, their financial value increases significantly as an average steel construction beam costs 20 - 50€/meter (Exchange, 2019).

Though these trends highlight the potential of CE within the Dutch railway sector, efforts are being made to bridge such gaps and optimize these potentials. ProRail has set its goals to reuse most of its wastes in valuable ways by 2030. It aims to discard only 5% of its total waste into landfills and incinerators, and to reuse at least 10% of all excess materials (Exchange, 2019). To embrace the CE principles, ProRail also participates in the 'Green Deal Circular Procurement 2.0' which focuses on agreements to recycle and reuse wastes (Exchange, 2019).

There are also circular design challenges held annually in which startups and inventors are challenged to explore secondary lives for old railway parts. A reused and recycling premises is currently present in Hilversum, in the Netherlands where secondary track materials are stored.

ProRail is also currently developing a digital platform as means of 'dating site for rail materials' wherein the supply and demand for materials such as sleepers, rails and ballast can be brought together (Exchange, 2019).

1.6 KNOWLEDGE GAP

The importance of CE is imminent from the previous sections, and the increasing demand and scarcity of resources are piling up on the global problems, for which CE can provide a valuable solution. CE has shown fast growing interest from major stakeholders in the field and substantial developments have been made in terms of implementing CE strategies and their assessment methods. However these existing methods which provide a common language to assess circularity, are still criticized for their lack of ability to encompass all aspects of CE. One major reason for this is the different definitions and perceptions that researchers have in regards with CE and its concepts. From the review of past studies, it is also evident that majority of the academic work that is conducted for the assessment of CE majorly focuses on buildings, and are seldom instrumental in assessing railway infrastructure. The importance of railways and its infrastructure, and at the same time the lack of research in terms of CE is appalling.

The Dutch construction sector can be divided into the building sector and the infrastructure sector, amongst which, the infrastructure sector has a large deficit in CE implementation. Review of past studies have shown that for the building sector, there have been multiple projects such as The Edge, Park 20|20 and CIRCLE (Sande L. v., 2019). Whereas for the infrastructure sector, CE has only been implemented in one project that was the circular viaduct in Kampen, the Netherlands (Rijkswaterstaat, 2019). Even though CE has shown signs of development, it can be observed from the previous sections that these are comparatively small-scale projects and a large gap is yet to be bridged for large scale infrastructure projects and their assessments. The ambitions of ProRail to reuse 10% of excessive materials does not take into account the reuse of materials at the end of their life but considers excess materials that are left after construction. Efforts to cascade materials and components into secondary lives after the completion of their initial life cycle is essential to minimize the waste flows to the landfills.

Fulfilling this research gap of understanding the extent to which CE is implemented in a railway infrastructure project in order to collectively reach the goal of attaining CE in the construction industry is therefore necessary. The contribution of the railway infrastructure projects cannot be neglected in terms of resource consumption and waste generation processes and therefore needs immediate attention, in order to reduce the adverse effects of the construction industry. This knowledge gap is acknowledged and the primary aim of this research will thus be to understand the concepts of CE in detail along with its implementation barriers for urban railway infrastructure. Taking into consideration the importance of assessment frameworks and indicators as described in section 1.1, this study will focus on generating an assessment framework for urban railway infrastructure.

1.7 PROBLEM STATEMENTS

In order to clearly understand the deficits of this research area and to help better formulate the research questions, it is necessary to highlight the major aspects that will be covered in this study. These points will be described as problem statements which will provide a brief outline of the main topics that need to be analysed.

Problem statement 1 – *The definition of circular economy is ambiguous*

Since its inception, CE has come a long way in terms of development and implementation of its principles. More and more businesses are embracing the concepts of CE and are actively making efforts to improve their methods. Even though CE was first introduced by EMF in 2012, there still exists ambiguity when it comes to its definition. One notable contribution in this field by Kirchherr, Reike, & Hekkert, 2017, who analyzed as many as 114 definitions of circular economy and studied the different perceptions that have evolved over time. The starting point of the 114 definitions of circular economy clearly depicted the absence of a single universally accepted defintion. The researchers concluded their study by defining CE in such a way that encompassed all different notions and point of views that they could analyse. Therefore, in order to generate a more appropriate framework, it is essential to study the different aspects and definitions of CE proposed in literature and find a suitable definition that can form the basis of this study.

Problem statement 2 – *The existing frameworks do not fully encapsulate all the major principles of circular economy*

Since CE is often differently interpreted, there exists multiple frameworks that try to encompass the different aspects that are developed on the basis of one of the many definitions. The existing frameworks also have multiple drawbacks such as the Material Circularity Indicator's (MCI) requirement of detailed data and material passports, which as of now, in large projects is yet to be popularised (Verbruggen, 2019). Inability of the existing frameworks that are analysed to consider clear distinction between the life cycle phases and concepts such as design for disassembly calls for attention towards such aspects. Forming the basis of the new framework by keeping in mind the current drawbacks of such frameworks is essential to avoid repetition of similar pitfalls and to make it acceptable.

Problem statement 3 – *There are lack of indicators and assessment frameworks for the evaluation of railway infrastructure*

In the research conducted by Saidani, Yannou, Leroy, Cluzel, & Kendall (2019), one of the reasons for the lack of implementation of CE in the construction industry resulted due to the lack of indicators and targets. Despite the undefined boundaries of CE definitions, there exists a need for methods to measure the CE progress (Moraga, et al., 2019). Assessment of CE is important, as the extent to which CE is implemented needs to be measured for further recommendations and improvements. Since the concept of CE has gained traction, some new methods have come up whereas at the same time, modifications to assessment methods that were previously used to measure sustainability have been made. The lack of information exchange regarding CE implementation and its knowledge is also cited as a constraint for the success of CE practices (Saidani, Yannou, Leroy, Cluzel, & Kendall, 2019). Indicators play an important role in generating an assessment framework as it forms the basis. So far according to literature, the study on indicators and their categorization has focused more on buildings and seldom for railway infrastructure projects. Therefore, a study of indicators is essential before devising a final framework as their importance has also been highlighted by The European Commission in its action plan for the CE (European Commission, 2015a).

Since CE in transport infrastructure lacks the basic study, it is also evident that a formal assessment/reference framework is absent. In order to overcome the knowledge deficit of CE in this sector, it is important to preserve and exchange the knowledge that is being implemented in such infrastructure projects. Assessment frameworks can prove to be crucial in this regard as they not only pose a reference for CE implementations but also help in restoring the methods of a particular CE infrastructure project that can be later used for future projects.

1.8 RESEARCH QUESTIONS

The introduction of the problem statements leads to the formulation of the main research question and the sub-research questions which are detailed hereafter.

Main research question

> HOW CAN URBAN RAILWAY INFRASTRUCTURE BE ASSESSED IN TERMS OF CIRCULAR ECONOMY PRINCIPLES?

Research sub-questions

In order to develop a suitable and feasible framework, it is necessary to understand the scenarios that lead to the formulation of such a research question. Hence, to better understand and sufficiently answer the main research question, it is important to break down the research into smaller work packages which can lead to the final solution in a more structured and systematic manner. Therefore, the first sub question will focus on understanding all definitions and what it entails before deciding on a particular perspective that is suitable for this study. This results in the first sub-question as:

Sub research question 1) What is circular economy in the construction industry and what are its current trends and barriers for railway infrastructure?

The answer to the first question will help in providing a clearer picture of the concept of circular economy in the construction industry and its development since its first implementation. The different principles of CE along with the plethora of definitions will be studied in order to form a concrete base for this research. This part of the study will be conducted by extensive review of past studies of academic papers and any relevant sources. Understanding the barriers in practice is essential and expert interviews will be conducted to analyse these barriers. The answer to this research sub-question will also resolve the first problem statement. Once the concepts are well understood, the next step in the research will be to study and understand the already existing assessment frameworks which are widely used. As already mentioned, many such frameworks exist but often come with specific drawbacks, and in order to develop a framework which is relevant, a deeper understanding of these frameworks is necessary. This leads to formulation of the second research question as:

Sub research question 2) What are the barriers and opportunities of the already existing frameworks to evaluate and assess CE?

The answer to this sub- research question will help in understanding the drawbacks of existing frameworks in order to avoid similar pitfalls and to encompass concepts and principles that were previously omitted. This step can be useful in understanding the method of development of such frameworks and form a strong base for the new framework of this study. Since majority of the already existing frameworks are based on the concept of indicators along with academic validation of their importance (Linder , Sarasini, & Loon, 2017), it is essential to develop a set of indicators that can help generate a base for the new assessment method. Indicators so far, as mentioned before, seldom focus on transport infrastructure and it is therefore necessary to develop new indicators, resulting in the formation of the third sub-research question of this study as:

Sub research question 3) What are the common indicators of circularity for urban railway infrastructure?

The answer to this sub-research question will help in outlining a set of indicators that can aid in the development of the backbone of the assessment framework of this study for the different life cycle phases. These indicators will generate a basis on which the transport infrastructure can be judged and can be categorized based on different criteria. The final step of the research will require translating these indicators into an assessment framework along with their score aggregation, appropriate weighting, categorization and prioritization which leads to the formulation of the final sub-research question:

Sub research question 4) What are the steps needed to formulate these indicators into the final framework?

The answer to this sub-research question will lead to the final formation of the assessment framework. The indicators generated in the previous step need to be formulated so as to develop a framework that can successfully achieve its goal. The importance of indicators may vary based on their contribution to the overall goal and would hence require appropriate sorting. Indicators for different life cycle phases also need to be weighed against each other to judge the difference in importance for the different phases. The previous steps outline a general idea regarding the multiple options within indicators and choices need to be made to substantiate and include the necessary indicators for the framework. Satisfactorily answering all the above sub-research questions will eventually help in answering the main research goal and develop an assessment framework for urban railway infrastructure whose results will be validated by performing 2 case studies.

1.9 STRUCTURE OF THE REPORT

Chapter 1 of this report establishes the research gap and the research questions of the study. The methodology adopted along with the scope of the project will be defined in chapter 2. Chapters 3 describes the theoretical background of circular economy, elaborates on its principles and definitions, and chapter 4 provides the basic theory regarding the different railway infrastructure components. The detailed design of the framework, the results from the interviews and the development of the different modules and substantiating the choices are described in chapter 5. Chapter 6 gives a general overview of the framework and its working along with a case study. Discussions regarding the results are described in chapter 7 along with the research limitations, followed by a conclusion and recommendations in chapter 8. The division of the research along with the contents of the chapters relating to the individual sub-research questions can be seen in figure 2.

1.10 SUMMARY

The chapter highlighted the clear need for a circular economy given the largescale consumption and waste generation patterns of the current linear economic model. Currently the waste streams are an afterthought, an annoyance. For the longest time, the planet was resilient, and it absorbed the waste we produced. With the current exploding population trend, we need to consider the impact of our actions. To overcome the problems associated with the waste streams, it is essential to create a shift in the paradigm by which we convert our waste into something valuable. This shift can be achieved by transitioning towards a circular economic model which decouples the economic growth from the finite resource consumption. Ideally, CE aims to eliminate waste streams altogether by closing the loop through endless reuse of materials (Alstom, 2016).

The global population is estimated to increase to 9.7 billion by 2050 out of which 70% of people will reside in urban areas (Alstom, 2016). This increase in population has a consequence on the global urban transport emission and can lead to generating twice as much as emissions of nearly 1 billion annual tonnes of CO_2 equivalent by 2025 (Alstom, 2016). To achieve the national and international goals set by governments and for cities to be green, the dependence on cars needs to be reduced which in turn increases the demands for trains (Alstom, 2016). This can result in an increased number of railway projects causing an increased material demand. In order to ensure that these upcoming projects do not pose any additional threats than the existing ones, efforts must be made to build such projects in the most sustainable and circular ways.

The current trends within the Dutch construction industry depict that the primary focus is on lowering carbon emissions and changes to the material consumption patterns are often overlooked (Alstom, 2016). Though carbon and other GHG emissions pose severe environmental problems, these can also be reduced by implementing circular solutions as cascading components can prevent the carbon intensive production processes of such materials.

The lack of implementation of CE principles can be attributed to the lack of indicators and targets (Saidani, Yannou, Leroy, Cluzel, & Kendall, 2019). Assessment and measurement of CE is important, as the extent to which CE is implemented needs to be measured for further recommendations and improvements. In order to overcome the knowledge deficit of CE in this sector, it is important to preserve and exchange knowledge which can be done by with the help of assessment frameworks. To bridge the gap and accelerate the transition towards CE, the research and sub research questions of this study were so established that they can aid in developing an assessment framework for urban railway infrastructure.

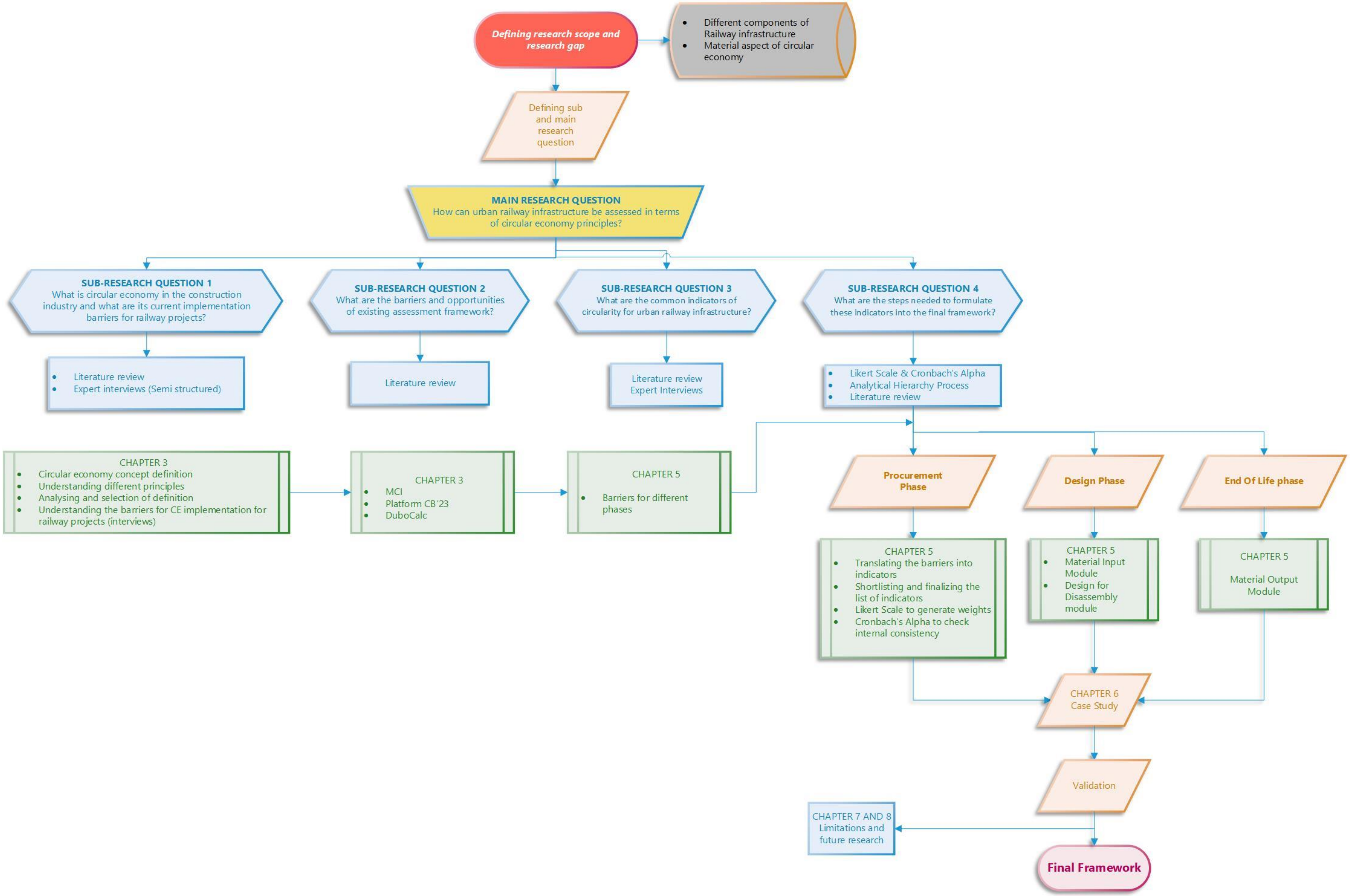

Figure 2:Research flowchart

2. RESEARCH DESIGN

This chapter outlines the scope definition along with the research methodology and the methods of data gathering. The chapter concludes by explaining the relevance of this research in different aspects.

2.1 SCOPE OF RESEARCH

CE in all its existence has a vast scope and encompasses many facets depending on the focus area. This research will focus on the material circularity aspect of CE along with the design for modularity and disassembly for railway infrastructure. Other aspects such as the environmental impacts and energy consumption patterns will not be included in this study. The study aims to focus on all the life cycle stages of a railway project, right from tender phase to the end of life cycle phase which makes it difficult to focus on all the aspects of CE given the limited time scale of this research. Moreover, the energy and environmental impacts have been extensively studied in relation to sustainability. Although these aspects are excluded, the basis of the framework for two of the life cycle phases (design and end of life phase) is the R framework which indirectly takes into consideration the different energy aspects for the different processes and to a certain extent the environmental impacts. Differentiating the importance between the different components of the railway infrastructure is based on GHG emissions. Thus, even though the environmental aspect is not explicitly considered, it has been incorporated in the framework to a certain extent. The railway infrastructure is defined as *"The railway track and all the civil engineering structures and systems/premises that ensure the railway traffic"* (PYRGIDIS, 2014, page 1)**.** Within this study, the primary focus will be on the railway track components along with the overhead line systems. Other aspects such as the civil engineering structures (bridges and tunnels) will not be included in this study. Facilities/premises fall within the scope of the building sector, on which a vast study relating to CE has already been performed, and hence, will be excluded as well. Detailed parts of the components that are included in the scope can be seen in figure 3.

2.2 RESEARCH METHODOLOGY

The overall research methodology that was used for this project was the "Double Diamond" method which was introduced by the Design Council in 2004. As the name suggests, this method involves two diamonds that represent a deep and wide exploration of a problem, keeping all aspects in the study open, and grasping the overall background knowledge (divergent thinking), followed by implementation of a refined and focused action (convergent thinking). The double diamond indicates that the diverging and converging phase happen twice; once to confirm the problem definition and once to create the solution (Bos, 2020). The diverging phases are carried out by an open-minded approach in order to gather data from all relevant sources, whereas the converging phases consist more of a logical analysis and feasibility study that can lead to an appropriate solution. The 4 phases that encompass the double diamond method are - discover, define, develop and deliver. On these lines, this research started with the problem analysis and the current state and goals of the circular economy in the construction industry.

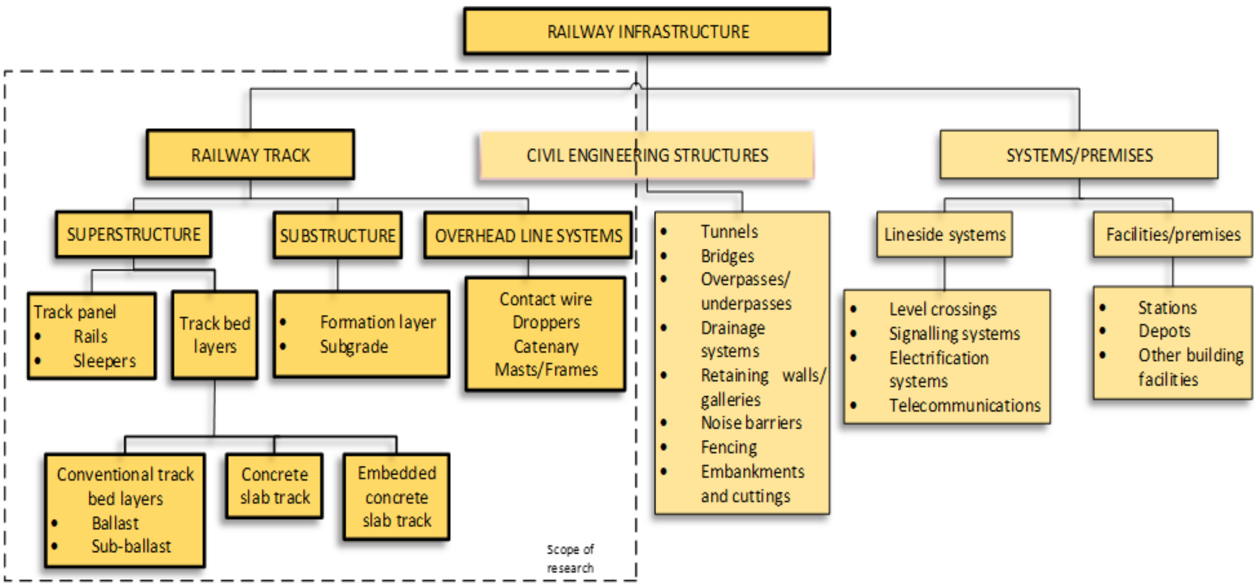

Figure 3: Components of Railway Infrastructure (Own illustration, Source: (PYRGIDIS, 2014))

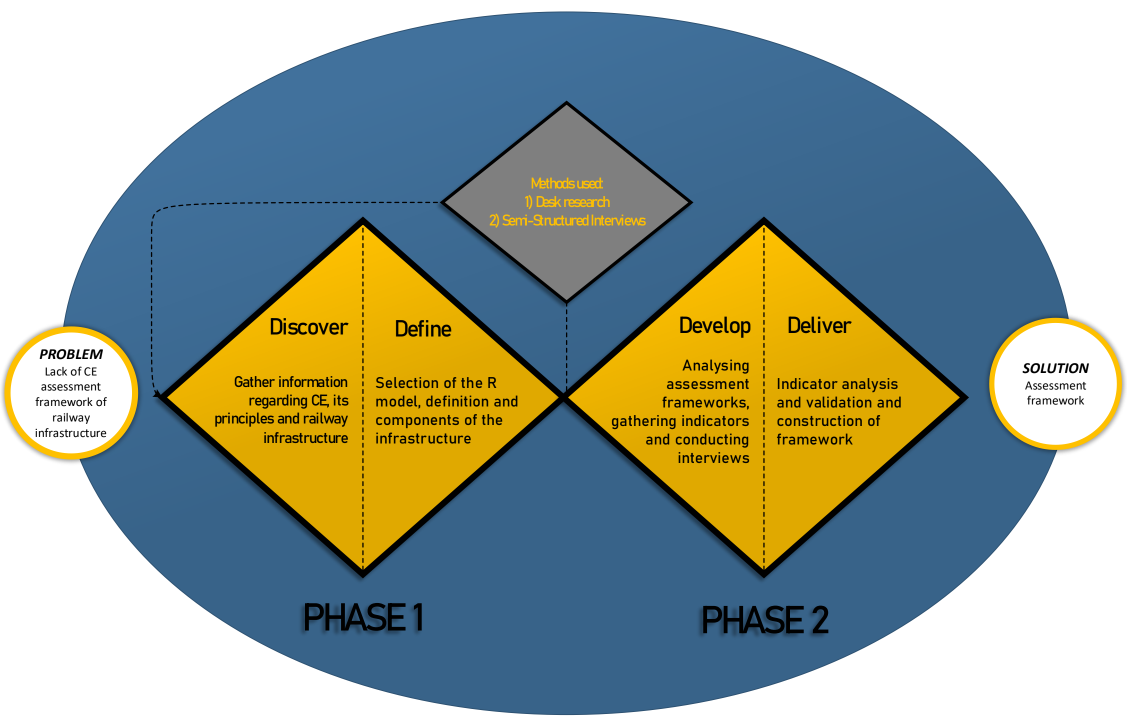

Figure 4: Double diamond method (Source: (Bos, 2020))

The discover phase: This phase helped to understand the vivid perceptions about CE. It aided in gathering information regarding CE definitions and its principles along with the study of the railway components that are defined in the scope.

The define phase: After understanding the concept and its related principles, this part focused on the selection of the R model and analysis of the definitions. The broad umbrella concept that CE is, was narrowed down by selecting a single definition that could encapsulate the necessary facets of the construction industry and could be referred to for this study to form its base.

The develop phase: Existing frameworks and their shortcomings were analysed in this phase along with exploring the possible indicators that exist in theory that can relate to urban railway infrastructure. Since there exists a lack of study in this field, it was necessary to conduct interviews with experts to gain deeper insights and barriers. Analysis of these indicators for the different life cycle stages was conducted and once the database was complete with the necessary indicators, the next stage of delivery phase converged this framework by formulating the final framework.

The deliver phase: This was an an iterative process as the final assessment framework was validated through case studies and experts. After the second diamond, the two case studies reflected the applicability and validity of the developed framework.

2.3 DATA GATHERING

The division of the research into its sub-questions makes it easier to focus on the individual aspects. Each sub-question can be tackled in a different manner to conclude on its answers. Various methods are used in this research to sufficiently answer the sub-research questions, such as desk research, semi-structured interviews, Likert scale and analytical hierarchy process. The outline and purpose of these methods is described in the following sections.

2.3.1 Desk research

To answer the first sub-question, the method of research will include an extensive review of past studies. Since it is important to know the already existing trends and concepts of circular economy in the construction industry, these can be found well embedded in academic literature and reports that are published worldwide. Search engines such as “google scholar” and “scopus” will be used to gather literature for this part of the study. The scope of this search will include papers and articles that focus their aim on CE primarily for the construction industry. Web articles will also be researched as they can include information on company websites regarding latest projects and trends. Sufficient data can be gathered by these means and will eventually help to satisfactorily answer the first two sub-questions. Since the frameworks do not usually provide their advantages and disadvantages at the source of their developers, it is essential to obtain neutral and critical viewpoints of researchers and experts who have expressed their views in academic literature.

Before diving deeper into the development of the framework, it is also essential to understand the various railway components and their developments overtime. Since the researcher lacked background regarding railway engineering and infrastructure, these topics were additionally studied. Educational books along with academic literature from similar sources were used for this purpose. Books were obtained from the worldwide web, the library at the Technical University of Delft and from the supervisors of this study. The uniqueness and detailed scope of the topic at hand, limited the study of indicators for urban railway infrastructure from academia to a very few articles. To bridge the gap and identify more of these indicators along with the barriers that hinder the implementation of CE in the railway industry, another form of data gathering was used by means of conducting interviews.

2.3.2 Semi-structured interviews

This method of data gathering is suitable for this research as it has a mixture of open and closed questions that also have the possibility of a follow up "how" or "why" questions (Bos, 2020). This can be helpful to gather data as the infancy of the topic limits data from academic literature. Interviews are conducted with the experts in the relevant field and the information obtained is further analysed. The interviews are aimed to be semi-structured and open ended in order to gain sufficient knowledge and vivid perspectives about the topic from the involved interviewees. This process was iterative and mostly aimed to achieve answers to sub-research questions 1 and 3. The interview template is presented in appendix A. Multiple rounds of interviews were conducted to achieve different goals. The first round of interviews were planned to understand the current state of CE in the railway industry, and its implementation barriers. The criteria for an 'expert' for this research was to include respondents that have been extensively involved with railway projects and are well versed with the different processes involved. Experience in relation to CE or at least sustainability was also necessary. This can be judged based on the understanding of the topic and its principles, as projects with CE implementation are very rare. For the first round, a total of 11 respondents were interviewed, details of which can be seen in table 1.

Table 1: Expert Panel

Respondent ID	***Role***	***Organisation***
Respondent 1	Senior railway consultant and project manager	Mott MacDonald, Netherlands
Respondent 2	Resource exchange manager	Network Rail, U.K.
Respondent 3	Group sustainability advisor	Mott MacDonald, U.K.
Respondent 4	Principal Carbon Management Consultant	Mott MacDonald U.K.
Respondent 5	Process manager sustainability	ProRail, Netherlands
Respondent 6	Circularity ambassador	ProRail, Netherlands
Respondent 7	Sustainability and innovation consultant	Metro and Tram, Gemeente Amsterdam, Netherlands
Respondent 8	Infrastructure Advisory and Sustainability Consultant	Mott MacDonald, Canada
Respondent 9	Sustainability and Circularity consultant	Copper 8, Netherlands
Respondent 10	Focus manager reuse and recycling	Voestalpine Railpro BV, Netherlands
Respondent 11	Head of Environment & Sustainable Development	Network Rail, U.K.

A second round of interviews was conducted for deciding the weights of the different life cycle phases, details of which will be discussed in the following section. The experts for this round were strictly chosen based on their experience in both CE and urban railway projects. For this, respondents 2,4,6,7 and 11 were interviewed. A third round of interviews was conducted with respondent 1 (table 1) and respondent 16 (table 3), while performing the case studies.

2.3.3 Analytical hierarchy process

AHP is described as a weighing method which aids decision makers to appropriately calculate weights instead of arbitrary assignments (Nardo, Saisana , Saltelli, Tarantola , & Giovannini, 2005). To begin with, a pairwise matrix is constructed in which the criteria that need to be scored are listed. These criteria are then judged by experts on a scale of 1 to 9, description of which can be found in table 2. Depending on how important each criteria is as compared to the other, the relative scores or weights are determined. In AHP, the scores are determined based on the consistency of the input matrices. This method also entails a consistency check measured through the consistency ratio (CR). Since the judgements of experts can be inconsistent, measuring the extent of this inconsistency is important. AHP allows inconsistencies up to 10% and provides a check during assessment (Gan , et al., 2017). The method involves comparing the criteria in pairs which makes judgements and calculations simpler and is therefore a "General theory of measurement" (Saaty, 1987). For calculation purposes in this research, a pre-existing Excel spreadsheet was provided by Mott MacDonald that was used for all the AHP calculations. Nevertheless, the steps involved are described in section 4.6 along with the results of the calculations.

Key features of AHP:

- It has been previously used to determine weights for sustainability indicators
- It is simple and flexible
- It provides a consistency check, which can be used as feedback for experts to revise their judgements and finally validate the results
- This method can be used for qualitative and quantitative data
- Clear prioritization
- Easy and proven tool available
- Pairwise comparison is straightforward and convenient
- Single round of interviews is sufficient, therefore less time intensive

There were 2 major instances that required the weighing of criteria quantitatively for appropriate assessment. First instance where the analytical hierarchy process (AHP) was used, was to assign weights to the different aspects that were included for the Design for disassembly (DfD) assessment of the framework. While generating the indicators for this part of the study, multiple indicators were analysed and choices were made to include the most suitable ones. To assess the components on these indicators, it was necessary to assign scores to each category. While for some categories the scores were referenced from literature, whereas for one subcategory, it was essential to develop scores. For this purpose, AHP was used and details about which will be further explained in section 2.3.3. The second instance of implementing this method was to determine the importance of the different life cycle phases of the project as compared to each other. During the interviews it was observed that different stakeholders considered certain life cycle phase to have a greater influence on circularity of a project as compared to another. In order to grasp this difference and to assign appropriate weights, AHP was used.

For the first instance that implemented the AHP was to assign scores to the DfD aspects. For the purpose of this assignment, the experts did not require specific knowledge about CE as these criteria were based on damage caused to the components and their applicability to be kept in a closed material loop. For this reason, supervisors of this study were deemed fit even though circularity was not their area of expertise, as over the course of the research their involvement provided them with sufficient background to assess these different criteria.

For the second instance regarding differentiating the different life cycle phases, it was necessary to select experts from the field who had specific knowledge and experience about circular economy in railway infrastructure projects. Therefore, 5 experts (Respondents 2,4,6,7 and 11) who matched the requirements were chosen and interviews were conducted online wherein the process of AHP was initially explained followed by the completion of the pairwise matrix.

Table 2: AHP score description (Source: (Nardo, Saisana , Saltelli, Tarantola , & Giovannini, 2005))

Intensity of importance	***Definition***	***Explanation***
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience slightly favours one indicator over the other
5	Strong importance	Experience strongly favours one indicator over the other
7	Very strong importance	One indicator is very strongly favoured over the other and the dominant nature is demonstrated in practice
9	Extreme importance	The evidence favours one indicator over the other in the highest possible affirmation
2,4,6,8 can be used to expressed intermediate values		

2.3.4 Likert scale

While analysing the qualitative indicators for the procurement phase, it is necessary to differentiate these indicators based on their level of influence and impact in terms of circularity on projects. To do so, AHP was not suitable for this prioritisation as it includes comparing each indicator in pairs with another, which would result in comparing 25 indicators with each other, for all the respondents. This would be a time-consuming process and was hence not a suitable option.

Another method amongst the many present in literature was the Likert scale, that can be used to produce hierarchies or preferences (Fellows & Liu, 2008). In the Likert scale, “the respondents are given a scale along with its brief description associated with each category. The categories are ordered in terms of scale position and the respondents are required to select the specified category that best describes the object being rated” (Fellows & Liu, 2008, page 169).

Though this scale is widely used, there is an ongoing debate regarding the categorisation of the Likert scale as either ordinal or interval scale. Joshi, Kale , Chandel , & Pal , (2015), highlight that since the distance and magnitude between two points on the Likert scale cannot be shown quantitatively, it cannot be treated as an interval scale. On the other hand, they also mention that “when the goal is to ‘combine’ all the items in order to generate a composite score for an individual rather than separate analysis of single item responded by all individuals, then this individualistic summative score of a participant shows a sensible realistic distance from the individual summative score of another individual, hence can be labelled as interval estimates" (Joshi, Kale , Chandel , & Pal , 2015, page 399).

The qualitative list of indicators developed for the procurement phase needed differentiation between the different indicators based on their contribution towards circularity. It was evident from the interviews that not all the listed indicators were equally important. Certain indicators were easily achievable but did not contribute as much as others in terms of circularity. This would eventually give rise to opportunistic behaviour in practice and unfair results. To prevent these shortcomings of the framework, it was decided to rank these indicators in a hierarchy and weigh them accordingly with the help of inputs from experts through the Likert Scale. A total of 14 respondents, who were selected based on the criteria defined in section 2.2.2, were requested to complete the survey. Among the respondents mentioned in table 1, respondents 3 and 9 could not participate in the survey due to time constraints on their schedules. In replacement, 5 new additional respondents were approached who participated in this survey, details of which are mentioned in table 3.

Table 3: Additional experts for Likert scale survey

Respondent ID	***Role***	***Organisation***
Respondent 12	Circular economy researcher	Technical University of Delft, Netherlands
Respondent 13	Asset manager tram track infrastructure	The Gemeentelijk Vervoerbedrijf, (GVB), Amsterdam, Netherlands
Respondent 14	Circular economy researcher	Technical University of Delft, Netherlands
Respondent 15	Lead Buyer and circular procurement	Gemeente Amsterdam, Netherlands
Respondent 16	Public Transport specialist and consultant	Mott MacDonald, U.K.

2.3.4.1 *Cronbach's alpha*

Cronbach's alpha can be used to determine the internal consistency of the questionnaire developed for the prioritization of procurement indicators. It demonstrates the fit for purpose characteristics of tests and scales (Taber, 2018). Internal consistency checks whether the indicator and the formation of the Likert scale measures what it is intended to measure, during the procurement phase. The Cronbach's alpha can vary from 0 to 1, and higher values of alpha depict greater internal consistency of the data.

2.4 RELEVANCE OF THE RESEARCH

2.4.1 Scientific Relevance

As stated earlier in the knowledge gap, the importance of transitioning towards more sustainable and hence CE methods is imminent. Given its significant impact on the climate, it is essential to develop circular methods to reduce the ill effects of the construction industry. Even though significant work is carried out for CE in theory, there is a lack of implementation. One of the reasons stated in theory for this drawback is the absence of sufficient knowledge and information transfer (Saidani, Yannou, Leroy, Cluzel, & Kendall, 2019). The transport infrastructure being an important part of the construction sector, is often neglected when it comes to the transition from linear to circular methods. To bridge this gap and satisfactorily develop a solution to this problem, this research works on understanding the hinderances for this transition in CE for infrastructure projects.

2.4.2 Practical Relevance

To transition towards CE for large infrastructure projects, companies and organizations require guidelines and information regarding the appropriate measures. The final product of this study can help companies to not only judge their work on its completion but also help them implement CE in new projects. It can act as a guideline and determine areas for which a certain project can further improve to minimize linear methods. Since the methodology of this project takes into account expert views and inputs, the product can be a close link between the CE and actual trends.

2.4.3 Governmental Relevance

In order to reach the goal set by the Dutch government and by the EU, it is important to work towards a successful transition from linear methods to more circular ones. The Dutch government has set its goal to reach complete circularity by 2050 and in order to do so it is important to take into consideration all the aspects that are included in the construction sector. The lack of focus on transport infrastructure can cause delays in reaching such targets and it is therefore necessary to work on these fronts.

2.4.4 Societal Relevance

The fast-rising temperature and climate change are the most important issues that pose a threat to mankind. If the current linear economic trends continue, apart from leading to the extinction of our resources, they also possess a threat to human existence. Resource depletion will soon result in a global problem that if not acted upon earlier, will lead to severe consequences. The introduction of CE in this regard can help prevent these problems from radically changing planet earth. The construction industry has played an important part in the economy of a country but at the same time also caused major environmental problems and therefore to continue reaping its multiple benefits, it is essential to move towards a more sustainable method.

2.5 SUMMARY

This chapter described the research design for this study and elaborated on the scope of the project. The environmental indicators have already been studied extensively in frameworks such as DuboCalc. From the complex system of urban railway infrastructure, the railway tracks consisting of the superstructure, substructure as well as the overhead lines were included within the scope.

Methods to gather data for satisfactorily answering the sub-research questions and the main research question included desk research and semi structured interviews. Review of past studies of different concepts of CE and the components of railway infrastructure provided an extensive knowledge base. For instances where current trends were to be studied and review of past studies did not provide sufficient information, semi-structured interviews with the experts from the field were conducted. Multiple rounds of such interviews helped in understanding barriers for CE implementation and for completing the case studies. The weighing method such as AHP also helped in determining weights of indices and for life cycle phases whereas the Likert scale aided the determination of indicator weights for the procurement phase.

3. THEORETICAL BACKGROUND on circular economy

Before developing a framework for the assessment of CE, it is essential to understand its core values and principles. Since the concept has been in the spotlight for a few years, various researchers have provided in depth study of CE concepts and their perceptions which are essential to understand. This chapter focuses on understanding the concepts and principles of CE and thus successfully answer the first sub-research question of this study.

3.1 INTRODUCTION TO CIRCULAR ECONOMY

Increasing climate and environmental problems have put a serious question mark on the healthy living of the future generations. The rise of global warming and erratic weather changes all over the world have forced researchers and scientists to suggest some drastic, yet important changes that need to be implemented in order to survive in the coming years. One major aspect that leads to such global problems is the heavy consumption of virgin raw materials and enormous amounts of waste production and carbon emissions. The current world population is expected to rise to 9.8 billion in 2050 (Towards the circular economy, 2013), which poses an increasing threat to the depletion of energy and resources. Therefore, the traditional "make-use-dispose" model which is heavily responsible for large amounts of raw material consumption and waste production, needs to be replaced by the more circular model. One industry that can make use of the circular ideology and drastically reduce its negative impact on society and the climate is the construction industry. Half of the annually excavated raw materials are intended for the use of the construction industry, and eventually leading to equal, if not more amounts of waste (Anastasiades, Van Hul, Audenaert, & Blom, 2020).

Though the mention of CE dates back to the 1970s (Zimmann, O'Brien, Hargrave, & Morrell, 2016) this concept has gained considerable attention from academia and practice over the past few years. One of the main frontrunners is the Ellen MacArthur Foundation that has led the developments in the field of CE and has since made its primary aim to help transition practices from the traditional linear methods to more circular methods. The current global economy is only 9.1% circular (Sande L. v., 2019), and given the increasing rate of development and the amount of materials consumed, the effect of such a transition on a large scale may be significant. The primary aim of CE focuses on closing the material loops and thereby reducing the amount of waste generated. This is mainly done by connecting the gap between the end-of-life (EoL) phase and the material inputs phase by using the products and materials which are at the end of their life cycle as feedstock for new constructions. This principle of CE builds on past sustainability ideas like the "People-Planet-Profit", "Cradle to Cradle", etc (Leendertse, Hendriksen, & Kerkhofs, 2018, ARUP, 2020). The EMF's visualisation of CE through the butterfly diagram (Figure 5) is also vastly used in understanding the concept and helps understand their vision for CE. The diagram depicts two loops, that represent two distinct material flows: one within the biosphere and the other relates to the technosphere. The materials that constitute the biological sphere consist of materials that are safe to be released back in the environment without any additional processes, and can return their embedded value and nutrients back into the environment. On the other side of the diagram, within the technosphere, the materials represent the ones that cannot be relesased back into the environment directly, such as metals, plastics, chemicals, etc. These technical materials are to be kept within the cycle while at the same time retain their highest possible value. These value retention loops are shown within the technosphere loop depicting various possibilities to maintain product value. The smaller loops are preferable to the larger loops as these require less energy to maintain the value as opposed by the outer, larger loops.

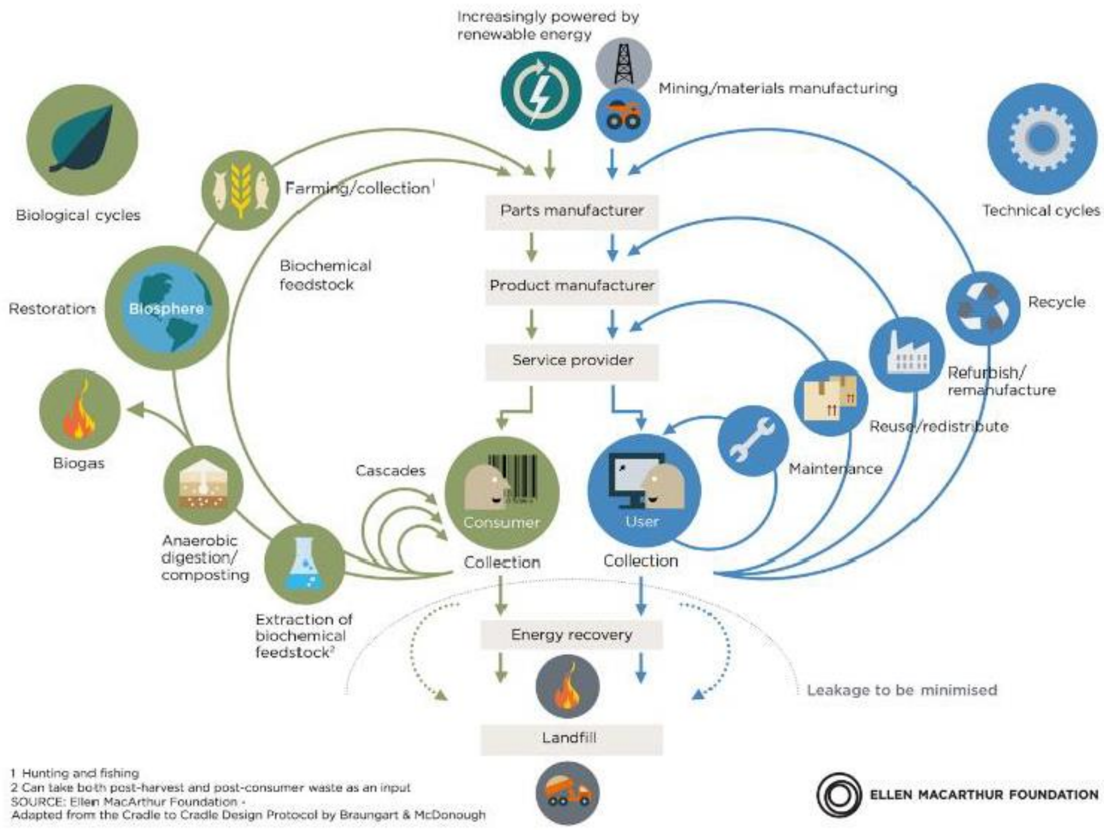

Figure 5: Circular Economy Butterfly Model
(Source: (The Ellen MacArthur Foundation, 2015))

CE not only focuses on reducing pollution by using preventive measures but also aims at improving previous production processes by designing better systems which helps in attaining higher values from resources (Duan, 2019).

3.2 PRINCIPLES OF CIRCULAR ECONOMY

As mentioned in the earlier sections, the concept of CE has gained a considerable interest over the past few years. A study by Kirchherr et. al (2017) showed that peer reviewed articles depicted an increase to more than 100 articles in 2016, whereas the number was as low as 30 in 2014. Kircherr et al (2017), distinguished two key principles of CE: the R framework and the systems perspective. Out of the two, the R framework is better known and is the base for multiple policies and frameworks. The latter highlights the need to make a fundamental shift in the system rather than making adjustments in the current model. The 3R framework that constituted the “Reduce, Reuse and Recycle” principle is the basis of the 2008 Circular Economy Promotion Law of the People's Republic of China. A later modification of this model which consisted of an additional R for "Recover" also forms the core of the European Union Waste Framework Directive (Kirchherr, Reike, & Hekkert, 2017). Multiple studies have also shown the further development of such models that include a total of 10Rs (figure 6). Potting, Hekkert, Worrell, & Hanemaaijer (2017) enlists the different 10Rs that are widely used in various frameworks. These Rs typically represent strategies from high circularity to lower circularity and have played an essential role in the formation of Dutch policies on waste treatment. The main and the common feature of these R frameworks is its hierarchial structure, in which the Rs are prioritised and different Rs which lie up in the ladder have a greater significance.

It is also observed that majority of the studies focus on "recycling", which might lead to a different perception of CE. Even though, recycling, is a sustainable environmental practice that slightly reduces the demand for virgin raw materials, usually involves stripping the product off of its original value and most often downcycling the product for an inferior application. This causes a significant loss of initial energy and hence goes against the main aim of CE which is to maintain products at their highest value with minimum energy loss (Verbruggen, 2019). For instance, in the Dutch construction sector, 95% of construction and demolition waste (CDW) is recycled, which would then indicate that the Dutch construction sector is almost completely circular as most of the products are recycled. However this recycling of materials and products involves downcycling such elements and using high grade materials for low grade solutions such as high strength materials being used for road foundations (Sande L. v., 2019). Recycling also utilises additional energy, input of raw materials and generation of wastes (Buren, Demmers , Heijden, & Witlox , 2016).

Thus the original demand for such new products still exists and therefore, maintaining and giving a fair share of importance to the R hierarchy framework is necessary to implement optimum CE methods. This R model forms the basis for the framework of this study in some of the life cycle phases. Though the different Rs that are depicted are well suited for the circular strategies, it is necessary to highlight that these were initially developed for product chains and not for the building and infrastructure sector. Due to this, some Rs (Refurbish, Remanufacture, etc) are used to a lesser extent in literature and the scope of these Rs is tailored to fit the context of the life cycle phase in chapter 5.

The need for a circular economy is evident but the transition steps are still unclear and require guiding principles in order for the industry to achieve a common goal. To produce a common language for a smooth transition, Rijksvastgoedbedrijf (the Central Government Estate Agency, Netherlands), De Bouwcampus, Rijkswaterstraat and NEN (Royal Dutch Standardization Institute) set up a body called the Platform CB'23 that worked with multiple stakeholders like clients, recyclers, policymakers, builders, etc to reach a set of agreements that can aid this transition, and provide working agreements and help measure circularity.This action team, in their report also outlined 3 core principles (NEN, 2020) of CE which are:

1. Protecting material supplies
2. Protecting the environment
3. Protecting existing value

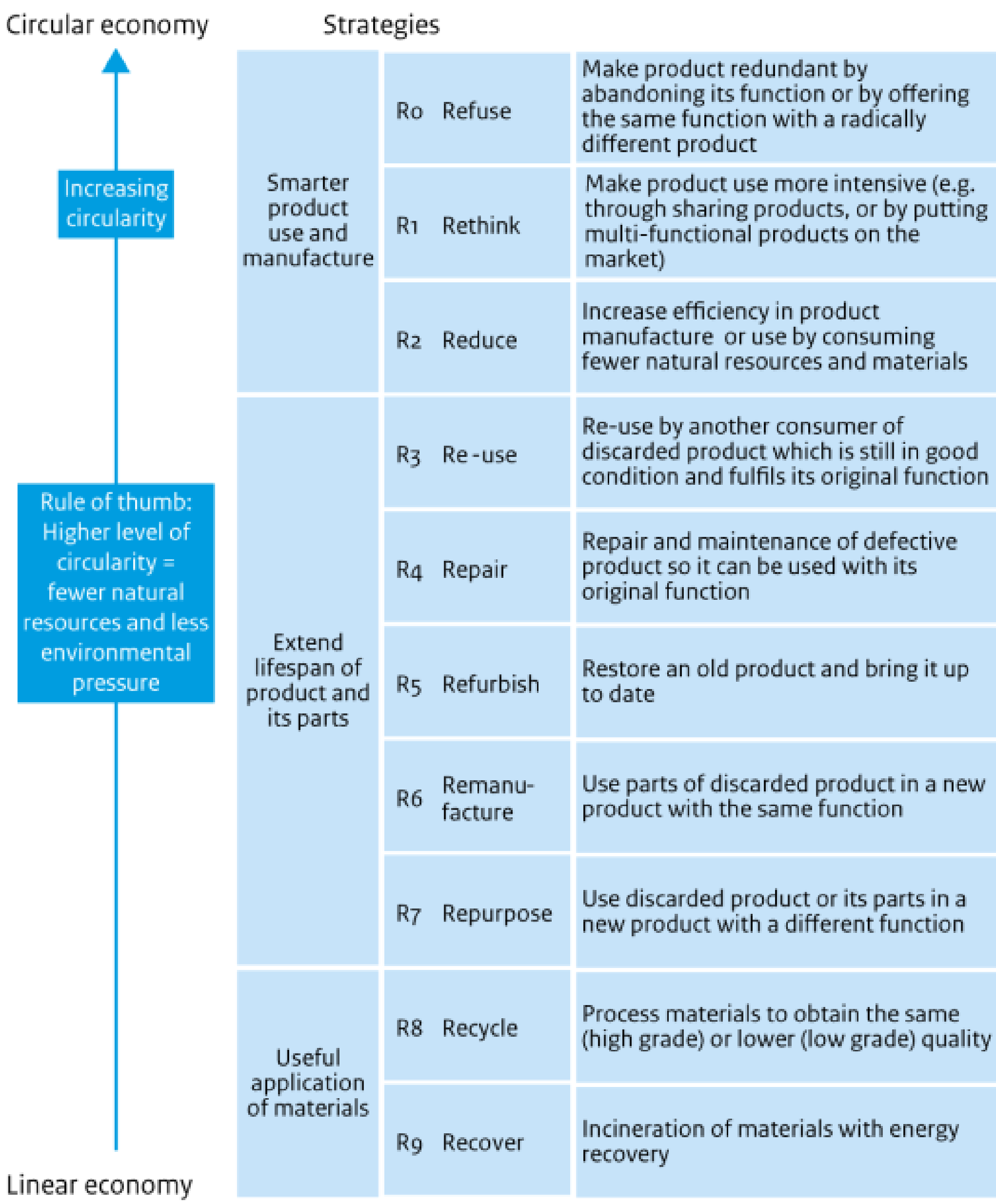

Figure 6: 10R Model (Source: (Potting, Hekkert, Worrell, & Hanemaaijer, 2017))

The EMF which has made immensely important and drastic contributions in the field of CE has also in its report, mentioned the core principles on which CE builds. The principles have evolved since their early development in the first report of 2012 but have stayed consistent after 2015. Even though there exists a difference in the definition of these principles, the intended aim behind it has always been the same. The principles that are included in the report of 2015 (Foundation, 2015,page 22) are:

- Design out waste

This principle aims to minimise waste generation and theoretically, produce zero waste. Generation of waste is often the result of decisions made during the design phase and therefore the intention behind this principle lies in the consideration of the end of life phase during the initial design phase, which can curb the problem of waste generation as the product can be reused, remanufactured or repurposed for the same or different technological cycle.

- Build resilience through diversity

The second principle sheds light on the diversity that is included in the natural system which helps it to thrive in adverse circumstances. This ideology should also be followed in the technological systems in which the methods are built to sustain changes and shocks that can occur due to changing conditions of the surroundings. Systems can derive greater value from diversity by sharing the resource pools.

- Shift to renewable energy sources

Thirdly, given the ever growing stress on fossils and other non-renewable sources, there is a drastic need to switch to more reliable and environment friendly sources in order to limit the damages on a global level.

- Think in systems

The EMF believes that in order to transit towards a CE it is important to think about all the actors involved in and changes within a single organisation or a company are not sufficient. To understand and work towards achieving a CE it is important to think about the system as a whole and not just about individual levels. It is necessary to understand the interrelationships of different actors and products within a system and work towards designing a cohesive system.

- Think in cascades

The last principle aims in extending the lifetime of products by reusing them at their highest value in similar or other applications. All these principles draw inspiration from the working of the natural systems and surroundings which have thrived despite human interferences.

3.3 DEFINITIONS OF CIRCULAR ECONOMY

There is an ever-growing interest to understand and successfully implement CE ideologies in the construction sector in order to operationalize the much-discussed concept of sustainability and also to achieve goals set by national and international governing bodies regarding circularity. As studied by Kirchherr, Reike, & Hekkert (2017), due to such interests, there exist an undefined boundary regarding the definitions of CE which leads to blurred concepts. In their study, they were able to generate a sample which consisted of 114 CE definitions, depicting the absence of a common universal definition. Measurement of circularity is not possible if the concept is not well defined. Since CE is the core concept of this research, it can be helpful in explicitly defining CE. The chosen definition can then be used to explain to the interviewees and to other participants of this research of how CE can be defined best that matches the aims of this study in order to obtain the best results. In this section, a definition tool developed by (Arntzenius, 2020) that was built to accelerate the process of definition selection is used. This tool was developed as a part of a master thesis research which categorised definitions based on 28 dimensions that were studied in literature. Since Kirchherr, Reike, & Hekkert, (2017) had performed similar research, the base of the samples used in the tool was built on their earlier work. Arntzenius, (2020) added 9 more, to the 114 already existing definitions, out of which, one definition was split into 2 and therefore generating a pool of 124 definitions in total. Efforts were made to add new definitions that were published since the development of the tool in 2019, upto December 2020. To maintain the uniformity of the tool, definitions were searched using similar databases and keywords. Therefore, the scientific database of 'Scopus' was used and the search term and limits that were applied were as follows:

"Circular economy" AND "definition" with a limit on the years of 2019-present, and the language to English.

This resulted in 42 documents which were scanned for relevance and for the presence of any new definitions. From these articles, 3 new definitions were found that had been developed and needed to be added to the definition samples. After this survey, 127 definitions of CE were eventually collected in the database of the definition tool. New definitions that are added can be found in table 4:

Table 4: New definitions of CE

	Definition	**Reference**
1.	*"The Circular Economy is a model adopting a resource based and systematic view, aiming at taking into account all the variables of the system Earth, in order to maintain its viability for human beings. It serves the society to achieve well-being within the physical limits and planetary boundaries. It achieves that through technology and business model innovation, which provides the goods and services required by society, leading to long term economic prosperity. These goods and services are now powered by renewable energy and rely on materials which are either renewable through biological processes or can be safely kept in the technosphere, requiring minimum raw material extraction and ensuring safe disposal of inevitable waste and dispersion in the environment. CE builds on and manages the sustainably available resources and optimises their utilization through minimising entropy production, slow cycles and resource and energy efficiency"*	(Desing, et al., 2020, page 7)
2.	*"Circular Economy is an economic system in which resource input and waste, emission, and energy leakages are minimised by cycling,extending,intensifying and dematerialising material and energy loops. This can be achieved through digitalisation, sharing solutions, long lasting product design, maintenance, repair, reuse, remanufacture, refurbish and recycle."*	(Geissdoerfer, Pieroni, Pigosso, & Soufani, 2020, page 3)
3.	*"CE is a strategy that emerges to oppose the traditional open-ended system, aiming to face the challenge of resource scarcity and waste disposal in a win-win approach with economic and value perspective"*	(Homrich, Galvao, Abadia, & Carvalho, 2018, page 534)

After these additions, the tool was used to determine a definition of CE that would best fit this research. Background information regarding the tool and its development can be found in Appendix B. Applying the different inputs for the search parameters of this tool resulted in no suitable definition. On further refinement of the input parameters it was noticed the resulting definitions were very vague and inconsistent. For example, one of the refinement cycles resulted in the definition given below,

"Therefore China's idea of circular economy has its own characteristics. The author believes at least the following characteristics are worth emphasizing. First, China's circular economy is an idea about the economic pattern in respect of nature rather than an idea about environmental management in some other countries, because China hopes to reduce resource consumption and pollutant production at sources and in the whole process by changing the economic pattern. It also hopes to achieve win-win in both economy and environment by circular economy instead of 'economy without recycle' or 'recycle without economy'; therefore the department proposed for planning circular economy as a whole in China is the State Development and Reform Commission which has a comprehensive nature instead of environmental management departments in some other countries. Second, China's circular economy not only aims at garbage economy or 3R economy for treating solid waste in respect of objects but at all scarce resources involved in China's economic development, including water, land, energy, materials and corresponding waste; to a certain extent, it is of more urgent significance for China to develop circular economy which deals with consumption of water, land, energy and other resources and control of related pollutants. Third, China's circular economy comprises different space levels in respect of scale and includes circular economy of individual enterprises, industrial parks and regions, etc. Fourth, China's circular economy stresses progressively increased practice forms on the following three levels in respect of pattern and emphasizes the need to develop from low-level recycle of waste based on ecological efficiency (to reduce consumption and pollution) to high-level recycle of products and services based on ecological effects (to prevent consumption and pollution)."

The above result gives a general idea about the CE goals of China and cannot be used as a definition. The decision was made to manually scan the portfolio of definitions and select a definition that best fits the context and scope of this research. This final selection was made in order to define CE in a way that can be related to the final framework and can also be used while discussion with the experts in the interviews that are to be conducted. The chosen definition states that,

"A CE aims to keep products, components, and materials at ***their highest utility and value at all times****. The value is maintained or extracted through extension of product lifetimes by* ***reuse, refurbishment, and remanufacturing*** *as well as closing of resource cycles—through* ***recycling*** *and related strategies. An alternative strategy for extension of product lifetimes may be to use products more efficiently through sharing them or making them multifunctional. All these strategies may be facilitated through changes in ownership relationships, such as leasing and product service systems (PSSs)"* (Bocken, Oliveti, Cullen, Potting, & Lifset, 2017, page 1).

This definition was chosen as it focuses on a greater R model than the 3R model and focusing on the material aspect of CE. Mention of value retention and changes in ownership models also highlights the need for not just technical changes but at the same time, organizational changes as well. Rethink of business models can play an important role in the transition towards CE. These factors align well with the defined scope of this study and is therefore chosen to be a suitable definition.

3.4 ANALYSING EXISTING METHODS OF ASSESSMENT

As discussed in section 1.1, implementation of CE is as important as its measurement. In order to successfully comment on the extent of CE being implemented in a project, irrespective of its industry, it is first important to determine a way to measure CE. The plethora of existing frameworks, focusing on different aspects of CE and the absence of such a framework for the railway infrastructure sheds light on the current problem. This section will analyse the most commonly mentioned and used frameworks for CE assessment in practice, which will help in understanding the logical steps in their development and also help in discovering their shortcomings.

3.4.1 Material circularity indicator (MCI)

This assessment method aims at assessing the circular flows of products and materials which was initially conceptualized by the Ellen MacArthur Foundation and Granta Design in 2015 and later updated in 2019. "It measures the extent to which linear flow has been minimised and restorative flow maximised for its component materials and how long and intensively it is used, compared to a similar industry average product" (Foundation, Circularity Indicators: An approach to measuring circularity , 2019, page 22) The 3 main characteristics that comprise the MCI are the mass of virgin raw material used for producing a component (V), the mass of unrecoverable waste (W) and a utility factor (X) that represents the lifespan and intensity of the product.

Comparing the principles of the R model, MCI solely focuses on recycle and reuse and overlooks the other Rs such as repurpose, remanufacture or refurbish. The scope of the MCI also states its unapplicability for construction of a railway line and deems it necessary to further improve the method in doing so. The calculations of the linear flow takes into account recycling, but does not differentiate between downcycling and upcycling. Similarly, the determination of the utility factor (L/L_{avg}), requires the knowledge about knowing the practical lifetime of a product, which is fairly unknown for railway infrastructure components since they usually have a very long lifespan. This can lead to an error in the final MCI value (Linder , Sarasini, & Loon, 2017). Another aspect that has also been mentioned in literature is that the MCI does not focus on the aspect of modularity, connectivity and disassembly (Saidani, Yannou, Leroy, & Cluzel, 2017). One of the design considerations that need to be taken into account is to design for adaptability so as to extend the lifespan of the product/component and keep it in use for longer periods. MCI focuses on industry processes and therefore is not the best option to assess infrastructure projects (Verbruggen, 2019).

3.4.2 Platform CB'23

This framework includes a detailed list of indicators for assessing circularity of buildings and civil engineering works and is one of the very few that also tends to focus on infrastructure projects. The first report of this guide, "Measuring circularity in the construction sector", published by Platform CB'23, was introduced in 2019 and second updated version in 2020. This group was set up by Rijkswaterstaat, the Central Government Real Estate Agency, De Bouwcampus and NEN (Royal Dutch Standardization Institute). A vast range of stakeholders are also involved in this framework and is planned to be used as an input for national and European measurement methods (CB'23, 2020). The team was able to conclude that there exists a need for a "harmonized core method" for CE on which they devised a detailed list of indicators focusing on materials, environment and energy aspects of CE.

Despite having most of the corners of CE covered, this method is still in its development phase and is yet to be completed. The method can only be used to gain insights but cannot be used to make a circularity assessment. Additionally, the lack of availability of the detailed data required for this method makes it difficult to implement. Nonetheless, reframing some of these indicators could serve to support the formation of the framework.

3.4.3 DuboCalc

This tool is one of the most often used tools in the Netherlands for the building and infrastructure sector. DuboCalc consists of multiple environmental cost indicators (MKI) that provide environmental sustainability of any infrastructure in monetary value. This is easier to compare when it comes to selection of tenders. Though it is frequently used, DuboCalc does not focus explicitly on closing material loops and similar aspects of CE (Coenen, 2019). The tool primarily focuses on sustainability and therefore on the energy and environmental aspects. This point was also confirmed from one of the interviews, where the expert agreed and stated that DuboCalc is focusing more towards the environmental aspect and the different scenarios of the EoL are not incorporated.

The analysis of the different assessment frameworks has provided valuable insights regarding different methods. One key observation from this analysis was the fact that not all Rs from the 10R model were taken into consideration (only Reuse and recycle). Another important observation was the inability of either of the frameworks to focus on all the life cycle phases. The industry can influence circularity of assets at different life cycle stages and better goals can be achieved by means of partnership and collaboration. Figure 7 shows the influence of different life cycle phases over circularity of an infrastructure asset and therefore to obtain the best results, it is important to focus on all stages. The high influencing potential of the planning phase makes it essential to focus on the early phases of an infrastructure project and will be taken as a starting point for the development of the framework.

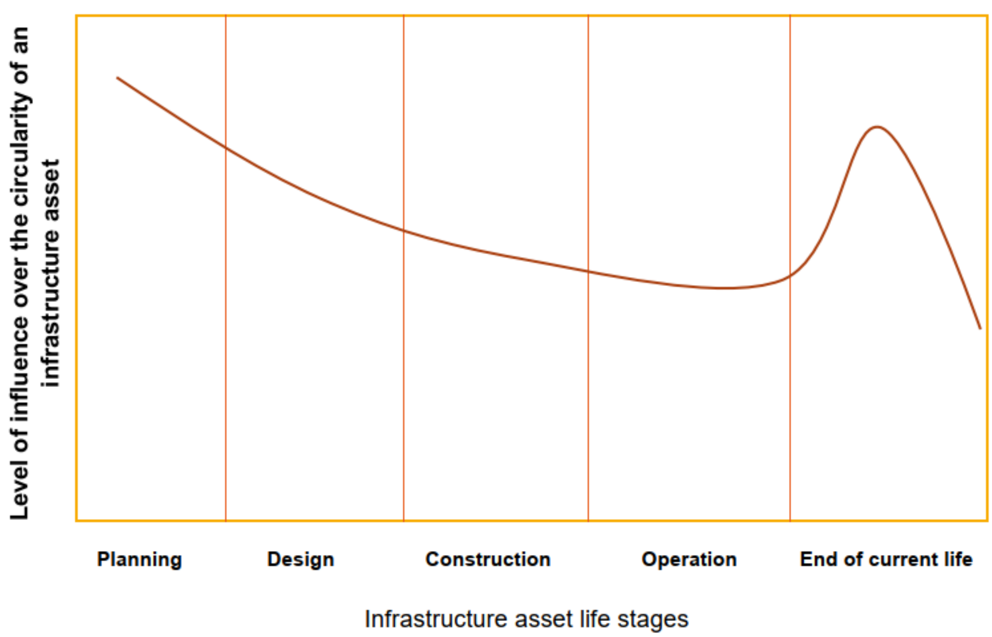

Figure 7: level of influence on circularity within asset life cycle

3.5 CIRCULAR PROCUREMENT PHASE

To understand the level of progress in terms of CE for the procurement phase, it is important to outline the basics of different forms of public procurement. Public procurement (PP) is defined as "*the process by which public authorities, such as government departments, regional and local authorities or bodies governed by public law, purchase works, goods or services from companies* (Public Procurement for a Circular Economy: Good practice and guidance, 2017, page 4). Over time, there have been modifications made and various forms of PP have been introduced that cater towards sustainability and CE. Green Public Procurement (GPP) is one such form which is defined as *"a process whereby public authorities seek to procure goods, services and works with a reduced environmental impact throughout their life cycle when compared to goods, services and works with the same primary function that would otherwise be procured"* (Public Procurement for a Circular Economy: Good practice and guidance, 2017, page 4). In order to reach the goal of GPP and to eventually procure goods in an environmentally sustainable way, it is essential to focus on the long-term impacts of such procurements and on not only the short term impacts. This also includes questioning the necessity of the product. Circular Public Procurement (CPP) is defined as "*the process by which public authorities purchase works, goods or services that seek to contribute to closed energy and material loops within supply chains, whilst minimizing, and in the best case avoiding, negative environmental impacts and waste creation across their whole life-cycle*" (Public Procurement for a Circular Economy: Good practice and guidance, 2017, page 5).

The lack of CE for railway projects is often attributed to the fact that the absence of CE requirements by the client for such projects, often lead to traditional ways of procurement (Public Procurement for a Circular Economy: Good practice and guidance, 2017). If CE principles are to be implemented for infrastructure projects, it is necessary to start from the preliminary stage of procurement and tender. Setting out CE requirements pushes the contractors to implement circular solutions and hence achieve the goals of circularity. The Dutch government introduced the Circular Procurement Green Deal in 2013 which aimed at accelerating the transition towards CE. In this program, a total of 45 public and private parties came together and decided to conduct two circular procurement pilot projects to develop experience, knowledge base, insights and to create a resourceful pool of good practice (Public Procurement for a Circular Economy: Good practice and guidance, 2017). The success of this program led to the authorities promoting CPP and consideration of Life cycle costs (LCC) in the "Roadmap to a Circular Economy, 2016" in which they also decided to increase CPP to 10% by 2020. EU Action plan apprehends PP as an important factor that should be worked upon for an effective transition towards the CE. It has devised multiple actions that need to be taken by the EU to promote the implementation of CE principles in GPP such as emphasizing CE ideologies in PP for the new or updated sets of EU GPP Criteria, supporting and encouraging European public bodies to implement GPP and CPP. It also aims to include such criteria for its own procurement and in the EU funding. Literature suggests that instead of considering circularity for the whole life of assets, this could be split across the infrastructure lifecycles, which will create distinct yet complementary circular strategies.

3.6 CIRCULAR DESIGN AND END OF LIFE PHASE

During the preliminary design and planning phases, decisions are made regarding materials which affect the function, appearance, maintenance and the environmental effects of the designated materials but there is seldom any discussion regarding the end of life phase, more specifically about how components can be disassembled to efficiently design out the waste streams. The available options to cascade components and materials at the EoL phase depends on the considerations given to the DfD aspect during the initial design phase. DfD for buildings is defined as “a method where the design team designs a building that facilitates not only adaptation and renovation, but also the reuse of building materials and components” (Kanters, 2018). It is estimated that if DfD is implemented in a project, it can reduce the embodied carbon effect by 49% (Kanters, 2018). DfD does not only have environmental benefits but also helps in creating jobs and a new market for salvage materials, thus positively affecting the social and economic aspects of society (Kanters, 2018). Implementation of DfD in the construction industry requires a change in overall perspective wherein the projects should not be considered static but rather dynamic that have the ability to adapt to the changing requirements.

The traditional method of a building or infrastructure disposal employs methods of destructive dismantling which leave very little or no room for material reuse. This way of disposal also negatively impacts the environment. To overcome such shortcomings, a more sustainable way could be achieved by implementing piece by piece dismantling which could maximise the component or material reuse potential. Material costs could be reduced by 56% if concrete components are reused, though there also exists a possibility of higher project costs due to specific component requirements (Akinade, et al., 2016).

Disassembly is an important phase for components in order to promote secondary life cycles of products. Products that are designed to easily disassemble can have multiple advantages during the maintenance and the end of life cycle stage such as value retention and higher opportunities for secondary use. The importance of evaluating these criteria during the design phase is essential as the decisions made in this phase are responsible for almost 80% of environmental effects (Bouyarmane, Amine , & Sallaou). The design phase also dominates not only the construction methods but also the ease with which the components can be maintained and taken apart. Despite the growing attention, there exists a void in terms of performance evaluation tools which limits stakeholders from setting goals for projects (Mayer & Bechthold , 2018).

Some of the key principles of DfD are outlined below (Rios, Chong , & Grau , 2015, page 1297)

- “Proper documentation of materials and methods for deconstruction”
- “Design accessible connections and joining methods to ease dismantling”
- “Design simple structure and forms that allow standardisation of components and dimensions”

3.7 SUMMARY

This chapter dives deeper into understanding the concepts and principles of CE. Importance of CE is imminent and the current global status of CE being only 9.1% circular depicts the potential and opportunities for its transition. EMF’s visualisation of the butterfly diagram differentiates between the technical and biological cycles and their individual internal loops. The focus of this study is only on the technical cycle due to the time constraints. The development of the R model from the initial 3R to the existing 10R model, highlights the developments of the CE concept and are often the basis of multiple frameworks and policies. CE aims at retaining material and component value during the multiple life cycles of a product and hence highlights the importance of the alternative cascading options such as reuse, refurbish, repurpose, etc over recycling.

The plethora of definitions that are available in literature, highlight the ambiguity and vagueness of CE. Within this chapter, such studies which investigate these different perceptions and definitions were analysed and a suitable definition was chosen by the help of a previously developed tool.

To develop the framework, existing methods such as MCI, DuboCalc and Platform CB'23 were analysed to understand the principles that are included and ones that are absent within these methods. Criticism of these methods from review of past studies helped in understanding the shortcomings of these methods and efforts were made to overcome such drawbacks. One such drawback was that these frameworks mostly focused only on the reuse and recycling aspect of the R model despite the existence of the 10R model. Apart from this, these frameworks also did not encapsulate the DfD principle which extensively been discussed in literature.

With the completion of this chapter, the review of past studies helped in successfully answering the first (partially) and second sub-research question. The second half of the first sub-research question which aims at understanding the current barriers for CE implementation for the railway industry will be discussed in chapter 5.

4. THEORETICAL BACKGROUND on Railway Infrastructure

This chapter sheds light on the different components of railway infrastructure that have been defined in the scope of this research. The substructure, superstructure and overhead lines along with their classification and track types will be the main focus of this chapter.

4.1 DIFFERENT TYPES OF RAILWAY SYSTEMS

The following sections, till the end of this chapter have been referenced from three academic textbooks, Profillidis (2014), PYRGIDIS (2014) and Lichtberger (2005).

In order to successfully develop a framework for railway infrastructure components, it is essential to define these components for the scope of this study and grasp a detailed understanding of each such components. The railway components and types of tracks used differ based on the system that is built. Figure 8 shows a broad classification of the different types of systems that are usually used for rail transport. The following sections outline a brief description about these different types.

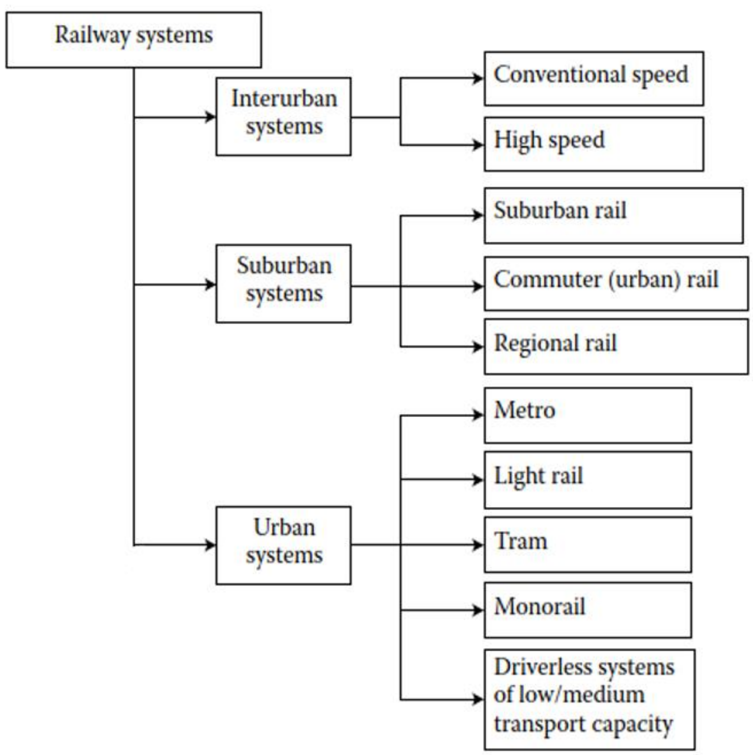

Figure 8: Classification of Railway systems (Source: (PYRGIDIS, 2014))

4.1.1 Interurban Systems: (High Speed Rail (Intercity))

These passenger rail transport have a travel speed significantly higher compared to the other modes. They tend to operate in a speed range of 200km/hr to 300km/hr although lower speeds are also common depending on the local constraints. These railway systems tend to use continuous welded rails in order to reduce track vibrations given the high speed of travel. Some peculiar characteristics can also be attributed to high speed rails, such as electrically driven, no level crossing, advanced switches using very low entry and frog angles.

4.1.2 Suburban Systems (Commuter Rail (NS Sprinter))

Also referred to as suburban rails, they usually provide connections between the city center and the outer suburbs and commuter towns or other locations that usually attract a large number of people to a specific city daily. Difference between other systems and commuter systems**:**

- Generally larger than Metros and Light rail transit systems (LRT)
- Provide a larger number of seating space than standing owing to its longer journey times
- Tend to have a lower frequency of service
- Shares its track with intercity or freight trains

4.1.3 Urban Systems

4.1.3.1 *Metro / Subway rapid transit system:*

The major difference between this mode of transport and he rest is that the fact that they have a grade separated exclusive right of way, without any interference from road traffic or pedestrians (Topp, 1999). They usually have a higher passenger capacity than LRTs and travel at higher speeds. One of the differences between these systems and LRTS lies in the fact that the rapid transit trains often comprise 6 to 12 cars whereas for the lighter systems, the number ranges between 3 and 4 cars.

4.1.3.2 *Light rail transit*

Light rail or light rail transit (LRT) is a type of urban public transport system that has passenger carrying capacity and speeds lower than metros but higher than traditional on-road tram systems. These transit systems usually feature electric rail cars that run on tracks separated from the other traffic modes but in some cases also share their path with traffic in city streets. This mode of transport, unlike the RRT has the tendency to be able to operate in mixed traffic which results in a narrower car body. They do not require a third live rail thus allowing their operation in mixed traffic conditions. When comparing these with the trams and streetcars, light rails have a higher carrying capacity and travelling speeds.

The classification of these transit systems based on the above terms can vary. In some cities the term 'metro' is used as a brand name without the presence of any of the above characteristics of a metro whereas certain systems are termed as light rail but meet all criteria of a rapid rail transit. The above categorization is based on a general understanding of the different transit systems that exist but are not determined to be a mandatory obligation for a certain category.

This research will only focus on urban light rails because: light rails also operate on the infrastructure that is used by the other categories of railway systems therefore it encompasses both, the integrated road tracks as well as the traditional ballast/slab tracks. To keep the scope broad of this study, it is therefore suitable to analyse both such track types. Monorails which also are enlisted as urban systems in figure 8, have a different construct method, using rubber tires (most common) on a single elevated concrete or steel beam making them non-compatible with any other railway infrastructure and therefore will be excluded due to the time constraint of this research. Apart from this, the monorails are not yet a common system within Europe. If metros are to be analyzed, underground construction of tunnels and stations are also important to be looked into and cannot be excluded. Given the time of this , it is therefore chosen to not focus on metros for its assessment in terms of circularity. Another deciding factor in narrowing down the scope was the involvement of Mott MacDonald and the experts who were involved in this research, as they worked majorly on LRT systems, hence it was only logical to focus on these systems to obtain the best results.

The overview of a traditional ballast track along with its components is described in the next section. Further modification and different types of tracks are discussed in the later section of this chapter. Even though the track layouts differ, the components that exist within these tracks are still to a very large extent similar and hence the subsequent sections will elaborate more on these different components.

4.2 TYPES OF TRACKS

4.2.1 Ballast track

These types of tracks are the most used traditional tracks that include a layer of ballast below the sleepers (figure 9). These tracks give more flexibility in construction and are cheaper than slab tracks. The quality of the track over its entire lifetime is dependent directly on the initial quality after track laying and the period immediately after.

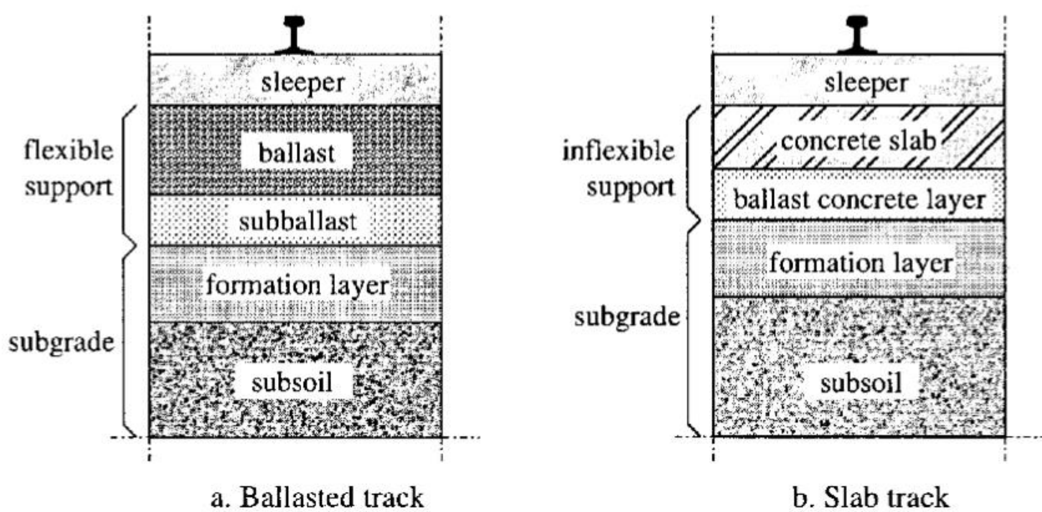

Figure 9: Comparison of Ballasted track and Slab track (Source: (PYRGIDIS, 2014))

4.2.2 Slab track

In such tracks, ballast as the load bearing material is replaced by another stable material such as concrete or asphalt. The plastic deformation of these materials is very slow in such circumstances. The required elasticity has to be provided by inserting elastic elements below the rail of the sleeper as the concrete or asphalt layer is very stiff. Slab tracks also require a subsoil which is virtually free of settlement. The rail can either lie directly on the slab or on sleepers which lie on the concrete slab. The next two layers after the concrete slab are that of the ballast concrete layer followed by the anti-frost layer (Profillidis, 2014). Comparison between the slab track and ballast track can be found in table 5.

- **Advantages:**
    - Low maintenance costs
    - Uninterrupted operation conditions
    - A slab track has a higher lifespan (50 to 60 years) as compared to ballasted tracks (15 to 30 years).
    - These tracks offer high transverse resistance and greater passenger comfort
- **Disadvantages:**
    - Generally, construction and maintenance are not automated which means high level quality assurance procedures leading to high construction costs. Also, noise emissions are higher than ballasted tracks and hence, appropriate noise protection measures are needed. However, these costs can be later recovered due to lower maintenance costs.
    - It requires a good quality of subgrade in order to prevent differential settlements. They are rigid foundation layers which can break after their operational strength has been reached causing rail fractures. Derailments can cause expensive track closures.
    - The rigid structure of the slab tracks allows only for a few improvements in the future. Adaptations to changed conditions such as changes in track geometry can be performed with extreme difficulty and high costs.

Table 5: Comparison between Slab track and Ballast track

Characteristics	***Slab track***	***Ballasted track***
Stability of track geometry	High	Low
Airborne noise emission value	Higher	Lower
Construction costs for installations on earth	Higher	Lower
Cost for vegetation control	Lower	Higher
Relaxed rules on maximum track superelevation	Yes	No
Maintenance cost	Lesser	More
Expected life cycle	50 – 60 years	30 – 40 years

4.2.3 Embedded slab track

In these types of tracks, a rail is embedded in a thick continuous slab track (figure 10). These contain a top layer that is flushed with the top asphalt layer of roads in case do not have a separate path of way. The top layer can differ and does not depend on the type of the supporting structure and such types are generally used in an urban setting.

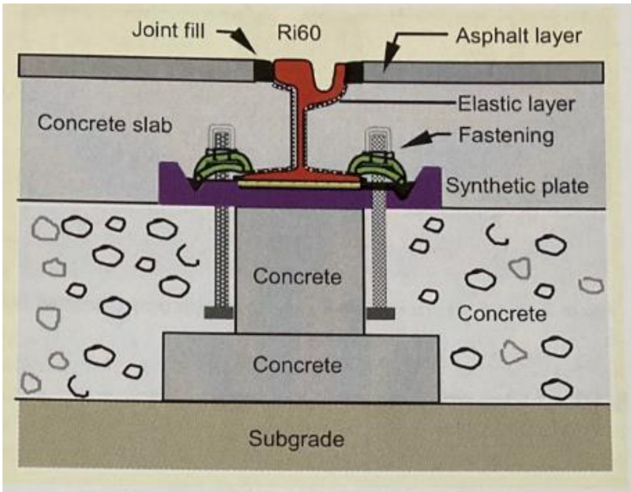

Figure 10: Embedded slab track (Source: (Profillidis, 2014))

4.3 COMPONENTS OF THE SUPERSTRUCTURE

The function of the superstructure is to support and guide the wheels of the train and evenly distribute the train loads to the substructure. These parts of the track system (figure 11) are often subjected to periodic maintenance to keep their functioning at the highest level. This part of the track system includes:

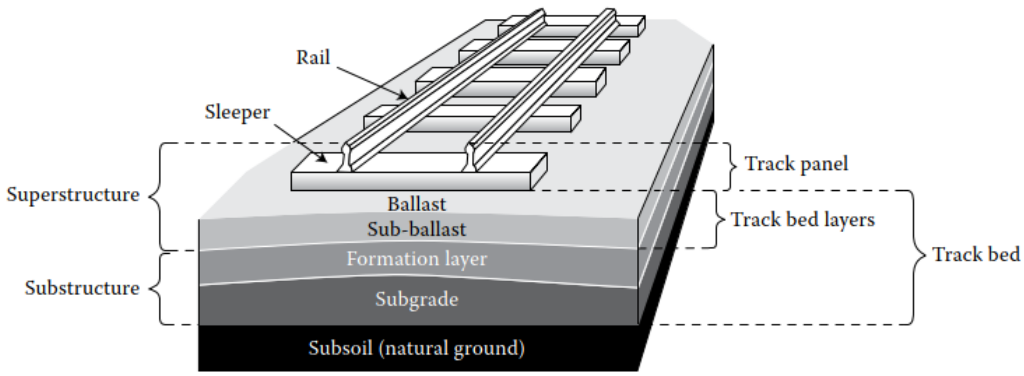

Figure 11: Components of a railway track (Source: (PYRGIDIS, 2014))

4.3.1 Rails

These are longitudinal steel members of the system that guide the train wheels and transfer the concentrated loads of the rail wheels to the sleepers. In order to perform this function satisfactorily, it is necessary for the rails to have sufficient stiffness. Different types of rails (figure 12) are:

- **Grooved rails:** These were one of the first designed rail types that are still being implemented across the globe. Mostly, the geometry of these rails is such that the rail top and the pavement surface lie on the same level that best suits the trams system as these share their path with mixed traffic and pedestrians. On very rare occasions, these rails can also be used on ballast track. The type of grooved rail considered for this study is grooved rail 59Ri2.
- **Double headed or bull head rails:** These rails could carry the wheels of the rolling stock on both its ends, resulting from the initial idea to flip the rails once the side was worn out. In practice this was not a feasible option and most of these rails were discarded in the beginning of the 20th century but they still tend to be in use in some parts of the United Kingdom.
- **Vignole rails (Flat bottom rail):** Named after its designer, these rails are the most common type of rails that are being used worldwide. These rails consist of a head, web and a foot (base) as can be seen in figure 12.

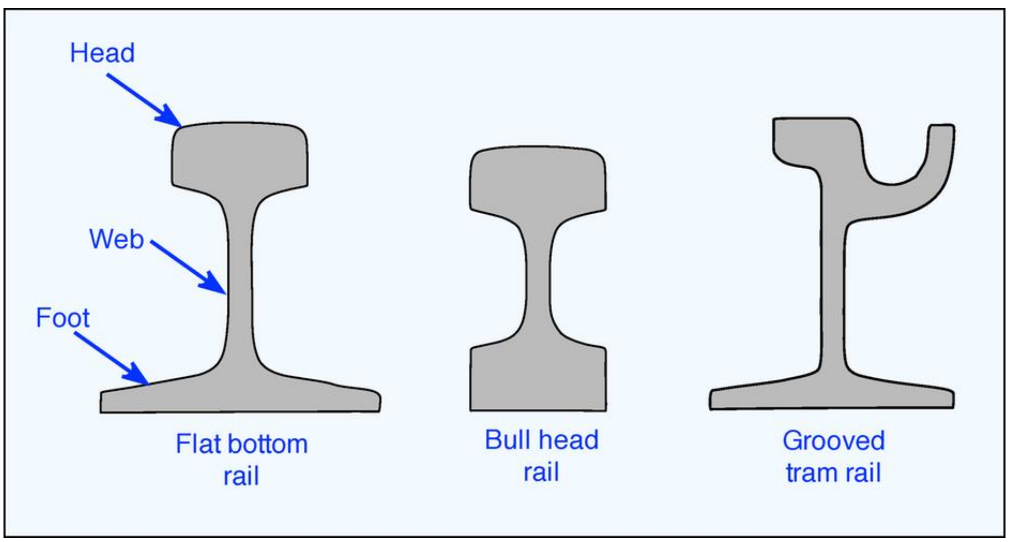

Figure 12: Types of rails

4.3.2 Sleepers

These are the components present between the rails and the ballast, primarily present to provide a better load distribution to the ballast and subsequently to the subgrade. Sleepers also help in maintaining the gauge between the two rails and provide sufficient strength in vertical and horizontal direction. The different type of sleepers used in this research are (Profillidis, 2014):

- **Timber sleepers:** timber was one of the earliest materials used for the construction of sleepers with an average lifespan of 25 to 40 years (different types of timbers have different lifespans). In the US, cyclic replacement of wooden sleepers is carried out every 5 to 8 years. Due to this reason, the new sleepers take up greater part of the load as compared to the old sleepers in the track, resulting in a reduction of their service life due to the additional stresses which were not initially accounted for during the design. To avoid such circumstances in Europe, all sleepers that are still serviceable are recovered and reused in secondary lines.
    - *Advantages*:
        - Distribute load better than the other sleepers
        - Suitable when the subsoil has a low bearing capacity
        - Additional insulation equipment is not necessary for signaling
    - *Disadvantages:*
        - Costs are higher
        - Lower lifespan
        - Susceptible to attacks from insects and bacteria
        - They are not suitable for high speed railways with speeds over 160 km/hr as their resistance to lateral displacements is 15% lower than concrete sleepers
        - Need for chemical treatment to prolong their lifespans renders them unfit for recycling.

- **Steel sleepers:** One of the major concerns with the wooden sleepers was their poor resistance against external weathering conditions and growing scarcity. These factors complemented by the increasing use of steel in the 19th century resulted in their obsolescence and the introduction of steel sleepers.
    - *Advantages:*
        - Termite resistant.
        - Service life is between 40 to 60 years
        - Lower weight therefore easier to handle
        - Lower overall height therefore lower quantity of ballast needed
        - End of life value is usually higher due to the available 'scrap iron' residuals
    - *Disadvantages:*
        - Lateral resistance is lower than concrete sleepers
        - Small particles due to the wear settle in the ballast and hamper the water permeability
        - Sensitive to corrosion, especially in the areas near the coasts and factories
        - Maintenance of such sleepers is difficult

- **Concrete sleepers:** The increasing speeds of trains demand higher stiffness from the sleepers which eventually resulted in the introduction of concrete sleepers that have a lifespan of 50 years.
    - *Advantages:*
        - Longer service life

    - Lower life cycle costs
    - Less expensive as compared to hardwood sleepers
    - Lower maintenance of the fastenings
    - Greater resistance to lateral forces
  - *Disadvantages*
    - Susceptible to shock and impact
    - Susceptible to fracture
    - Higher corrugation in the rails
    - Manual replacement and handling can be difficult owing to their high weight
    - In situations where the soil bearing capacity is low, a thicker layer of ballast is required
- **Twin block reinforced concrete sleepers:** Normal stress distribution in a sleeper shows considerably lower stress in its center which allows for a reduced cross section in such parts. Using this principle, twin block reinforced sleepers consist of 2 trapezoidal reinforced concrete sections (figure 13), joined by a connecting bar.

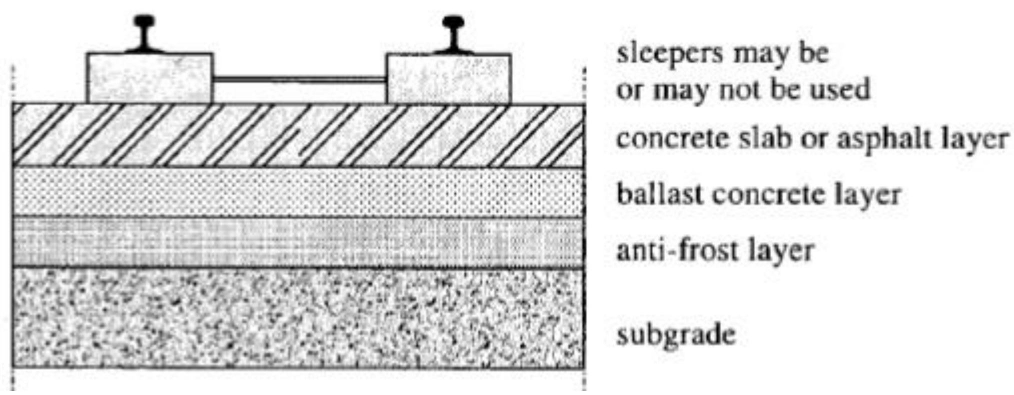

Figure 13: Twin block reinforced concrete sleeper (Source: (Profillidis, 2014))

  - *Advantages*:
    - Greater weight provides higher transverse track resistance and hence makes them more suitable for high speed trains.
    - Higher lifetime
    - Less expensive than timber sleepers.
  - *Disadvantages:*
    - higher maintenance is needed to ensure that both the blocks do not have a differential tilt and are still in contact.
    - Load distribution as compared to other sleepers is unsatisfactory or poor.
    - Higher weight causes problems in handling.
    - Special equipment for signalling insulation.

- **Monoblock reinforced concrete sleepers:** these blocks can be pre-tensioned or post tensioned and usually have a lifetime of 50 years.
    - *Advantages:*
        - Longer lifetime than timber.
        - Distribute loads better than twin block but not as good as timber sleepers.
        - Can adapt to different speeds and load conditions.
    - *Disadvantages*:
        - Transverse resistance is lower than twin block but greater than timber sleepers.

4.3.3 Ballast

This layer forms the bed for rails out of crushed stone and in exceptional cases out of gravel. In theory, it is recommended to have the life cycle of ballast, rails and sleepers are same so they can all be replaced during the same cycle. For high speed tracks, ballast renewal is done every 15 to 20 years whereas the sleepers and rails can be used for an additional 30 years. Measures such as increasing the width of the ballast layer, using ballast stones with greater hardness or implementing a more homogenous compacting of the layer can increase the life time of ballast by 4 to 7 years and simultaneously result in a reduction of maintenance costs by 40% with 10 years. Ballast helps to transmit the stresses from the sleeper to the underlying soil layers and also resist the longitudinal lateral sleeper movement. It plays a significant role in attenuating the greatest part of train vibrations.

4.3.4 Sub-ballast

This layer forms the division between the subgrade and the ballast layer and is usually made up of gravel. The thickness of this layer has a value of 15 cm, however for some railway systems this layer is replaced by a thicker layer of the formation layer, which is usually present on top of the subgrade. One of the functions of the sub ballast is to prevent the penetration of the ballast into the upper surface of subgrade and to further help in distribution of stresses.

4.4 SUBSTRUCTURE

The function of the substructure is to provide a sufficient foundation to the track so that the loads can be carried evenly. The loads are transferred from the ballast to the subsoil via the formation layer. In order to design a long lasting and safe railway system, the subgrade should have good drainage characteristics and adequate load bearing capacity. The track formation layer forms the intermediate layer between the sub-ballast and the subsoil and absorbs and dissipates the loads of the railways. This part of the substructure is also prone to weather effects.

4.5 OVERHEAD LINE EQUIPMENT

The overhead line equipment provides the trains with its source of electric energy for successful transit. The entire system comprises of the masts, gantries and wires. Overhead lines are also the most preferred means of powering trains owing to their advantages of operationality, environmentally sound and passenger service and comfort. Moving to the electric source of energy was essential as these trains are lighter, cheaper, quieter and faster to accelerate. The overhead line equipment consists (figure 14) of:

- Contact wire
- Droppers
- Catenary
- Masts or frames

It is essential to keep the **contact wire** stationary to provide continuous flow of power and reduce the wear of the system. To attain this situation, the contact wire is tensioned between support structures in order to withstand the high wind forces and temperature variations. These cables are held in positions by vertical **droppers** that are in turn supported by the **catenary.** These systems are supported by **masts** or **frames** that are well spaced throughout the length of the track. In order to prevent the wear of the pantograph shoe in a fixed place, the catenary wire runs in a staggered/zig-zag pattern along its length. This orientation is usually achieved by the help of "pull off arms" that are attached to the supporting structures. In situations where more than two tracks are present, the cantilever masts are no longer a viable option. Steel portal frames are then used which are connected by a horizontal boom that are usually made up of H sections or lattice steel. Drop tubes are used to support the wires from these booms.

- ***Advantages*** *(as compared to other power sourced (coal/steam or diesel)**:***
    - The lower weights of these trains allow them to accelerate and break faster
    - Capital costs, maintenance costs and operational costs of rolling stocks are low due to much smaller number of moving parts
    - Higher reliability
    - Reduced greenhouse gas emissions
    - Lower levels of noise pollution
    - Lower vibrations, improving the level of passenger comfort
- ***Disadvantages:***
    - High installation costs
    - Safety risks from high voltages

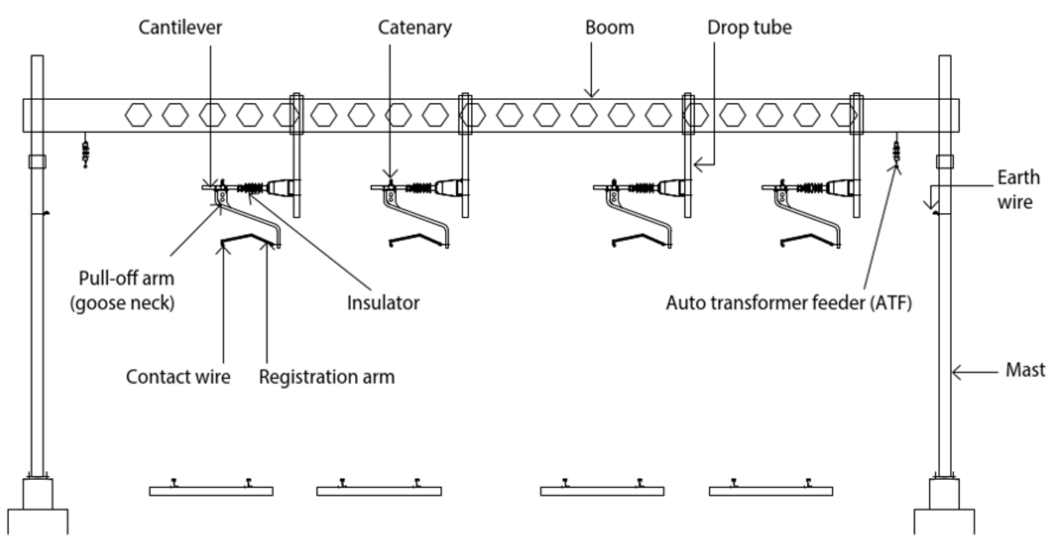

Figure 14: Components of Overhead systems

4.6 THIRD RAIL

In the absence of overhead line equipment, power to locomotive is provided by the means of a third rail that is installed alongside or between the rails of a railway track. These types of additional rails are employed in transit systems that have their own segregated right of way and are not mixed with other traffic. These third rails often supply direct currents. On most systems these are placed on the sleeper ends outside the running rails but a central conductor rail can also be used. To satisfactorily conduct the electricity, the trains are equipped with metal contact blocks called “shoes” which are in contact with the third rail.

- **Advantages:**
  - Cost effective and cheaper to install as they do not require additional structures to carry the overhead equipment.
- **Disadvantages:**
  - Electric shock hazard
  - Additional measures to prevent pedestrians from walking onto the third rail at crossings
  - Have tendencies to short circuit rails at the crossings hence a gap needs to be provided.
  - Not suitable for trains with fewer shoes as the gaps in the conductor rails at crossings and crossovers can result in such trains to stop at a position where all the conducting shoes are at the gaps.

4.7 SUMMARY

The focus of this study is solely towards the light rail transit systems within the urban setting, though the infrastructure components described, are to a large extent common to the ones implemented in other systems such as metro, trams and high speed trains. The light rails distinguishes itself from the other modes of urban system on the basis of the passenger carrying capacity (lower than metro but higher than trams) wherein they operate in road traffic as well as have their separate right of way. LRT carries around 13.6 billion passengers every year (45 million daily) (Rahman, Kadir , Osman , & Amirulddin , 2020). The ever growing trend in population will only increase the load on these systems causing new and redevelopment of such projects.

Within these systems, different types of tracks such as the ballast track and slab (ballastless) track are employed. The difference between these lie in the presence of the ballast layer in the ballast track, which forms the bed of the rails out of crushed stones. Slab tracks replace this layer with a concrete slab which provides the necessary function. Rails can be embedded in these types with different top layer finish. The rails can vary based on their geometry and often rest on sleepers for ballast tracks. The rails, sleepers, ballast and sub-ballast layers form the superstructure of the track systems. The substructure consists of the formation layer and the subgrade, which provides sufficient foundation to the track. The overhead line equipment is responsible in providing electricity to the trains for their successful transit. These systems consists of catenary, contact wires, droppers and masts.

5. FRAMEWORK DESIGN

This chapter begins with the results from the interviews conducted, by describing in detail the barriers faced in practice for the implementation of CE in the railway industry. It also explains the formation of the framework and discusses the different aspects that need to be considered in the final framework. The reasoning for the decisions made is elaborated and the calculations for the different phases and categories is illustrated in this chapter.

5.1 BARRIERS FOR IMPLEMENTATION OF CE

The interviews conducted during the course of this research helped in gathering some insightful barriers regarding the implementation of CE. Different stakeholders were interviewed as described in section 2.3.2 in a semi-structured interview format and the results of which are discussed in this section. These barriers along with indicators from literature, are further translated to form the indicators.

One of the major barriers which was cited by all the interviewees was the **lack of requirements** of CE by clients. CE is seldom stated as a requirement for these projects and room for CE solution is also limited due to the cost constraints in tenders. Although considerable amount of attention is given to sustainability and the carbon footprint of projects, very little focus lies on CE. Within sustainability of materials, recycling is often included either as a source of input materials or as the destination of the product at the end of its lifecycle. This confirms the fact stated in section 3.2, in which literature sheds light on the progress made by Netherlands for having a recyclable environment wherein **95% products** are recycled. Reflecting back on the R model of CE, the lower preference given to recycling shows the difference in perspective of this sector and the absence of CE transition. A reason for the lack of client requirements for CE in projects accumulates due to the fact there exists a **lack of awareness and clear understanding about CE and its concepts**. Some stakeholders have a misconception about CE and focus completely on recycling whereas some stakeholders do implement CE principles, such as reuse of materials but are not labelled as CE or are unaware about its relation to CE. This lack of knowledge and the vagueness about the topic, depicts the need for a clear understanding and definition for CE within the industry.

It was also observed that the **market for CE is fragmented**. Solutions within the railway industry market exist that meet CE requirements, but due to the unawareness of these market groups, these products are often categorised as sustainable. Though CE is well within the scope of sustainability, overshadowing its CE principles can lead to misinterpretation of the readiness of the supplier market. Another factor that plays a role in the lack of client requirements for CE arises due to **the inability of organisations to transition towards more CE innovations** and their lack of leadership. Experts suggested that CE not only needs a technical shift but at the same time it is important for organisations to change on a system level. Even though organisations have individuals working on CE, the decision-making power is not always vested with these individuals therefore, for a successfully transition, organisations need to make sufficient changes in their structure and be more acceptable of CE solutions. For example, within Mott MacDonald, sustainability leads and carbon principals exist, whereas a lack of committee or a group that focuses on CE hinders its progress within the organisation.

Lack of stricter government regulatory policies and incentives also affects the implementation of CE in public projects. Even though the Dutch government has larger policies in place in regards with CE, such as the Green Deal Agreement, Paris Agreement and the commitment to go completely circular by 2050, on a smaller scale, the implementation tools to achieve these goals are still lacking. Tenders for major public infrastructure projects are still based on EMAT or cost and quality parameters. Since CE requires innovation and focuses on increasing lifespan of materials and products, these can sometimes lead to expensive solutions or solutions with a longer construction time. Such considerations need to be given for CE solutions and the requirements should not be completely based on the technical aspects, but at the same time also focus on specifying more functional requirements.

Lack of collaboration between different stakeholders is also one of the prime barriers. It was observed that in one of the interviews, the interviewee mentioned that regarding reducing carbon emissions, the designers and engineers expect solutions to be drawn by the carbon experts on which they can further elaborate. Arguing on this point, it was highlighted that working together with engineers was the only correct solution and embedding CE principles with a certain stakeholder will not yield appropriate results. Internal and external collaborations with different organisations and stakeholders, will provide the best solution for CE. The market for such projects is aware of CE solutions but due to lack of collaboration in the early design phases, these solutions are often overlooked and the traditional solutions are chosen. The choice of traditional materials and components is also a result of the perception of these reused materials not being up to the required standards in terms of their technical and functional capabilities. **Absence of a standard** to judge the technical life of reused products, leads to the reluctance of usage of reused components, especially for critical components. Interviewees agreed to the fact that given a choice, for critical components, they would rather opt for new components and materials. The risk relating to reuse is still a grey area that prevents its reuse. Introduction of materials passport can be a breakthrough in this regard. Data regarding the content of the material used within a component and its technical and functional history can paint a clearer picture and ease the decision-making process for reused components.

5.2 DEVELOPMENT OF INDICATORS FOR THE PROCUREMENT PHASE

Reflecting on the barriers discussed in the previous section, it is necessary to introduce indicators that help in overcoming such hinderances and provide a clear and complete understanding of CE ideas. The barriers that were discussed in the previous sections are compared to the ones in literature. This section explains the choice of the indicators along with their description that can accelerate the implementation of CE in the procurement and tender phase and will form the basis of the procurement framework. The description entails why these indicators are necessary and which barriers they can help to overcome.

5.2.1 Description of the indicators

Clear definition of the Scope of CE in requirement specifications

According to Partoredjo (2019), one of the problems faced by the contractors specifically, is a lack of clear definition of circularity within the official tender documents. Overcoming this drawback can help to develop better solutions that fit well with the client's need for circularity. Furthermore, improper definition of CE and its scope often leads to insufficient formulation of circularity requirements. Respondents of this research also shed light on similar aspects thereby validating the need of clear client demands. They suggested that lack of implementation of CE in railway projects was majorly due to the absence of demands from the client and its lack of definition. Therefore, identifying the aspects of circularity that are important for a client is necessary. Partoredjo (2019), was also able to conclude that majority of the contractors could present a better solution if circularity was better embedded in the scope of the project. Unclear definitions of circularity can also lead to different interpretations and eventually give rise to conflicts. Clear tender documents and client demands can thus stipulate clear solutions, as the contractors are dependent on the client to define the direction of circularity (Alhola , Ryding , Salmenpera , & Busch , 2018).

One good example of what this entails can be further explained by referring to the demands from a case performed by Partoredjo, (2019) where unclarity regarding the scope of CE exists, "…..The client focuses on circular economy for which the goal is keeping raw materials in the loop. This means: less waste and high-quality reuse of residual materials as a valuable resource for new products" (Partoredjo, 2019, page 35). Though the client's demands are expressed for circularity, terms such as 'less waste' can still be relative and subject to perception of individuals and need further explanation. Given the above importance, it is essential to include an indicator in the procurement phase to assess whether the scope is sufficiently defined and thus results in the following indicators:

- ***Indicator 1 -*** *The scope of circular economy is clearly defined by the client*.

In order to satisfy this indicator, it is essential to include a clear circularity clause in the requirement specifications, which entails the aspects that are necessary for clients (material flows, modular design, secondary flows, etc).

Defining circular award criteria and incentives

Public infrastructure projects are still awarded based on the aspects of cost and time and seldom focus on aspects such as circularity. Due to the vagueness of circular economy principles and the infancy of the topic, implementing circular solutions can be challenging and time consuming, and are often perceived to be expensive as compared to the traditional solutions. Providing additional incentives for circular solutions can also help in promoting circular ideas and increase tender competition. Majority of the tenders are still evaluated based on their financial aspect. In order to promote innovative solutions and more circular thinking amongst the contractors and suppliers, providing a financial incentive can not only accelerate these new solutions but also guarantee the initial level of circularity (Van Oppen , Croon, & Bijl de Vroe, 2018). This approach can help accelerate the procurement of better quality products and services in terms of circularity.

Vagueness of the topic along with the unclear definition of CE within the scope, can sometimes contradict the existing award criteria and therefore not only need additional criteria for circularity such as reuse of materials, lifespan extension, etc but also essential is to ensure these award criterias do not conflict with CE demands and criteria. (Alhola , Ryding , Salmenpera , & Busch , 2018). Alhola , et al. (2018), mention that even though circular criteria are slowly becoming evident, they often conflict with other award criteria. Optimisation of product lifespan and making conscious efforts to extend their original lifespan is possible by regular maintenance of the components involved. For public projects where maintenance can hamper the regular functioning of necessary commodities like railways, it is often proposed to reduce the maintenance activities to the minimum. This in turn contradicts to the original ideas of CE and stating both these requirements of extended lifespan with minimum requirements can be contradictory.

To prevent these from happening and to have an earlier check for this drawback, these are formulated in the framework as:

- ***Indicator 2 -*** *Additional incentives are provided for circular solutions*
- ***Indicator 3 -*** *Circular criteria does not conflict with other award criteria for tenders (For eg. Maximum maintenance free period along with demand for higher lifespan is required. Though for higher lifespan, regular maintenance is essential)*
- ***Indicator 4 -*** *Suppliers can challenge the criteria if they see opportunities to improve circularity*

These indicators can also be assessed after analyzing the requirements specifications and are judged for a project, based on the details mentioned in the documents.

Technical specification vs functional specifications

Another change that is often mentioned in literature is that of the requirements specified in the tender phase. In order to transition to CE, CPP demands a shift from technical specification to more functional specifications as these allow greater range of freedom for designers and contractors to provide innovative solutions. Traditional procurement processes are often based on technical specifications (Van Oppen , Croon, & Bijl de Vroe, 2018). Inclusion of technical specifications over functional specifications can often limit the creativity and innovation of suppliers to provide new solutions. These innovative solutions can be an important driving factor that can accelerate the transition to a circular economy. Figure 15 depicts that with the technical specifications, the circular solutions are limited to those that are available at the instance of drafting these requirements (orange line). In the case of functional requirements, suppliers and contractors have the freedom to create new solutions themselves while submitting their offers (yellow line). With proper collaboration from the initial stages, these can have even larger potentials. Partoredjo, (2019) studied that almost half of the contractors preferred functional requirements in tenders which would provide them with the required freedom to implement circular strategies. These aforementioned points were thus included in the framework through:

- ***Indicator 5 -*** *Functional requirements (Performance based requirements) are specified over technical requirements for components/materials*
- ***Indicator 6 -*** *If technical requirements are specified, they should be in line with circular economy principles*

Supplier and stakeholders are involved through market dialogue to promote CPP

Implementation of CE ideas is not the sole responsibility of the client but also of the market and the involved stakeholders. Client's unawareness regarding the status of the circularity in the market can also lead to opting of traditional methods or products. Alhola, Salmenpera, Sven-Olaf , & Busch, (2017) state that "if an efficient service provider network or after-market exist, circular procurement is more attractive. A more structured overview of related potential suppliers and what the market can offer can be achieved through market analysis" (Alhola , Ryding , Salmenpera , & Busch , 2018, page 11). The preference of suppliers and contractors as mentioned before lies with the functional requirements. Involving these actors at an early stage of the project can help accelerate implementation of newer solutions. Furthermore, the technical requirements can be better set up by a knowledge exchange between the client and the contractor/supplier.

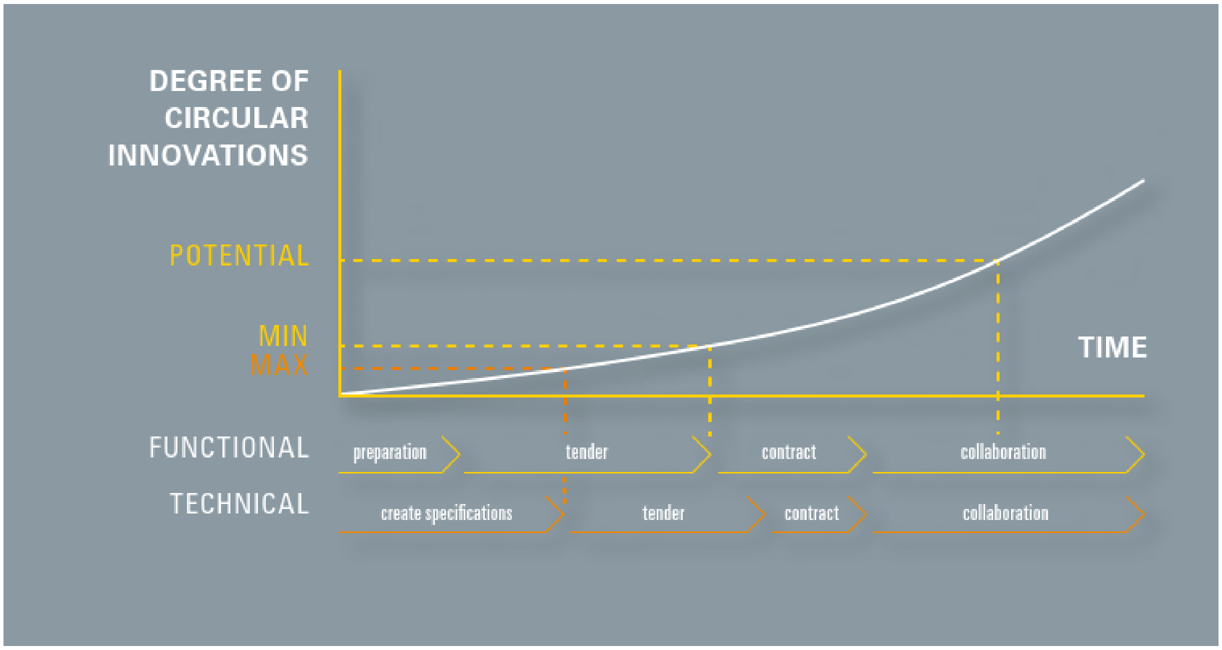

Figure 15: Functional Vs Technical Specifications (Source: (Van Oppen , Croon, & Bijl de Vroe, 2018))

Absence of a certain circular product that is required in such projects, can be overcome by establishing partnerships between the client and the contractors. To set realistic specifications and goals within the requirements, it is essential to understand the current state of the market which can be done by conducting pre-procurement market consultation activities and acquiring knowledge or information from potential suppliers. This shows the multiple advantages of collaboration between the parties that can aid the transition towards a more circular procurement method. Rijkswaterstaat for the A6 project calculated a reference design of environmental impact prior to tenders and the market was challenged to submit a design with a lower environmental impact. Initially the reduction was targeted for 20 to 25% lesser but has since been increased to 50-60%. They set a reference of around 100,000 tonnes of CO_2 emissions and in the tender phase, requested for environmental impacts of 50% less. The successful tender offered a design with a carbon emission of just over 40k tonnes (60% lower) (Public Procurement for a Circular Economy: Good practice and guidance, 2017). Promoting dialogue between client and contractor and supplier can help the supplier and contractor better understand the demands and ambitions and to a certain extent, these interactions can help strengthen relations and trust (Van Oppen , Croon, & Bijl de Vroe, 2018). Table 6 depicts how collaboration can help achieve solutions that are beneficial for suppliers and buyers.

The indicators that are attributed to these points are:

- ***Indicator 7 –*** *There is a collaboration between the client and contractor to successfully implement circular ideologies from the initial phases of the project*
- ***Indicator 8 –*** *Suppliers and stakeholders are involved through market dialogue to promote circular public procurement*
- ***Indicator 9 –*** *Involved organisations (Contractors, sub-contractors, designers, advisors, etc) need to have certain experience with circular solutions*

Table 6: Importance of collaboration (Source: (Van Oppen , Croon, & Bijl de Vroe, 2018))

	BUYERS		
SUPPLIERS		*COMPETITION*	*COLLABORATION*
	COMPETITION	Not circular and not within budget	Not circular and within budget
	COLLABORATION	Circular and not within budget	Circular and within budget

New knowledge partners

Innovative procurement can also include the involvement of new knowledge partners as the client organisation/procurer are not always aware of the developments in the market and hence should also be willing to accept new knowledge and learning in order to implement circular ideas. In order to successfully implement circularity in projects during the procurement phase, new stakeholders, tools, and activities can help to identify the circular implications and effects of the products and services before they are developed or constructed. The client organisations hence need to amend their practices and gain new competences or partners who have the required expertise. These collaborations can be detailed or general depending on the willingness of the client to implement CE. Inclusion of knowledge partners in the early phases of a project is also listed as a driving force to implement CE in literature (Kristensen, Mosgaard, & Remmen, 2021). Though this is the case, current practices depict the lack on involvement of such knowledge partners but instead collaboration with the same groups that provide guidance for green procurement which, by definition, cannot be expected to contribute to circular procurement. This problem can also be traced back to the barrier of lack of clear understanding of the circular concepts.

- ***Indicator 10 -** Networks and organisations are used as knowledge partners while drafting tenders (For eg, involvement of organisations such as TNO, PIANOo, EMF or universities)*

Off the shelf purchasing is reduced

Public procurement practices across the EU primarily consists of purchasing off-the-shelf products or services whilst overlooking innovation of newer products, services or solutions (Kristensen, Mosgaard, & Remmen, 2021). The infancy of core circular ideas for material flows and value retention conflicts with the traditional product design or processes. In order to optimise the CE ideologies, it is necessary to look beyond the traditional products and discover new methods of constructing and designing. For instance, design for disassembly or modularity can be attributed to being a comparatively new thinking process in which the products are designed keeping in mind their use for multiple life cycles and hence retaining their original value (Kristensen, Mosgaard, & Remmen, 2021). Inclusion of R&D activities in public procurement can also promote CE (Alhola , Ryding , Salmenpera , & Busch , 2018). Public procurement processes should provide conditions which help stimulate and promote innovative solutions that align with CE principles. Alhola, Salmenpera, Sven-Olaf , & Busch, (2017) states that in order to prioritise and capitalise on the benefits of CE, a systematic multi-level change is essential which also includes technological innovation. This point result in the formation of:

- ***Indicator 11 -*** *Design for disassembly/demountability/modularity is implemented*
- ***Indicator 12 -*** *A specialised design team in design for disassembly/demountability/modularity is involved*
- ***Indicator 13 -*** *Eligibility requirements are set up for the design (for disassembly) team in terms of competence and experience*
- ***Indicator 14 -*** *Deconstruction team/organisation is included in the consortium from the design phase*
- ***Indicator 15 -*** *Off the shelf (standardized/ traditional) purchasing is reduced OR circular off the shelf products are required (as means to promote innovative solutions)*

Rethink in ownership and supplier take back systems

Promotion of innovative solutions is not limited to the final product but can also be related to processes. One that is often mentioned in literature is changing the type of contracts from traditional to product-service systems, leasing concepts, shared use, buy per use and buying and selling back (Alhola , Ryding , Salmenpera , & Busch , 2018). These types not only ensure secondary life for the products and services but also ensure maximum utilisation of products in the current life cycle. One of the respondents of this study also mentioned that transferring the ownership of components of railway infrastructure also allows the contractor to have an increased sense of responsibility of the components as maximum utilisation of owned products or regular maintenance and lifetime extension of products can increase its reuse and be highly beneficial for the asset owner. The United Nations Environmental Programme (UNEP) mentions two distinct pillars for circular procurement that present CPP as either **"**promoting circular supply chains or new innovative business models" (Building circularity into our economies through sustainable procurement, 2018; page 6). Therefore, these different contracting forms can exhibit new methods of defining CE contracts (Kristensen, Mosgaard, & Remmen, 2021). Contract modalities as that of the buy back or purchase and resale agreements also promote closed loop production and multiple consumption cycles. These new contracting methods have high potential to produce significant resource efficiencies, reduction in risks and in turn promote circularity (Building circularity into our economies through sustainable procurement, 2018).

- ***Indicator 16*** - *There is a "Rethink" in ownership where public organisations do not purchase products but instead implement pay per use contracts or performance based contracts.*

Extending lifespan

Product lifespan extension is defined as "the postponement or reversal of the obsolescence of a product through deliberate intervention" (Building circularity into our economies through sustainable procurement, 2018; page 9). By extending the lifespan of a product, the consumption rate of resources and waste production can be reduced drastically. These ideas can be embedded in the procurement phase by specifying the need for reuse, repair, refurbish, or by focusing on longer guarantee periods of products and extended availability of spare parts and components. In order to be able to cascade components, it is essential to extend their lifespan and retain their functional value by regular maintenance. Apart from reuse and recycle specifications, other Rs from the R framework can also be promoted, not only for the products and materials but also for aspects such as packaging and nearby material flows and by-products. (Alhola, Salmenpera, Sven-Olaf , & Busch, 2017).

- ***Indicator 17 -*** *Requirements are specified for using Reused/Refurbished/Remanufactured/ Recycled (Secondary materials) or products as a certain fraction or as a whole*
- ***Indicator 18*** *- Requirements are specified for circular packaging of materials/products*
- ***Indicator 19 -*** *Requirements are specified for utilizing nearby secondary material flows of components/materials*
- ***Indicator 20 -*** *Extensive maintenance and repair agreements are included to ensure maximum lifespan extension of components*
- ***Indicator 21*** *- Requirements are specified for a longer guarantee period along with easily available spare parts during the operation phase*

Material passport

Knowledge about the origin and previous functions of materials and components is necessary to determine its applicability for a secondary lifecycle. For critical components where safety is of utmost importance, presence of such information can help to make better decisions regarding the use of secondary products. Development of material passports can provide the designer of the current and the consecutive life cycle information about the component and material composition, its source of origin, and environmental performance. The purpose of this idea is to permit information transfer through time along with the product (Alhola , Ryding , Salmenpera , & Busch , 2018). Implementing these from the procurement phase can therefore be a good indicator for CE as it expands the possibilities of materials and component use for cascaded life cycles.

- ***Indicator 22*** *- Requirements to develop and maintain material passports to better assess the applicability of the material/component for its subsequent life cycles*

Thinking of end of life stages

CE's primary aim to close the material loops makes us consider materials and components beyond their useful life. Focusing on the end of life cycle stage is an important aspect if closing material loops is to be achieved. Working on the end of life aspects of different components can significantly reduce waste production and achieve goals of CE. Sufficient attention therefore for end of life phase is necessary and needs to be incorporated in the early phases such as the design and procurement phase. An important development in this regard is the new EU directive which focuses on the change related to the procurement setting and stresses on focusing on life cycle perspective which shifts aim to EoL phase (Alhola, Salmenpera, Sven-Olaf , & Busch, 2017).

- ***Indicator 23*** *- End of Life scenarios of the components are required to be planned out during the tender*

5.2.2 Assigning weights to the indicators

The above indicators are translated into a final list of indicators which forms the framework for the procurement phase and can be seen in table 8. As described in section 2.3.4, there is now a need to prioritise these indicators based on the impact they have in implementing CE for projects. This step is done by formulating the indicators in a Likert scale survey which was completed by the experts mentioned in table 1 and table 3. Details of the analysis of this survey is explained in this section.

The scores assigned to each point on the scale are based on the level of importance for each indicator. Indicators that are considered to be highly important by majority of the respondents in that way eventually achieve a higher score. In order to maintain continuity, the difference in magnitude between the different points on the Likert scale was assumed equal. The Likert scale survey was created as a 'Microsoft Form' online in which each indicator was to be rated on an importance scale by the respondents. The importance scale was a 5 point scale distinguished as, "Very Important", "Important", "Moderately Important", "Of Little Importance", "No Importance/Does not affect CE". An additional option of "not sure" was provided to avoid forcing the respondents to choose one of the importance levels in case their experience or knowledge prohibited them from assessing any indicator. The Likert scale in this research does not consist of a 'neutral' or a mid-point option solely because the scale employed only consists of variations of the positive extreme. If the scale was also to include categories to judge whether some indicators negatively affect the circularity of the project, then it would be suitable to provide a neutral category. Each choice made by respondents was also asked to be justified, though this was not made mandatory as it would make the survey very long and time consuming to complete.

To calculate the quantitative value from the hierarchy, the mentioned scales were each assigned a *criteria weight* between 4 and 0 in regular intervals of 1, with 4 corresponding to 'Very important' and 0 to 'No importance/Does not affect circularity'. This helped in assigning weights to each indicator based on the judgements of the respondents. Each *indicator score* (IS) was then calculated by multiplying the criteria weight to the number of times that criterion (level of importance) was selected by all respondents and then adding up all these values obtained from each criteria. For example, if a certain indicator was graded as 'Very Important' by 10 respondents and 'moderately important' by the remaining 4, it achieved a score of 48 (4*10 for very important and 2*4 for moderately important). The final weight of this indicator was then determined by dividing the individual indicator score by the sum of all the individual scores of all indicators. While assessing a project in question, the indicators that were fulfilled by the project would get the full final weight whereas ones that were not implemented in the project would score 0. Eventually the final score would then be the sum of all final weights that were implemented in the project. The maximum score that could be achieved for this framework would be 1, depicting that all the indicators have been implemented and thereby achieving complete circularity, as per the scope and boundaries of the framework, in the procurement phase. Table 8 shows the final list with the weight of each indicator, and the detailed calculation can be found in Appendix C.

5.2.3 Consistency check for the Likert scale

In order to ensure that the survey created for the Likert scale measures its intended purpose, a consistency check by calculating the cronbach's alpha is performed. The formula used is (Taber, 2018),

$$\alpha = \frac{K}{K-1}\left[1 - \frac{\sum s^2 y}{s^2 x}\right] \qquad \text{equation (2)}$$

where, $\sum s^2 y$ = sum of item variance

$s^2 x$ = variance of total score

The resulting alpha for the Likert scale survey was 0.8. Comparing this value with the values from table 7, shows that the Likert scale survey had a good internal consistency. The detailed calculation can be found in Appendix D.

Table 7: Alpha Values (Source: (Taber, 2018))

Cronbach's Alpha	**Internal Consistency**
0.90 and above	Excellent
0.80 - 0.89	Good
0.70 - 0.79	Acceptable
0.60 - 0.69	Questionable
0.50 - 0.59	Poor
Below 0.50	Unacceptable

5.3 DEVELOPMENT OF INDICATORS FOR DESIGN AND END OF LIFE PHASE

5.3.1 Material input Module for design phase

To design the framework for the design phase, similar methodologies as the existing frameworks that were already analysed in section 3.4 were used partially. The design framework had two main components, each of which focused on separate principles of CE. One of the components took into account the extent of material loop closure by assessing the input flow of materials and components for the design phase. Each component that was included in the scope of this research was assessed based on its origin. The R framework discussed in section 3.2 formed the basis for this judgement. Though as discussed there is an extensive list of Rs ranging from 3R to 10R, a modified list was adopted for this aspect of the framework based on the suitability of the Rs. Analysing the 10R model, the Rs of Repair, refurbish and remanufacture were not suitable for this research.

On discussion with the experts involved in the design team of railway infrastructure components, it was advised that for railway components defined in the scope, components are seldom 'refurbished or remanufactured'. This is because the components that are not fit for repair or repurpose are usually sent for recycling as they consist of homogenous components and replacing a single part of, for example, a concrete sleeper is not possible. It will involve breaking down of the component into constitute materials thus causing loss of value. For railway infrastructure components direct reuse of secondary products is not always possible. Due to the wear of components in its lifetime, the component might need some additional repair work before being suitable for reuse. Since this step can include addition of new materials and energy, it is differentiated from direct reuse and is categorised as "repair and reuse". Apart from these, the Rs of refuse, rethink and reduce are considered before the actual design phase and are also included in the procurement phase indicators. Arguments can be made regarding rethinking of traditional design methods, but this aspect is accounted for in the second component of this design framework and will be discussed in the next section. This modification of the Rs, resulted in a model that eventually constituted of Reuse, repair and reuse, repurpose, recycle and recover (recover being part of the EoL framework) definitions of which are provided in table 8.

Table 8: Final list of indicators for procurement phase with their calculated weights

No.	Indicator	weights
1	The scope of circular economy is clearly defined by the client	0.049
2	Additional incentives are provided for circular solutions	0.040
3	Circular criteria does not conflict with other award criteria for tenders (For eg. Maximum maintenance free period along with demand for higher lifespan is required. Though for higher lifespan, regular maintenance is essential)	0.035
4	Suppliers can challenge the criteria if they see opportunities to improve circularity	0.051
5	Functional requirements (Performance based requirements) are specified over technical requirements for components/materials	0.039
6	If technical requirements are specified, they should be in line with circular economy principles	0.049
7	There is a collaboration between the client and contractor to successfully implement circular ideologies from the initial phases of the project	0.058
8	Suppliers and stakeholders are involved through market dialogue to promote circular public procurement	0.040
9	Involved organisations (Contractors, sub-contractors, designers, advisors, etc) need to have certain experience with circular solutions	0.042
10	Networks and organisations are used as knowledge partners while drafting tenders (For eg, involvement of organisations such as TNO, PIANOo, EMF or universities)	0.018
11	Design for disassembly/demountability/modularity is implemented	0.047
12	A specialised design team in design for disassembly/demountability/modularity is involved	0.030
13	Eligibility requirements are set up for the design (for disassembly) team in terms of competence and experience	0.026

14	Deconstruction team/organisation is included in the consortium from the design phase	0.026
15	Off the shelf (standardized/ traditional) purchasing is reduced OR circular off the shelf products are required (as means to promote innovative solutions)	0.035
16	There is a "Rethink" in ownership where public organisations do not purchase products but instead implement pay per use contracts or performance based contracts	0.033
17	Requirements are specified for using Reused/Refurbished/Remanufactured/Recycled (Secondary materials) or products as a certain fraction or as a whole	0.042
18	Requirements are specified for circular packaging of materials/products	0.042
19	Requirements are specified for utilizing nearby secondary material flows of components/materials	0.037
20	Extensive maintenance and repair agreements are included to ensure maximum lifespan extension of components	0.05
21	Requirements are specified for a longer guarantee period along with easily available spare parts during the operation phase	0.043
22	Requirements to develop and maintain material passports to better assess the applicability of the material/component for its subsequent life cycles	0.049
23	End of Life scenarios of the components are required to be planned out during the tender	0.042

Table 9: Definition of Rs

R	***Definition***	***Weights***
Reuse	direct reuse of components for same purpose without any additional repair	1
Repair and reuse	reuse of components for same purpose after repair	0.8
Repurpose	reuse the product for a different purpose	0.6
Recycle	component is broken down into constituent materials and is recycled	0.4
Virgin materials	Materials used are new resources	0

The inputs for this aspect of the framework comes from the design input of the components. Depending on the previous life of the component that is going to be used for the project in question, inputs are filled in accordingly.

Since these Rs already exist in a well acknowledged hierarchy, weights were assigned to these Rs from 1 to 0 with decrements of 0.2. Therefore 'Direct Reuse' was assigned the highest weight of 1 whereas 'recycled' a weight of 0.4. Input for virgin materials were scored 0 since these contribute to linear flow of materials. To get the circularity score of a component, the weights assigned with the Rs are multiplied with the total percentage of that component and the final circularity score is the sum of all individual components.

5.3.2 Design for disassembly module for design phase

Another important parameter as already mentioned, in closing the loops is designing for modularity or disassembly by which components and products can be cascaded for further use. While deciding the factors to consider for design for disassembly for this research, the articles that were analysed are further discussed below.

Bouyarmane, Amine , & Sallaou (2020) proposed a new framework for assessing the ease of disassembly during the design phase. The proposed tool employs 4 indices – type of disassembly tool, accessibility and operator's posture, time and end of life scenario. Selection of the necessary indices that can be used for this study was made on the basis of applicability. The index of end of life scenario was considered separately and to avoid double measurements was excluded from this section. Since the focus area of this article was not the construction industry, indices such as accessibility and operator's posture and disassembly time were not looked in for the same reason as these would be different for disassembly operations for railway infrastructure. The tool type classifications used, reflect on similar tool types that are or can be used for railway projects and are hence analysed. This index was categorised into 4 different tool types with scores for each type been calculated by using the AHP method. The classification is shown in table 10.

An important differentiation for not being able to use design for disassembly frameworks that are usually used for consumer products is due to the fact that railway projects are constructed in situ, hence the disassembly of the infrastructure also happens on site. These exterior conditions are less controllable as compared to the disassembly environment in a factory for consumer products. The focus on subassemblies rather than the entire infrastructure as a whole is also necessary due to the existence of multiple and individual lifespans (Mayer & Bechthold , 2018).

Table 10: Tool type classification (source: Bouyarmane, Amine , & Sallaou (2020).

Tools	***Description***	***Score***
No tool	Disassembly is performed by hand	1
Simple tool	Screwdriver, wrench, etc	0.7
Special tool	Drills, riveting, pneumatic tools, etc	0.51
Big tool	Welding machines, grinders, saws, etc.	0.36

Another study in this regard was done by Mayer & Bechthold , (2018) in which the authors developed an evaluation framework, the "Material Recovery Potential Index (MRPI)" for buildings. This framework consists of different categories for material and assembly levels which together contribute to the total evaluation of the building. The preliminary disadvantage of this framework is its orientation towards the building sector. Nevertheless, similarities regarding some of the indices used in this research can be translated for railway infrastructure components. The MRPI framework consists of a 'product level recovery potential', assessment of which is to be performed by manufacturers and an 'assembly level recovery potential' that needs to be performed by the design team. Since the production and manufacturing phases of components and materials are excluded from the scope of this study, the former assessment potential is not analysed, and the components of the latter are discussed hereafter.

Mayer & Bechthold , (2018) elaborated on the disassembly time index, the values and sub categories used for this research were based on field observations that were conducted for the building sector. Though efforts were made to relate these time categories for the different components of railway infrastructure defined in the scope of this research, they were not relatable. Estimation of disassembly times for each component and for the multiple connection types with multiple tools would be a very lengthy and exhaustive process. Also, when it comes the disassembly of components in the construction sector, such projects usually have a better tolerance for time delays as compared to the product disassembly operations (Mayer & Bechthold , 2018). The planning and scheduling for these projects, usually take account for such risks and are more flexible. Considering these factors, a decision was made to exclude disassembly time index in the assessment of design for disassembly for this framework.

Separation damage index: this index encompasses a 5-point damage scale consisting of values between 0 and 1 (in regular increments of 0.25) with 1 being most desirable result (table 11).

Table 11: Separation Damage Index (Source: Mayer & Bechthold , (2018))

Separation Damage Index	***Description***	***Score***
Fully Reusable	Part can be separated in perfect conditions	1
Minor Damage	Part require some repair but can still be reused	0.75
Non-reusable	Part that can be easily recycled but not reused	0.5
Extensive Damage	Part requires further sorting prior to recycling	0.25
Destructive damage	Part is damaged to such an extent which deems it unfit for conventional recycling	0

Tool type index – consists of 5 tool categories in order to define the index with values ranging from 0 to 1 (in increments of 0.25), 1 being the most desirable result (table 12).

Table 12: Tool type Index (Source: Mayer & Bechthold , (2018))

Tool Type Index	***Description***	***Score***
Manual disassembly	Assembly can be taken apart using no tools	1
Hand held tools	Include any non power tools such as crowbar	0.75
Hand held power tools	Includes any personal power tools such as a drill	0.5
Construction vehicles	Includes any type of deconstruction equipment heavier than a personal power tool	0.25
Inseparable	The assembly cannot be taken apart for any recovery processes	0

Another article that was referred for the DfD principles was that of Cottafava & Ritzen, (2021) which highlighted the lack of standardized framework for circularity and aimed at developing such a framework by combining the Building Circularity Indicator (BCI) and Predictive building Circularity Indicator (PBCI) which encompasses the design for disassembly criteria, for the building sector. For this study, the specific design for disassembly evaluation will be analysed further and will focus on 2 of the 4 sub-criteria. Type of connection and connection accessibility will be studied whereas, crossing and form containment will be excluded since it solely caters to the building sector. The distinction between the different connection types established in this study can be found in table 14 and the classification of the connection accessibility in table 13.

Table 13: Connection accessibility (Source: Cottafava & Ritzen , (2021))

Connection Accessibility	***Score***
Freely accessible	1
Accessibility with additional actions that do not cause damage	0.75
Accessibility with additional actions with repairable damage	0.5
Not accessible, irreplaceable damage to objects	0.25

Selection of indices and their scores

Analysing the above articles, decisions can be made regarding the selection of aspects that will be embedded in the new framework. Despite the extensive list of connections from table 14, few of these were deemed inapplicable for the connections of railway infrastructure components defined within the scope of this study. This conclusion was drawn after a thorough discussion with one of the designers from Mott MacDonald (UK), who suggested that connection types such as kit and foam are not suitable for this research. Evidently, all the mentioned articles described the importance of considering the connection type and the tools used. It does not only take into account the level of force applied but also inexplicitly categorises the tool types based on the energy needed to operate these tools. It also has the potential to capture the essence of uniqueness of the tools, wherein handheld tools such as wrenches and screwdrivers are not specifically designed for any particular type of connection. These can therefore be used for the disassembly of more than a single component and have a broader range of application. This is reflected with the higher score for such tools. Heavy machinery that could possibly be used for ballast cleaning or tamping in the case of railway infrastructure, have a very specific built and application and cannot be used for any other purpose. Considering all these aspects, the tool type index was decided to be implemented in the new framework.

The tools types mentioned in table 10 and table 12 were similar to a very large extent. For instance, the first category in both cases was manual disassembly, whereas simple tool category related to the handheld tool category by description and also by the given examples. Due to these similarities, the categories were combined and the weights/scores of table 10 were chosen as they were determined by the AHP, as opposed to the arbitrary values of table 12.

Table 14: Connection type (Source: Cottafava & Ritzen , (2021))

Connection type	***Connection sub-type***	***Weight***
Dry Connection	- Dry connection - Click connection - Velcro connection - Magnetic connection	1
Connection with added elements	- Ferry connection - Corner connections - Screw connections - Bolt and nut connection	0.8
Direct integral connection	- Pin connection - Nail connection	0.6
Soft chemical compound	- Kit connection - Foam connection	0.2
Hard chemical connection	- Glue connection - Pitch connection - Weld connection - Cement bond - Chemical anchors - Hard chemical connection	0.1

The index of separation damage and connection accessibility reflects on the interfaces of components and the ease with which they can be accessed for disassembly. Given the importance it has in the fundamental concept, connection accessibility and separation damage were chosen to be the other parameters. The scores for the accessibility type index were used from that of literature whereas for separation damage index, these values were determined with the help of practitioners through the AHP method as the article suggested values with regular intervals which did not depict the same level of difference by definition. The final weight of the separation index is shown in table 15 and detailed calculations can be found in appendix E.

After the values have been finalized, the final score for the disassembly module is obtained by taking the geometric mean of all the chosen indices.

It can be observed that for the tool type and the separation damage index, the values range from 1 to 0 whereas for the connection accessibility, the lowest value is 0.25. This is because the last categorization of tool type index refers to inseparable wherein the assembly cannot be taken apart for any recovery processes, not even 'recycling' or 'recover'. Since the material is then to be disposed into landfills and does not fit into any of the Rs from the R framework, this is assigned a value of 0. Similarly, for the separation damage index, the destructive separation also renders the components unfit for recycling as per the definition and thus has a value of 0. Whereas for the connection accessibility, the components that suffer irreplaceable damage can still be recycled and hence have a non-zero value.

Table 15: Weights of separation damage index

Separation Damage	***Weight***	***Normalised weights***
Full Reusable	0.512	1
Minor Damage	0.246	0.44
Non – reusable	0.131	0.2
Extensive Damage	0.072	0.074
Destructive Separation	0.038	0

5.3.3 Material output module for EoL phase

Since the design phase considered the material input for the project, the end of life phase should aim at the outflow of materials. At the end of life, similar framework as the material flow module from the design phase framework is considered based on the R model. Only difference for this phase is the sub categorization of the recycle criteria into downcycling and upcycling and 'dispose' as the least favorable option (table 16).

Table 16: R model for EoL phase

R	***Definition***	***Weights***
Reuse	direct reuse of components for same purpose without any additional repair	1
Repair and reuse	reuse of components for same purpose after repair	0.8
Repurpose	reuse the product for a different purpose	0.6
Recycle (upcycle)	component is broken down into constituent materials and is recycled for similar or higher value use	0.4
Recycle (downcycle)	component is broken down into constituent materials and is recycled for lower value use	0.3
Recover	incineration of materials with energy recovery	0.2
Dispose	Materials are discarded into landfills without energy recover	0

5.3.4 Weighing of different components

The final step in the development of the framework for the design and EoL phase was to establish the importance of the different railway infrastructure components as compared to each other. Due to the different amount of materials used per component, it was necessary to distinguish these components in order to avoid unjust results. For instance, increasing the circularity of a component with very little material input would be easier and would therefore result in a similar overall score as compared to another project with higher circular efforts for components with heavier material inputs. To direct the circularity principles towards components with larger material flows and significant environmental impacts, this step was necessary. Inputs provided by the experts in the field of not only circular economy but also from the railway sector suggested that the current trend focuses on the carbon footprints and greenhouse gas emissions (GHG) of components to assign relative significance. Thus, to maintain the adaptability of the framework, the components were judged based on their GHG emissions. An important and clear study conducted by Schmied & Mottschall (2013), is used as a main source of reference for this part of this research. The authors of this report conducted a detailed study to calculate the GHG emissions for light and heavy rails of the German Rail system. Majority of the components analysed coincided with the components defined for this research and data used was well justified by European codes which made it suitable to adopt these calculations for this study.

Schmied & Mottschall (2013), determined the GHG emissions for the construction, maintenance and operation of the rail infrastructure and the manufacture and maintenance of the rail vehicles by analysing the material flows of the individual components. For the consideration of GHG, apart from carbon dioxide, relevant emission factors for methane and nitrous oxide were considered.

The report considers the emissions arising during the extraction of the raw materials, their transport and the emissions during the processing into basic materials (eg, concrete, steel, copper). Apart from these, the emissions that arise due to transport of materials to the construction site and the energy consumption on the construction sites were also considered. It gives a final estimate of GHG emissions for majority of the component studied in this research with very detailed considerations to minor aspects. Despite these advantages, the final GHG emission values for these components could not be directly utilized because for some of the structures these values were combined with more than one element. For example, final values of the CO_2 equivalent for ballast, sleepers and the fasteners were given as a single combined value. Since for this study the individual values are necessary to prioritize each component separately, these precalculated values could not be used. Though this was the case, the individual values of the weights of the different components were given which were eventually used to calculate the GHG emissions. The downside of not being able to use the calculated values was the omission of the aspects such as transport distances, construction emissions and end of life cycle disposal.

The current values of the GHG emissions for each component therefore only highlights the embedded emissions during its use life phase. These weights from the existing reports vary depending on the type of track and also based on the different types of components used and the detailed quantities can be found in appendix F. These are then multiplied with the emission factors given in table 18 to determine the GHG emissions per component. To eventually determine the contribution of GHG emissions of each component to the overall system, the individual contribution of each component was divided by the total GHG emission of the system. The functional unit to determine the weights of individual components was taken to be a kilometer of double track. A sample calculation can be seen in the table 17 which is performed for a double ballasted track with its weights. The values of 'construction per km' and maintenance 'per km annually' are taken from the report. The values of construction per km annually is obtained by dividing per km annually values by the lifespan. The sum of the construction and maintenance quantities per km annually is then used to calculate the resulting CO_2 equivalents for tonne/km/annually.

After these calculations, in order to obtain the final value of the design framework, the arithmetic means of scores of the design for disassembly module and material input module are taken and multiplied by the weights obtained after the GHG calculations, which determines the score of the complete design on a scale of 0 to 1, with 1 being the most circular. Similarly, for the EoL phase, the scores of the material output module are multiplied by the weights from the GHG calculations which gives the score of the EoL phase.

Maintenance phase

Assessment of circularity for the maintenance phase was found to be a challenging issue. This phase of the study, in order to assess the circularity, should focuses on the repair cycles and methods used. Furthermore, during one of the interviews it was discussed that the impact of maintenance phase on the overall sustainability is minimum. The specifications for maintenance are set in the tender phase therefore this phase conducts what is specified in the requirements and in the design outlined in the design phase. It was also observed that the widely used package of DuboCalc, when calculating the MKI values, tends to neglect the maintenance phase due to its minor contribution. A DuboCalc file from a present project was analaysed with respondent 7, which showed the MKI assigned to the maintenance phase was zero. Another aspect that goes on during the use phase is the amount of energy consumption and pattern of use. Since these factors are dependent on the energy consumption aspect of the rolling stocks and were since out of the scope of this study, the use and maintenance phase was decided to be of little impact and thus excluded. The low influence of the maintenance phase can also be seen in figure 7. Despite this exclusion, the requirements for maintenance and repairs were included in the indicators of the procurement phase. The existing assessment frameworks also take into account the materials at the input (design) and output (EoL) stages alone (MCI). During the maintenance phase the lifetime extension is ensured by regular maintenance, assessment of which can be difficult. Maintenance schedules can be looked into but this can result in a very project specific analysis and may also vary depending on the type of contract implemented. The majority of the effect during the use and maintenance phase in terms of material flow, is the replacement of components which indirectly hints at the EoL of the component to be replaced. The only possible assessment here could be to check whether the replacement of the component has occurred at either before or after the prescribed end of its functional lifespan. Due to these reasons and owing to the strict time constraints the maintenance and use phase was decided to be excluded from this research.

Table 17: GHG emission calculation

COMPONENT	TYPE	DETAILS	LIFESPAN (years)	Construction		Maintenance	A total of	CO2 equivalent t/km/a	weights
				per km	per km anually	per km anually	per km anually		
Contact wire	100 mm2	c/s area 80 mm, 100 mm and 120 mm, Copper/copper-silver (CuAg 0.1) and Copper-magnesium (CuMg 0.5)	7	2	0.2	0.01	0.2	0.19	0.01
Droppers	Re200/250			1.3	0.07	0	0.07	0.2	0.01
Catenary			20	included in contact wire				0.19	0.01
Masts/Frames	Concrete		60	38.2	0.64	0.13	0.76	2.39	0.10
Rail	Vignole/Flat Bottom Track (Rail S54)		30	218.2	7.273	0.05	7.32	12.53	0.54
Sleeper	Monoblock reinforced	Type B70. 2.6 m long, weigh 280 kgs	35	380 m3 (concrete). 23.3 t (reinforcing steel)	10.86 m3 (concrete) 0.67 t (reinforcing steel)	0.11 m3 (concrete) 0.01 t (reinforcing steel)	10.97 m3 (concrete) 0.67 t (reinforcing steel)	4.52	0.19
Concrete Slab	N/A		60	-	-	-	-	-	
Ballast	Yes	30 cm thick, density 1.65 t/m3	15	7099 t	473.3 t	7.1 t	480.4 t	1.93	0.08
subballast layer	Yes		20	3549.5 t	236.65 t	3.55 t	240.2 t	0.97	0.04
Formation layer		1) 40 cm thick and 8.6 m (single track) /13.30 m (double trrack) 2) Density for gravel sand 2.80 t/m3	60	14,896	248.3	0	248.3	0.496	0.02

Table 18: Emission factors (Source: Schmied & Mottschall, (2013))

Material	***Unit***	***CO_2 Equivalent***
Sand, ex works	kg / kg	0.002
Gravel, crushed, from the mine	kg / kg	0.004
Limestone, from the mine	kg / kg	0.002
Cement, re-specified, ex works	kg / kg	0.759
Concrete, ex works	kg / m^3	323,841
Anhydrite, ex works	kg / kg	0.002
Brick, ex works	kg / kg	0.238
Steel, converter, low-alloy, ex-works	kg / kg	2.04
Steel, low-alloy, ex-works	kg / kg	1.716
Reinforcing steel, ex works	kg / kg	1.444
Copper, primarily, from the refinery	kg / kg	3,100
Copper production, avg. Metal processing	kg / kg	1,825
Bronze	kg / kg	2,899
Aluminum, production mix, ex-factory	kg / kg	7.043
Lead, primary, ex-works	kg / kg	2.102
Tin, from regional warehouse	kg / kg	17.031
Zinc, primary, from the regional warehouse	kg / kg	3.361
Flat glass, coated, from the factory	kg / kg	1.09
Flat glass, uncoated from the factory	kg / kg	0.233
Polyethylene (HDPE), granules, from the factory	kg / kg	1.929
Polyvinylchloride (PVC), from the factory	kg / kg	1,967
Glass fiber reinforced plastic, polyamide, ex works	kg / kg	8,791
Beech wood, ex works	kg / m^3	64,433
Tar oil, ex works	kg / kg	1.586

Importance of different life cycle stages

During the initial interviews, it was noticed that respondents valued a certain life cycle stage over another. This aspect was therefore considered essential to take into account while assessing the results of the framework. In order to gather insights regarding the difference in importance of the life cycle stages, another round of AHP was conducted with 5 experts. The final results of which are mentioned in table 19. The individual comparison matrices can be seen in appendix G along with the final aggregated comparison matrix.

To assess the final score of a project, for all its life cycle phases, the individual life cycle phases are multiplied with the values obtained in table 19 to get the final project score.

Table 19: Weights of life cycle phases

Life cycle phase	***Weight***
Procurement phase	0.319
Design phase	0.495
End of Life phase	0.186

5.4 SUMMARY

To understand the reasons for the current status of CE and to generate appropriate indicators, it was also essential to first understand the barriers for the transition towards CE. The main source to understand these barriers were with the help of semi-structured interviews with experts. The obtained barriers along with the discussions during the interview helped in the formulation of the indicators for the procurement phase. Efforts were made to overcome the barriers with the help of these 23 indicators. The list was kept generalized to avoid project specific indicators as this would restrict the applicability of the framework. It was also necessary to determine the relative importance of these indicators to avoid unfair results. This was performed with the help of the Likert scale survey which was completed by the respondents.

For the design phase framework, the division into two modules was made to ensure the inclusion of more than just the material flow aspect for the assessment of CE. As observed from the drawbacks of the existing frameworks, the DfD aspect was absent in all. The importance of DfD studied previously needed to be included to provide a complete assessment. Different categories within the DfD aspects were analysed from literature and selections were made based on applicability and suitability that resulted in the final module consisting of connection tool index, connection accessibility index and separation damage index.

The material flow module was replicated for the EoL phase framework with differences highlighted in the adaption of the R framework. Lesser significance of the maintenance and use phase on circularity resulted in the exclusion of this life cycle phase. To provide a just and fair result, it was also essential to analyse the contribution of the different components to the overall score as these had different amounts of material inflow along with varying lifespans. In order to capture the essence of this difference, GHG emissions were calculated and weights were assigned to each component.

During the interviews it was also observed that the different life cycle phases had varying influence on the circularity of the project. The final framework thus weighed the different phases based on scores obtained from the AHP which was conducted along with experts that had experience in CE for railway projects.

6. FRAMEWORK OVERVIEW AND CASE STUDY

This chapter gives a final overview of the framework that was created in an Excel workbook with points to reconsider and its applicability. It explains the working and includes the case studies that were performed to validate the results.

6.1 EXPLANATION OF THE TOOL

6.1.1 Procurement phase framework

In order to assess a project for its procurement phase, detailed documents that elaborate on the requirement specifications and preferably a team member who has been involved in the entire process can be helpful. Each indicator is to be checked for its applicability for the project and accordingly filled in the cells next to it from a drop-down list of either ‘Yes’ or ‘No’. None of the cells are to be left blank and once the assessment is complete, a final score for the procurement phase will be displayed in the cell at the bottom of the sheet.

In table 20, some indicators are marked with an asterix. These indicators have pre-requisites in order to obtain full points as they depend on the material and component specifications. In order to prevent similar scores for 2 projects with these requirements specified for different components, this differentiation is necessary. For example if project A and B are being compared, and specifications of project A suggest detailed specifications of reused/recycled materials for rails, (which has a higher GHG emission) as compared to project B with similar specifications for project B, but for components with the least GHG emissions, such as droppers, in the absence of this differentiation, would be scored equally whereas the actual impact of project A is comparatively larger. To prevent this, while comparing these indicators, a requirement is set to at least specify these requirements for 3 components, one of which needs to be a component amongst the top 2 GHG emissions found in section 5.3.4.

6.1.2 Design phase framework

Material input Module

As can be seen in table 21, the components are listed along with the possible choice of material/component to be used for the new design. Based on the design input, values in the yellow cells are be filled. In addition, choices regarding the type of sleeper, rail and ballast track or slab track is to be made from the drop-down list, indicated in the blue cells. Once the table is completed, a check is performed to see if the values inputted are correct. In case of a slab track, the row for ballast needs to be made zero, failing which an error will be generated in the ‘input value check’ column and no result will be displayed. In case of ballast tracks, the blue cell adjacent to it needs to be selected as “yes” , as this deactivates the input value check .

Table 20: Procurement framework

INDICATORS	
The scope of circular economy is clearly defined by the client	Yes
Incentives are provided for circular solutions	Yes
Circular criteria does not conflict with other award criteria for tenders (For eg. Maximum maintenance free period along with demand for higher lifespan is required)	Yes
Functional requirements (Performance based requirements) are specified over technical requirements for components/materials	Yes
If technical requirements are specified, they should be in line with circular economy principles	Yes
There is a collaboration between the client and contractor to successfully implement circular ideologies from the initial phases of the project	Yes
Suppliers and stakeholders are involved through market dialogue to promote circular public procurement	No
Suppliers can challenge the criteria if they see opportunities to improve circularity	Yes
Networks and organisations are used as knowledge partners while drafting tenders (For eg, involvement of organisations such as TNO, PIANOo, EMF or universities)	Yes
Involved organisations (Contractors, sub-contractors, designers, advisors, etc) need to have certain experience with circular solutions	Yes
Design for disassembly/demountability/modularity is implemented	Yes
A specialised design team in design for disassembly/demountability/modularity is involved	Yes
Eligibility requirements are set up for the design (for disassembly) team in terms of competence and experience	Yes
Deconstruction team/organisation is included in the consortium from the design phase	No
Requirements are specified for using Reused/Refurbished/Remanufactured/Recycled (Secondary materials) or products as a certain fraction or as a whole*	Yes
Off the shelf (standardized/ traditional) purchasing is reduced OR circular off the shelf products are required (as means to promote innovative solutions)*	Yes
There is a "Rethink" in ownership where public organisations do not purchase products but instead implement pay per use contracts or performance based contracts	Yes
Requirements are specified for circular packaging of materials/products*	Yes
Requirements are specified for utilising nearby secondary material flows of components/materials	Yes
Extensive maintenance and repair agreements are included to ensure maximum lifespan extension of components*	No
Requirements are specified for a longer guarantee period along with easily available spare parts during the operation phase*	Yes
End of Life scenarios of the components are required to be planned out during the tender*	Yes
Requirements to develop and maintain material passports to better assess the applicability of the material/component for its subsequent life cycles	Yes

Final circularity score	▲ 0.874

Table 21: Material input module

CATEGORY	COMPONENT	TYPE	MATERIAL INPUT					INPUT VALUE CHECK	MATERIAL MODULE VALUE
			Directly Reused	*Repair and reused*	*Repurpose*	*Recycled*	*Virgin materials*		
			1	0.8	0.6	0.4	0		
OVERHEADLINE SYSTEMS	Contact wire		50.00%			40.00%	10.00%	OK	0.66
	Droppers		10.00%	10.00%		50.00%	30.00%	OK	0.38
	Catenary		20.00%			30.00%	50.00%	OK	0.32
	Masts/Frames		0.00%	0.00%	0.00%	50.00%	50.00%	OK	0.20
SUPERSTRUCTURE	Rail	Grooved Track	30.00%	0.00%	10.00%	40.00%	20.00%	OK	0.52
	Sleeper	N/A	0.00%	50.00%	0.00%	20.00%	30.00%	PLEASE MAKE SURE VALUE IN THIS ROW IS ZERO	0.48
	Concrete Slab	Yes	0.00%	0.00%	0.00%	0.00%	0.00%	PLEASE ENTER CORRECT VALUES	0.00
	Ballast	N/A	50.00%	20.00%	0.00%	30.00%	0.00%	PLEASE MAKE SURE VALUE IN THIS ROW IS ZERO	0.78
	Secondary concrete layer	Yes	10.00%	0.00%	20.00%	30.00%	40.00%	OK	0.34
SUBSTRUCTURE	Formation layer		0.00%		40.00%		60.00%	OK	0.24

Table 22: design for disassembly module

CATEGORY	COMPONENT	TYPE	DESIGN FOR DISASSEMBLY ASPECT						DfD module value
			Connection accessibility		Connection Tool		Separation Damage		
OVERHEADLINE SYSTEMS	Contact wire		Freely accessible	1	Special tools/Hand held power tools	0.51	Minor Damage	0.44	0.61
	Droppers		Freely accessible	1	Special tools/Hand held power tools	0.51	Minor Damage	0.44	0.61
	Catenary		Freely accessible	1	Special tools/Hand held power tools	0.51	Minor Damage	0.44	0.61
	Masts/Frames		Accessibility with additional actions that do not cause damage	0.8	Big tools/Construction vehicles	0.36	Minor Damage	0.44	0.50
SUPERSTRUCTURE	Rail	59Ri2 (Grooved)	Accessibility with additional actions with reparable damage	0.4	Special tools/Hand held power tools	0.51	Minor Damage	0.44	0.45
	Sleeper	Monoblock reinforced	Accessible with irreplacable damage to components	0.1	Big tools/Construction vehicles	0.36	Destructive Seperation	0	0.00
	Concrete Slab	Yes	Accessible with irreplacable damage to components	0.1	Big tools/Construction vehicles	0.36	Extensive Damage	0.074	0.14
	Ballast	N/A							-
	Secondary concrete layer	Yes	Accessible with irreplacable damage to components	0.1	Big tools/Construction vehicles	0.36	Extensive Damage	0.074	0.14
SUBSTRUCTURE	Formation layer		Accessibility with additional actions that do not cause damage	0.8	Big tools/Construction vehicles	0.36	Minor Damage	0.44	0.50

Primarily, the component is looked at as a whole, without accounting for its individual materials. This is done because considering the materials used, rather than the whole component, gives rise to the problem of loss of value. For instance, if while looking at a concrete sleeper, if the material used is assessed, based on its previous functions or use, it results in breaking down the component from its original form and thus violating the principle of value retention. In case the sleeper is judged based on the previous use, well in this case as a sleeper itself, then direct reuse has more value. In this case, if the constituent materials consist of reused components, for example the cement in the concrete is from slag or fly ash, this eventually is then assessed based on the contribution of that material to the complete composition of the sleeper. If the material constitutes for more than 50% of the total composition of the material by weight, the component can then be classified as 50% recycled whereas if the remaining constitutes material are from virgin sources, the remaining 50% can be inputted as virgin materials in the framework.

The functional unit of the framework is a kilometer of double track. Therefore, all inputs should be based on similar unit.

Design for disassembly module
For this part of the framework, selection is to be made for all the three indices mentioned in the previous chapter. This module consists of a drop-down list with all the mentioned options and a final score is calculated (table 22). For the calculation of these indices, in case of components with two or more connections, the worst-case scenario is to be assumed. This is so because, for example, a component with multiple connections suffers extensive damage at a certain interface, then that component as a whole cannot be directly reused and has a higher chance of being discarded.

6.1.3 End of Life phase framework

This framework is similar to the material input module of the design framework with different Rs and hence needs to be completed on the same lines.

6.2 APPLICABILITY OF THE TOOL

1) This tool cannot be a stand-alone third-party tool as it requires involvement of, and mutual agreement of both contractors and clients in some regards. Indicators such as ensuring early collaboration with the contractors, needs mutual acceptance from both parties. Situations where client regards a certain level of contractor involvement as sufficient for this criterion can be perceived as unsatisfactory involvement by the contractors. Therefore, this tool is more suitable as self-assessment tool for client and contractors.
2) Clients or procuring organisations can use this tool to
    a. Assess the circularity of the procurement and tender specifications after drafting them and improve their requirement specifications, if necessary.
    b. Use the procurement framework as a guideline and ensure that maximum, if not all indicators, are embedded in the requirements specifications before drafting the specifications.
    c. Use the design and EoL framework to evaluate designs submitted during tender or final design on the basis of circularity and choose the most circular solution.
    d. Set a certain cut-off score in the tender for designs.

3) Contractors can use this tool to
    a. Judge the circularity of the requirement specifications
    b. Assess different design options of different track types to compare and select most circular design
    c. Use the procurement framework to highlight the principles that are most important based on the client's requirements and subsequently implement those in the design

6.3 CASE STUDY – UITHOORN LINE

6.3.1 Description of the project

The Amsterdam Transport Region aims at delivering a high quality of public transport system within the area by ensuring fast and high frequency, high reliability and high degree of comfort. It also aims at including similar high quality for cyclists and pedestrians so as to strengthen the chain. The responsible authorities have heavily invested in the quality of the public transport over the recent years. The Amsterdam Zuid Station is aimed at being a high-quality public transport hub. To ensure these aims are fulfilled, the municipalities of Uithoorn and Amstelveen, Province of Noord – Holland and the City Region of Amsterdam decided to extend the renovated Amstelveen Line to the center of Uithoorn at the current bus stop Stationsstraat over the route of Spoordijk. The new lines consist of 3 tram stops at Aan de Zoom, Uithoorn Station and Uithoorn Centrum and replaces the current bus connection between Uithoorn to Amstelveen and Amsterdam with an estimated budget of 70 million euros.

Figure 16: Route of Uithoorn Line

Preliminary exploration to check whether the new Uithoorn line was a feasible and an attractive solution was completed in 2014. Currently the planning of the project is outlined as follows:

- 2020: design and planning work, preparatory work
- Q1 2021: start of work on Amstelveen industrial estate
- Q3 2021: start of work in Uithoorn
- Q2 2023: construction work to be completed and to commence the test period
- Q3 2024: commissioning Uithoornlijn

The current status of the project is in the preliminary design phase with the completion of the procurement and tender phase, hence this project will be assessed for its circularity for the procurement phase alone. This case study is performed with the help of the procurement and tender documents that provided an overall view of the requirement specifications of the projects along with consultation interviews with the 'overall systems integrator'. These interviews helped in discussing and guiding the study, through the extensive documents that were originally in Dutch. Translated documents that were used to draw conclusions, were cross checked in the final interview to make sure the meaning of the specifications was not lost in the translation.

6.3.2 Results

The documents presented for the study, were carefully examined per section to check which indicators were fulfilled from the list of the framework. The following section shows the points from the tender documents that promote circularity within the project. These specifications are reformulated in order to preserve the confidentiality of the project documents since this project is not yet completed.

The requirements specifications for the infrastructure components stated the need for easy and safe accessibility of components during the maintenance cycles. The design of such components was also required to be modular. Additional maintenance requirements for simplistic designs were also stated such that they would require little specialist knowledge during its maintenance and can be operated with simple tools and equipment.

The above points mentioned in the requirements specification clearly depict the client's needs for design for modularity. Not only the modularity in structure is requested explicitly but due attention is also given to the accessibility and ease of maintenance of these structures during maintenance phase. These factors though highlighting only the points for maintenance, would also eventually ease the disassembly of components at the end of their life. Such requirements mentioned in the specifications relate to the indicator 11, "Design for disassembly/demountability/modularity is implemented" of the framework and is therefore assessed as a "Yes".

Requirements are also specified to have a guaranteed supply of spare parts for at least 10 years for the infrastructure components and materials. The overall tram infrastructure lifespan is also specified to last minimum of 50 years, unless otherwise specified in other requirements. At first glance, this seems to shed light on the indicators for lifespan extension of components and maintenance agreements. On further analysis it can be observed that the minimum duration of 10 years for the supply of guaranteed spare parts is not sufficient to maximise the lifespans of components. The majority of the components have an average lifespan of more than 20 years except the overhead catenary, contact wire and droppers which have an average lifespan of less than 10 years. These components when checked for their overall influence in the design phase show very little contribution to the overall score. Thus, in order achieve the points for this indicator, it is necessary to specify spare parts for a period more than the most heavily contributing components from the infrastructure components.

Apart from the documents provided, the interview also highlighted the fact that encouragement and requirements were also specified to implement and develop material passports for the components of the infrastructure that are to be implemented in this project. These were specified in other confidential documents that were not available for this study and hence indicator 22 was also satisfied. In order to ensure no other additional information was missed out from those documents, the list of indicators was revisited with the respondent by going through each indicator.

Considering all the information, the Uithoorn line in its procurement phase scores only on 2 indicators and resulted in a very low score in terms of circular economy. It achieves a score of 0.096 (approx. 10% circular) out of 1. This depicts that the tender documents and specifications do not focus much on the circular aspects for the project. The major aspects of circularity such as closing material loops by implementing reuse and other Rs for the materials were not specified in this project. Moreover, it was also observed that the requirements regarding the different components were highly technical, leaving little or no room for innovative solutions. Circularity was not one of the spearheads of the project and was therefore also not mentioned in the scope or within the clauses for sustainability. Award criteria was also based on the traditional cost and time parameters and no incentives were provided for circular solution. Apart from these omissions, end of life scenarios for components were also not planned or assigned ownership which drives the project score to the lower side.

6.3.3 Discussion

The results from the case study show that although there exist opportunities within railway infrastructure projects for more circular solutions, the efforts within the industry do not match the gap. Cost and time often play a pivotal role in most of the decisions whereas sustainability and circularity take a back seat. Lack of reference projects and standards to implement CE forms a major barrier. Opportunistic behaviour from contractors in order to win the tenders, also makes clients hesitant to opt for certain CE ideas such as more functional requirements over technical requirements. On discussion during this case study, regarding the specification of technical requirements over functional, it was informed that often when this is done, contractors tend to go for the cheapest solution possible as these contracts usually include only design and build. Therefore, to ensure high quality of products and materials, clients need to specify technical requirements. This can also be seen in the case of the Uithoorn line, where the specifications for the rail types and ballast were precisely specified and no room for the selection of choices was left to the contractor. Lack of governmental approved standards to check durability and safety for critical components also hinders the implementation of secondary products. Though circularity has vast growing interests in academia, the practical implications yet seem to be far.

6.3.4 Validation

The results of this case study were discussed with the respondent to check for its validity. Initially the results were thought to be lower than expected since the project had implemented, according to the respondent, a good amount of sustainable practices. On further discussion, it was noticed that the comparison made was in relation to previous projects where minimum or no sustainability and circularity requirements were specified or implemented. Comparing these results with the potential impact and opportunities of circularity within railway projects, these results produced by the framework were acknowledged to be acceptable and a good representation of the extent of circularity for the project of Uithoorn line.

6.4 CASE STUDY – UTHOF LINE

6.4.1 Description of the project

The Utrecht region administration (Bestuur Regio Utrecht – BRU) drafted the need for a high-quality public transport connection between Utrecht Central Station and the Utrecht Science Park/De Uithof. De Uithof region was growing well before the construction of this line, partly due to the expansion of the Utrecht University, and other neighbouring institutions (RIVM, Princess Maxima Center, etc). It was estimated that due to these reasons, the number of students, employees and visitors traveling to Utrecht will grow by 25% (Project Organisation Uithoflijn, 2020). The then existing bus lines were deemed to be insufficient to accommodate the growing passenger numbers. In June 2011, the city council of Utrecht decided to convert the bus lane into a tram line between Utrecht Central Station and De Uithof. In June 2012, BRU and the municipality of Utrecht signed an administrative agreement and the Uithof line Project Organisation (POUHL) was established. On behalf of BRU, the POUHL took care of the tenders for the tram infrastructure and tram vehicles and the preparations for the operation and management. 2013 saw the establishment of the initial design of the Uithof line following which the tender for the tram infrastructure and tram equipment began. In 2014, the Tram Infrastructure Engineering & Construct (E&C) contract with Koninklijke BAM Groep was signed and a number of parts of BAM went on to carry out the work as BAM Combinatie Uithoflijn Utrecht BV (BAM-CUU), which took on the responsibility of the design and realization of the tram infrastructure (Project Organisation Uithoflijn, 2020). The construction of the Uithof line made an important contribution to BRU's ambition to realise a network of 5 tram lines in the Utrecht region. The first works started in 2012 including the tendering for various components of the substructure and superstructure, the purchase of new tram equipment and realisation of the tram infrastructure and after facing some challenges and delays, the Uithof line was able to provide services from December 2019 and stretches a total distance of 8 kms with 9 tram stops and with the frequency of 16 trams per hour per direction with the capacity to withhold 20 trams per hour per direction in the longer term.

Figure 17: Uithof line route and stops (Source: (Project Organisation Uithoflijn, 2020))

6.4.2 Analysis of superstructure and substructure

Since the Uithof line is currently in service, the project can be assessed for the procurement and design phases and also the EoL phase (based on the requirements specified in the initial phases). Method to analyse the procurement phase of this study is similar to that of the Uithoorn line wherein the documents for requirement specifications were scanned and analysed for the indicators from the framework. For the design phase, the documents provided focused more on the structural design and calculations which were less helpful for the assessment of circularity. Therefore, interviews with the project manager of the Uithof line were held to discuss the different components and their design methodologies.

The entire stretch of the project has 14 combinations of the track structure that varied depending on the type of rail, the top layer finish and the track type. For this study, due to the extensive list of types of tracks, selections were made to simplify the analysis for the case study. The project implemented 2 most commonly used types of rails (Grooved rail and Vignole rail), both of which were analysed in this research. One of the variations of the vignole rail was the head hardened rail (49E1- R350Ht) which was also used in some parts of this line and contributed to a total of 1174m of the entire project. This type was not considered in this study since apart from having a smaller stretch as compared to the rest, this rail also differed in its weight. Change in its weight would result in recalculating the GHG emissions for this type, which given the time allocated for this case study was not possible. Apart from this, the GHG calculations also included the amount of material required for maintenance. The reference report did not analyse the 49E1 – R350Ht rail type which resulted in the absence of this required data and hence made it difficult to complete the GHG calculations.

The variations for the initial two types of rails was based on their construction type and their type of finish. Differentiation based on the type of top layer finish was neglected since this component was not included in the scope of this research. The choices made for the latter categorisation, based on the track type, is further analysed in the following sections.

6.4.2.1 Rheda City type

This type of track is a modified version of the ballastless track which consists of prefabricated concrete sleepers with lattice girders installed in a concrete pavement layer (Rail One, 2013). This type is further classified into C, D and grass type which varies based on its top layer finish and type of design. The overall structural layers for these types of tracks shows 2 distinct concrete layers with the rail embedded in the top layer.

Type C of this class is designed as a continuously supported rail, therefore rendering the function of sleepers as temporary (Rail One, 2013). The primary function of the sleepers in type C is to provide track geometry and track gauge during construction and these types of construction requires less maintenance and has a positive effect on the service life of the track construction (Rail One, 2013).

Type D of this class is designed by considering the rail mounted on a specific number of supporting points (by sleepers) and is therefore designed as a discretely supported rail. The Type G is a further classification of type D with focus given to the finish of the top layer (grass). As already mentioned, due to the exclusion of top layer, these types were analysed as one system and no differentiation was made on D and G. Furthermore, since the components are similar and the difference lies in the method of structural design, the differentiation based on continuous or discrete (D or C) also did not affect the aspects of circularity for this study and was therefore considered as one system.

6.4.2.2 Edilon type

These types of track are embedded slab tracks without sleepers. They consist of concrete slabs which are first poured in-situ followed by placement of the rails. This type of track also consists of subcategories, such as the urban slab track systems (USTS), embedded rail system – light rail (ERS-LR), embedded rail system – low impact to environment (ERS-LITE), for which the construction methods vary, whereas the overall section remains to a very large extent similar. This conclusion was made based on the discussion during the interview and was therefore decided to analyse the Edilon systems as a single type, without differentiating between its sub-types.

Thus, the final list of track types that are analysed for this research, after extensive consultation with the senior project manager and analysing the provided documents, are:

- Vignole with RHEDA City type (2116m)
- Vignole with Edilon type (744m)
- Grooved with RHEDA City type (526m)
- Grooved with Edilon type (2683m)

The different type tracks considered for this case study cover around 75% of the total length of the Uithof line.

6.4.3 Analysis of overhead lines

For the Uithof line, the overhead line masts are consistent in terms of the material used and make use of HE masts with movable arms. The main differences lie in multiple systems and single systems, in which the plurality is defined based on the number of contact wires used. On discussions during the interview, it was observed that the variation in the overhead line systems lies also based on the diameter of the contact and catenary wires, which either take values of 100 mm^2 or 150mm^2. Since this variation does not affect the analysis method of this study for circularity, it is neglected and considered as same systems, but due attention is given in the calculation of weights based on GHG emissions. Apart from these, the other variations for the overhead line equipment for this project were in terms of their design principles and tensioning systems which also did not influence the CE parameters defined within the scope of this research and were therefore considered as one type of system for the entire track.

6.4.4 Results

After analysing the documents, it was observed that the procurement phase of the project had very little focus on circularity. Majority of the CE principles that were encapsulated in the new framework were absent in this project and even the umbrella concept of sustainability was seldom focused on.

> "Tram Infrastructure of Uithof Line (TIUHL) must be technically available for 99.0% of the time"

Criteria for availability were specified to a much larger extent than maintainability. The analysis showed that requirements for maintainability were absent in the documents which overlooked the principle of lifespan extension of components. Apart from the maintainability clauses, the required lifespans of components that were specified in the documents were usually lower than the average lifespan. The deviation from its average lifespan to even lesser expected lifespan shows the lack of efforts to maximise component lives.

The requirements also specified that for the tram infrastructure, "components used must have been previously used and applied under comparable conditions at least 2 LRT companies in the European Union or in related industries such as heavy rail and automotive". This shows lack of room for the implementation of new and innovative solutions. Off the shelf products can be implemented if these align well with circularity principles, which according to the implemented designs, do not seem to satisfy these principles.

The only circular indicator that is specified in the procurement phase of the Uithof line project is that of modular designs. The specifications state that "Tram Infrastructure of Uithof Line (TIUHL) must be made up of modular subsystems and components for the most efficient maintenance process". Apart from this, components are also required to be accessible for maintenance which is highlighted by "TIUHL is set up in such a way that all components can be maintained and managed effectively and efficiently".

Since only one indicator from the entire list of the framework for CE was fulfilled, the procurement phase of this project scored 0.05 (5%) out of 1.

For the design phase, the material input was completely virgin raw materials. All components of the project were constructed from new raw materials and no importance was given to using secondary material and therefore leading to an overall score of 0. For the design for disassembly aspect, it was observed that the design documents provided, seldom focused on the material connections and their methods. Primary focus was on the structural design and the design choices made along with its assumptions. The construction methods and their tools were not mentioned in the reports. This made it difficult to assess this module and was thus evaluated by conducting interviews with the project manager. 2 interviews were conducted, one of which focused on the substructure and superstructure, and the other on overhead line equipment. As depicted in the section 6.4.2.2, there were 4 types of tracks to be analysed, results of which for the design for disassembly module can be seen in tables 24, 25, 26 and 27.

The final scores for the different track types, combining their material input module and design for disassembly module along with their GHG calculations can be seen in table 23. The scores obtained are on a scale of 0 to 1, with 1 being the most circular.

Table 23: CE scores for different track types

No.	***Track type***	***CE score (including GHG emissions)***
1	49E1 (Vignole) Rheda city	0.12
2	49E1 (Vignole) Edilon	0.16
3	59Ri2 (Grooved) Rheda city	0.12
4	59Ri2 (Grooved) Edilon	0.16

Table 24: Dfd module for 59R2 (Rheda)

CATEGORY	COMPONENT	TYPE	DESIGN FOR DISASSEMBLY ASPECT						DfD module value
			Connection accessibility		Connection Tool		Separation Damage		
OVERHEADLINE SYSTEMS	Contact wire		Freely accessible	1	Special tools/Hand held power tools	0.51	Minor Damage	0.44	0.61
	Droppers		Freely accessible	1	Special tools/Hand held power tools	0.51	Minor Damage	0.44	0.61
	Catenary		Freely accessible	1	Special tools/Hand held power tools	0.51	Minor Damage	0.44	0.61
	Masts/Frames		Accessibility with additional actions that do not cause damage	0.8	Big tools/Construction vehicles	0.36	Minor Damage	0.44	0.50
SUPERSTRUCTURE	Rail	59Ri2 (Grooved)	Accessibility with additional actions with reparable damage	0.4	Special tools/Hand held power tools	0.51	Minor Damage	0.44	0.45
	Sleeper	Monoblock reinforced	Accessible with irreplacable damage to components	0.1	Big tools/Construction vehicles	0.36	Destructive Seperation	0	0.00
	Concrete Slab	Yes	Accessible with irreplacable damage to components	0.1	Big tools/Construction vehicles	0.36	Extensive Damage	0.074	0.14
	Ballast	N/A							-
	Secondary concrete layer	Yes	Accessible with irreplacable damage to components	0.1	Big tools/Construction vehicles	0.36	Extensive Damage	0.074	0.14
SUBSTRUCTURE	Formation layer		Accessibility with additional actions that do not cause damage	0.8	Big tools/Construction vehicles	0.36	Minor Damage	0.44	0.50

Table 25: Dfd module for 59R2 (Rheda)

CATEGORY	COMPONENT	TYPE	DESIGN FOR DISASSEMBLY ASPECT						DfD module value
			Connection accessibility		Connection Tool		Separation Damage		
OVERHEADLINE SYSTEMS	Contact wire		Freely accessible	1	Special tools/Hand held power tools	0.51	Minor Damage	0.44	0.61
	Droppers		Freely accessible	1	Special tools/Hand held power tools	0.51	Minor Damage	0.44	0.61
	Catenary		Freely accessible	1	Special tools/Hand held power tools	0.51	Minor Damage	0.44	0.61
	Masts/Frames		Accessibility with additional actions that do not cause damage	0.8	Big tools/Construction vehicles	0.36	Minor Damage	0.44	0.50
SUBSTRUCTURE	Rail	59Ri2 (Grooved)	Accessibility with additional actions with reparable damage	0.4	Special tools/Hand held power tools	0.51	Minor Damage	0.44	0.45
	Sleeper	N/A						0	-
	Concrete Slab	Yes	Accessibility with additional actions with reparable damage	0.4	Big tools/Construction vehicles	0.36	Extensive Damage	0.074	0.22
	Ballast	N/A						0	-
	Secondary concrete layer	Yes	Accessibility with additional actions with reparable damage	0.4	Big tools/Construction vehicles	0.36	Extensive Damage	0.074	0.22
SUBSTRUCTURE	Formation layer		Accessibility with additional actions that do not cause damage	0.8	Big tools/Construction vehicles	0.36	Minor Damage	0.44	0.50

Table 26: Dfd module for 49E1(Rheda)

CATEGORY	COMPONENT	TYPE	DESIGN FOR DISASSEMBLY ASPECT						DfD module value
			Connection accessibility		Connection Tool		Separation Damage		
OVERHEADLINE SYSTEMS	Contact wire		Freely accessible	1	Special tools/Hand held power tools	0.51	Minor Damage	0.44	0.61
	Droppers		Freely accessible	1	Special tools/Hand held power tools	0.51	Minor Damage	0.44	0.61
	Catenary		Freely accessible	1	Special tools/Hand held power tools	0.51	Minor Damage	0.44	0.61
	Masts/Frames		Accessibility with additional actions that do not cause damage	0.8	Big tools/Construction vehicles	0.36	Minor Damage	0.44	0.50
SUBSTRUCTURE	**Rail**	**59Ri2 (Grooved)**	Accessibility with additional actions with reparable damage	0.4	Special tools/Hand held power tools	0.51	Minor Damage	0.44	0.45
	Sleeper	**Monoblock reinforced**	Accessible with irreplacable damage to components	0.1	Big tools/Construction vehicles	0.36	Destructive Seperation	0	0.00
	Concrete Slab	**Yes**	Accessible with irreplacable damage to components	0.1	Big tools/Construction vehicles	0.36	Extensive Damage	0.074	0.14
	Ballast	**N/A**							-
	Secondary concrete layer	**Yes**	Accessible with irreplacable damage to components	0.1	Big tools/Construction vehicles	0.36	Extensive Damage	0.074	0.14
SUBSTRUCTURE	Formation layer		Accessibility with additional actions that do not cause damage	0.8	Big tools/Construction vehicles	0.36	Minor Damage	0.44	0.50

Table 27: DfD module for 49E1 (ERS)

CATEGORY	COMPONENT	TYPE	DESIGN FOR DISASSEMBLY ASPECT						DfD module value
			Connection accessibility		Connection Tool		Separation Damage		
OVERHEADLINE SYSTEMS	Contact wire		Freely accessible	1	Special tools/Hand held power tools	0.51	Minor Damage	0.44	0.61
	Droppers		Freely accessible	1	Special tools/Hand held power tools	0.51	Minor Damage	0.44	0.61
	Catenary		Freely accessible	1	Special tools/Hand held power tools	0.51	Minor Damage	0.44	0.61
	Masts/Frames		Accessibility with additional actions that do not cause damage	0.8	Big tools/Construction vehicles	0.36	Minor Damage	0.44	0.50
SUBSTRUCTURE	**Rail**	**49E1 (Vignole)**	Accessibility with additional actions with reparable damage	0.4	Special tools/Hand held power tools	0.51	Minor Damage	0.44	0.45
	Sleeper	**N/A**				-		0	
	Concrete Slab	**Yes**	Accessibility with additional actions with reparable damage	0.4	Big tools/Construction vehicles	0.36	Extensive Damage	0.074	0.22
	Ballast	**N/A**				-		0	
	Secondary concrete layer	**Yes**	Accessibility with additional actions with reparable damage	0.4	Big tools/Construction vehicles	0.36	Extensive Damage	0.074	0.22
SUBSTRUCTURE	Formation layer		Accessibility with additional actions that do not cause damage	0.8	Big tools/Construction vehicles	0.36	Minor Damage	0.44	0.50

In order to evaluate the score of the entire Uithof line for the design and EoL phase, the percentages of each track type from the complete line were determined and multiplied with their individual scores and finally added to get the score of the entire Uithof line (table 28). This calculation resulted in an overall score of 0.14 out of 1 for the design phase.

Table 28: Contribution of different track types

No.	***Track type***	***CE score (including GHG emissions)***	***Percentage of total track length considered***
1	49E1 (Vignole) Rheda city	0.12	35%
2	49E1 (Vignole) Edilon	0.16	12%
3	59Ri2 (Grooved) Rheda city	0.12	9%
4	59Ri2 (Grooved) Edilon	0.16	44%

The end of life scenarios for this project were also not determined for the components in the procurement or the design phase and therefore, all of the components were considered to be disposed, resulting in score of 0 for the end of life phase.

After analysing the individual life cycle phases, the final score was to be determined based on the importance of each phase as calculated in section 5.3.4 (table 21). Considering these values and the above obtained results, the final score of the Uithof line for all the life cycle phases combined was 0.085 out of 1 (with 1 being the most circular) and can be seen in table 29.

Table 29: Final score of Uithof line

Life cycle phase	***Importance weight***	***CE score***	***Final CE score***
Procurement	0.319	0.05	0.016
Design	0.495	0.14	0.067
End of life	0.186	0	0
Total score			***0.085***

6.4.5 Discussion

From the analysis, it was evident that CE principles were not the spearhead of the project and hence low scores were to be expected. On discussion with the project manager, it was acknowledged that for the Uithof line project, CE was not the main award criteria but was majorly awarded based on cost, time and safety. Scope of the project and the requirements specified, apart from CE, also had very little attention given to sustainability. The requirements did not include any specifications for using secondary materials and thereby not contributing to closing the material loops. All the components hence used for this project were from virgin materials thus not satisfying one of the main principles of CE. Planning for the secondary lifecycles of the components by including the possible EoL scenarios and strategies for components were also absent. This combined with the lack of attention to secondary materials in the design phase depicts the lack of CE implementation for this project. Apart from closing the loops, efforts for lifetime extension of products was also lacking. Maintenance agreements and requirements of spare parts were not extensively mentioned. The absence of specifying EoL scenarios can also to a certain extent be compensated by implementing material passports due to higher lifespan of these components, although this was not the case in this project.

6.4.6 Validation

The results of this case study were also discussed with the respondent to check for its validity. The results were thought to be a reasonable estimate, given the absence of circularity and sustainability criteria within the different life cycle phases of the project. The areas with the lowest circularity score were highlighted and discussed. Absence of secondary material input and at the same time poor direction for the products at their EoL phase depicted the lack of efforts to close the material loops. These factors along with the possible potentials within the project for CE were acknowledged to be acceptable and a fair representation of the extent of circularity for the project of Uithof line.

6.4.7 Takeaways from the case studies

One of the major outtakes from the case studies performed is the lack of efforts to close the material loops. Neither of the projects provided sufficient attention and specifications to secondary use of materials. The Uithof line was completely constructed from virgin raw materials whereas the Uithoorn line also lacks specifications for secondary use of materials or components. The specifications for the EoL phase are also absent, thus overlooking one of the main principles of CE. To successfully develop circular projects, the material flows should be carefully looked into. As seen in section 1.5, goals set by ProRail to reuse at least 10% of the excess materials can be a starting point. Until the uncertainty pertaining to the technical and functional capabilities of secondary materials is overcome, these excess materials can be implemented and kick start the transition towards a CE.

Design for modularity was the common indicator which is fulfilled by both the projects. Despite not specifying the EoL scenarios for the different components involved, modularity requirements accounted for a certain extent of the EoL phase consideration. To ease the assessment of DfD, documents should include connection details and disassembly details as it was observed that the current documents focus primarily on the structural design and material quantity estimation. Inclusion of such details can also aid in the development of material passports as such information can be helpful in determining the conditions of components that are overshadowed by multiple interfaces.

The requirement specification that were prescribed for these projects were technical. Efforts should be made to specify more functional requirements. Change in such requirements can provide room for innovation for contractors. Since the risks of opportunistic behaviour by contractors is high, technical specifications can be aligned with CE principles. Specifying requirements based on the current available circular solutions rather than traditional solutions can be helpful in this regard.

It was also observed that the stakeholders interviewed were not fully aware about the extent of circularity. Carbon emissions and recycling were still the topic of discussion when lack of circularity for these projects was questioned. Lack of awareness regarding the CE concepts needs to be reduced by promoting the collaboration of knowledge partners. Awareness regarding CE within the stakeholders is essential so as to maximise the benefits from such practices.

7. DISCUSSION AND LIMITATIONS

This chapter discusses the results obtained during the course of this research and highlights its limitations.

7.1 DISCUSSION

From the perspective of clients and contractors, it is quite interesting to see the dependence on each other to implement CE in railway projects. Contractors demand clear specifications from client regarding scope whereas at the same time they also prefer room for innovation and more functional requirements. They state that the sole reason for the lack of implementation of CE is due to the absence of requirements from clients. The projects are mainly awarded based on time and cost parameters which needs to be changed, or incentives for CE solutions should be provided. Based on interactions during interviews, the lack of client demands regarding CE can be attributed to two factors. Firstly, It is observed that clients believe to have sufficient amount of knowledge regarding CE and its principles whereas in reality, this was not the case. Topics such as recycling being prioritized and reduction of carbon footprint often were suggested as tools to achieve circularity whereas in practice, these concepts do not have a significant contribution in closing the material loops. Secondly, lack of standards to not only embed CE strategies into the projects but also to evaluate solutions were absent. The results obtained in this regard can help clients and contractors to use this tool as a guideline to overcome the barriers, and also help in assessing the situation of existing projects.

Ambiguity regarding the concept of circular economy

Reflecting on the case study, it is quite evident that, even though efforts are being made in the construction industry to implement CE, railway projects still lack sufficient efforts. The case study made it evident that lack of efforts from the client to specify more circular demands is one of the major problems. Moreover, the interviews and the survey confirmed that the stakeholders acknowledged that scope should be clearly defined to achieve circularity, though it is still not being fully done. The extensive technical requirements in the Uithoorn line depicted the limited room to implement innovative solutions and restricted the freedom of contractors to make free circular choices. Though the reasoning for specifying technical solutions may arise from past experiences wherein contractors provided cheap and short lasting solutions, the developed framework can ensure the avoidance of such situations. Indicators within the framework specify the need for functional requirements, but at the same time, also ensures that agreements regarding extension of lifespans and availability of spare parts are specified which can guarantee a certain expected quality and duration of products. Since the topic is still in its early stages, stakeholders believe taking big leaps and designing a fully circular railway project is difficult at this point. Collaboration with contractors, knowledge partners is therefore essential to conduct pilots and ensure the results can be embedded in actual practice.

Lowest preference for the involvement of knowledge partners

The lack of knowledge about CE amongst clients and organisations was not only mentioned in literature but was also observed during the interviews. To ensure the stakeholders involved can still implement CE ideas based on their limited knowledge, the framework includes indicators which would help understand the principles and aid stakeholders with limited knowledge to sufficiently implement CE ideas. The limited knowledge often results in implementing partial circular ideas and expecting fully circular results. Therefore, it can be beneficial to involve expertized partners that can smoothen the implementation of CE. The hesitance to include knowledge partners in these processes arises due to the tender drafting and procurement procedures being internal and 'commercially sensitive'. Involving knowledge partners due to this confidentiality is conflicting and respondents suggests that due to the novelty of the topic, knowledge partners can still be involved to a limited extent where they might be able to help with setting a clear direction for how circular economy can or should be applied.

Another interesting insight regarding the design aspect was that the respondents acknowledged that implementing design for modularity/disassembly is of significant importance and has a very high influence on circularity (based on the Likert scale survey). Contradictorily, the remaining indicators that specified involving the experts from the disassembly team in the early phases and setting up requirements for their eligibility, were not welcomed with same enthusiasm. The contrast was such that indicator for implementing design for disassembly was deemed important and scored in the top 5, whereas the remaining were in the lower 5. On further analysis, it was observed that the difficulty in predicting the end of life conditions of assets that have a lifespan of over 25 years or more can be difficult. Furthermore, upskilling of designers is more important than bringing in specialist designers as then there would not be a chance of organisational learning and hence no long-term change. There is a considerable amount of room for designers to improve their skills and be independent. It was also observed that requirements specifying a specialised team with prior experience results in an unequal playing field and reduces competition. Although the long-term effect is desirable with equal opportunities for all contractors, specialist support will be required in the early stages of maturity development of CE due to current limited pool of information with the clients and contractors. This criterion then possibly can be discarded after the topic gains enough traction.

The dynamicity of the construction sector makes it difficult to precisely predict what the future holds and the state of the asset after these components reach their end of life. Nevertheless, for CE, determining the EoL scenarios is one the important aspects in order to close the material loop. Efforts can be made to at least ensure asset owner's responsibility to implement CE strategies at EoL and cascade components and materials depending on the situation. Rethinking of ownership of assets in this regard can play an important role. If the ownership of the asset lies with a supplier or contractor, higher chances of secondary use is possible in order to maximise benefits. Respondent from Gemeente Amsterdam highlighted that currently for projects that are undertaken, demolition plans are requested in the early stages, showing that possibility of the transition. Designing for disassembly can maintain the quality of the product at the end of its lifecycle by proper disassembly. Since the degradation of the product or component is unavoidable during its use life, care should be taken to not further damage the quality while separation from the entire system. Higher quality of material at the EoL can provide more chances of reuse for secondary life cycles. Overall, the simplicity in the calculations and methodology followed in developing this framework makes it adaptable to changes and can easily accommodate future developments. The idea for a new framework to assess the circularity of railway infrastructure components was enthusiastically welcomed during the interviews.

7.2 LIMITATIONS

During the course of the research, many choices and assumptions were made due to time, data or scope constraints. This section describes the limitations that arise due to these choices.

1) Life cycle assessment database Ecoinvent used was old (version 2.1)

For the calculation of the GHG emissions, the database to determine the impact factors was relatively old, from 2010. Though revisiting the source of the database suggested that the newer versions included more categories and materials and less of a change for the values of the existing materials, due to financial constraints of this research, access to the new version of such database was not possible.

2) Does not consider biological cycle

Based on the distinction made by EMF regarding the two cycles within CE, this framework only focuses on the technical cycle. The biological cycle where the organic materials and components are restored back in the biological sphere are not considered. Time constraints of the research made it difficult to include this cycle.

3) Criteria for experts and panel size

Throughout this research, though the criteria included opting for people with certain CE background, there were also instances where senior officials were interviewed with extensive knowledge on railway projects but comparatively little awareness about CE principles. This was done to take into account the different problems that can arise due to implementing CE. The experts in the field of CE due to the newness of the topic, lacked experience in regards with its pitfalls. For example, as mentioned in the case study results, the opportunistic behaviours of contractors to opt for cheaper materials when functional requirements are specified were not mentioned as a barrier by any CE experts during the interviews. Furthermore, the panel size for assigning weights for the different life cycle phases was also limited. Since this assignment was due to a reiterative process of interviews, respondents could not provide enough time for more interviews due to their busy schedules and hence the research lacked sufficient number of respondents for such tasks.

4) Exclusion of the top layer from research

Urban railways often have an additional layer for embedded tracks of different material types such as grass type, concrete or asphalt. In this research due to lack of data for the carbon calculations and time constraints, this layer was decided to be excluded. If concrete layer for the top is employed, it can significantly change the weights of individual components.

5) Certain indicators can be difficult and time consuming to measure

To assess certain indicators, it can be a challenging task to determine the completeness of that indicator. For instance, for the indicator from the procurement phase that ensured the avoidance of conflict regarding the award criteria, it is necessary to include individuals who can determine these interconnections and conflicts between such award criteria and CE. The useability of the framework can be improved to make it easier for use for individuals with lesser knowledge about CE.

8. CONCLUSION AND RECOMMENDATIONS

This chapter concludes on the research done for this study and sheds light on possible future recommendations.

8.1 CONCLUSION

Sub research question 1) What is circular economy in the construction industry and what are its current trends and barriers for the railway infrastructure?

Majority of the current construction practices undertake the traditional linear material consumption patterns wherein resources and materials are taken from the earth to make final products which at the end of its life, is discarded without any secondary use. CE aims in transitioning from this linear model to a much more circular approach in which materials and products have multiple life cycles, keeping the resources within the system and thus closing the material loops and reducing the amount of waste generated. While reusing products during secondary or consecutive life cycles, due attention should also be given in preserving the original value of the product. Literature highlights the existence of multiple definitions of CE but the definition of CE provided by Bocken, Oliveti, Cullen, Potting, & Lifset, (2017) has been used throughout this study, which defines CE as, *"A CE aims to keep products, components, and materials at their highest utility and value at all times. The value is maintained or extracted though extension of product lifetimes by reuse, refurbishment, and remanufacturing as well as closing of resource cycles—through recycling and related strategies. An alternative strategy for extension of product lifetimes may be to use products more efficiently through sharing them or making them multifunctional. All these strategies may be facilitated through changes in ownership relationships, such as leasing and product service systems (PSSs)"* (Bocken, Oliveti, Cullen, Potting, & Lifset, 2017, page 1). This definition was chosen as it focuses on greater R model than the traditional 3R model and focusing on the material aspect of CE. Mention of value retention and changes in ownership models also highlights the need for not just technical changes but at the same time, organizational changes as well. Rethink of business models can play an important role in the transition towards CE. These factors align well with the defined scope of this study and is therefore a suitable definition. Different principles are outlined in literature, but they all contribute to the bigger picture of closing material loops. Some principles focus on protecting the material supplies and existing values thus portraying the result that is needed to achieve, whereas some highlight the principles in terms of the processes or methods that need to be implemented, such as design out waste, think in cascades etc.

The R framework has formed the basis of multiple framework and policies and has been developed over the years from a 3R to a 10R model. The primary feature of these R frameworks lies in its hierarchial structure, in which the Rs are prioritised and contribute higher than the rest in terms of CE. Narrowing the focus down to the construction industry, it is observed that the CE is conceptualized with the technical life cycle. Barriers of CE are mainly attributed to the unawareness of the railway sector towards CE ideas and principles. Lack of clear CE requirements from clients, and award criteria still being based on costs and time, hinder the transition towards CE for railways. CE ideas need a shift in thinking and not only in design principles. Vagueness regarding the topic of CE within stakeholders often leads to misinterpretation of CE ideas. Lack of clarity between the recycle economy and circular economy often hampers the transition towards CE. Not only is this the case with the clients, but the market conditions also reflect on this ambiguity. Circular solutions are often termed as sustainable, which undermines their potential and portrays a false image regarding the readiness of the market.

Clients for these projects often suggest that strict government laws and regulations are necessary to accelerate the CE implementation. The absence of such standards for secondary products and materials prevents their use due to risk, safety, durability concerns. In some cases, the contractors have the potential to implement and design circular solutions, but due to the technical requirements of the client, room for innovation is minimum. This highlights the need for early stakeholder collaborations where contractors and client can mutually deicide on circular ideas and the possible alternative solutions.

Sub research question 2) What are the barriers and opportunities of the already existing frameworks to evaluate and assess CE?

Currently, the railway infrastructure faces a deficit for CE not only for its implementation but also its assessment. Multiple frameworks exist that cater the building industry but owing to its differences relating to the design and construction processes, it is difficult to directly implement these frameworks across the two sectors. Nevertheless, understanding the methodology and the development of these frameworks highlighted the common and important aspects that were necessary to take into account while devising the new framework to maintain continuity and adaptability. Understanding the drawbacks and processes included in these frameworks was essential to provide a starting point. Existing assessment tools such as the MCI, Platform CB ’23, DuboCalc were studied. Preliminary analysis showed that these frameworks focused on assessing the material flows by reflecting upon the R framework proposed in literature. In this regard, Dubocalc seemed to be the least applicable framework for CE as it focused more on the environmental and sustainability aspect rather than the material flows or end of life scenarios.

The MCI takes into account the different Rs from the R model and assess the circularity of components based on their material flows and preferences given to the end of life scenarios. One important drawback in this framework is its lack of attention to the other Rs within the R model. Literature shows the presence of a 10R model whereas MCI in its framework only accounts for reuse and recycling, even in which there is no clear differentiation between upcycling and recycling. Apart from this, the limitations for the MCI report, explicitly state the inapplicability of the framework for assessing the construction of railway lines. The current status of construction industry already shows the high recycling rate of products, which makes it essential to shift focus on the other Rs to achieve optimum circular results. Platform CB’23, is still in its development stages and requires a very detailed amount of information of individual materials. For the complex railway projects with the multiverse of stakeholders, accounting for such detailed data can be problematic in the current scenario. This can be easier with the implementation of material passports. The framework also doesn’t differentiate the different indicators based on the various life cycle phases. Overall, another major aspect of CE that deals with designing for modularity and disassembly is not considered in either of the frameworks. The description of principles and importance of design for disassembly aspects therefore needs to be implemented for a complete assessment of circularity.

Sub research question 3) What are the indicators of circularity for urban railway infrastructure?

Since majority of the already existing frameworks are based on the concept of indicators and as also positively studied in literature, (Linder , Sarasini, & Loon, 2017), it is essential to develop a set of indicators that can help to generate a base for the new evaluation framework. For the procurement phase, since the topic is still in its premature phase within the railway infrastructure projects, topic specific indicators were absent. Furthermore, each project for railways is unique and therefore developing indicators that are extremely specific can be problematic. Requirements and criteria for each project are different and therefore to increase the applicability of this framework to more than just a case specific project the indicators were developed on a higher level. Nevertheless, efforts were made to cover multiple aspects of CE such design for disassembly and modularity, material flows, stakeholder collaboration and promotion of innovation. In order to do so successfully, indicators also check for the requirements for eligibility of specialised design team and possible inclusion of the disassembly team in the early stages of design and procurement. Efforts were made to translate the barriers that were discussed in the interviews into appropriate indicators. Though one of the barriers suggests lack of knowledge within practice, this could not be translated directly into an indicator. As a logical next step, indicators which highlighted CE principles and promote its acceleration were used. Thus, in order to promote CE concepts and better understand the topic, efforts were made to do so through indicators. These indicators can help propagate the principles of CE and increase awareness, while at the same time also judge the circularity of the project. For instance, indicators to incorporate secondary materials other than recycled products or materials or thinking about possible EoL scenarios in the early stages.

Considering the methodologies of the existing frameworks, for the design phase it was best suitable to consider the material flows. Indicators for the design phase therefore focused on assessing the material and component inputs for the design by incorporating more than just reuse and recycle. The framework included other Rs from the R framework such as repurpose and repair, modifications to which were made based on its applicability to the components of railway infrastructure. The Rs were assigned values based on their prioritisation which helped in assessing the extent of circular loops. Apart from these, assessing the design for modularity and disassembly based on the aspects of separation damage, tool requirement and ease of accessibility also provides the coverage of an additional CE principle apart from just material flows. Implementing these DfD indicators in the framework helps to overcome one of the shortcomings of the analysed frameworks.

Sub research question 4) How can the indicators be used to generate a complete assessment framework?

For the procurement phase, prioritisation of the indicators was necessary to prevent false results. It was essential to weigh each indicator appropriately so as to produce results that were proportionate to the effect that indicator had on the circularity of the project. To do so, the list was formulated in a form of a survey of a Likert scale, where the respondents were requested to assess each indicator on an importance scale. The results of this survey helped identify the relative importance of the indicators. These were then assigned weights based on the generated hierarchy which formulated the final framework for the procurement phase.

For the design phase, the Rs that were decided to be included in the framework to analyse material flows, were assigned values based on their hierarchy. In this manner, the linearity of the material flow could be estimated. Apart from this, this phase also included the aspects to assess the modularity and design for disassembly of designs. Different aspects were analysed from literature, such as time for disassembly, connection accessibility, separation damage, tool type. Substantiation of these aspects based on applicability to the scope of this research and availability of data led to the selection of three aspects, namely – connection accessibility, separation damage and tool type. Values for these were extracted from literature and some were calculated. These indicators along with the earlier defined material flow indicators, together formed the framework for the design phase.

On similar lines, for the EoL phase, material output indicators were the most suitable indicators to assess the flow of materials. To ensure that materials do not end up as waste, the EoL framework consisted of the R framework which evaluated each component and assigned scores based on what its secondary life was to be. The Rs implemented in this life cycle phase were slightly different from those in the design phase, as it was necessary to differentiate between upcycling and downcycling.

Main research question,

HOW CAN URBAN RAILWAY INFRASTRUCTURE BE ASSESSED IN TERMS OF CIRCULAR ECONOMY PRINCIPLES?

Answers to the research sub questions eventually leads to the formulation of an assessment framework for railway infrastructure. With the use of the newly developed framework, railway infrastructure components can be assessed on the principles of CE by analysing their material flows, specifications in the tender, and modularity of their designs during the design phase. This framework has different methods and indicators for 3 different life cycle phases, procurement phase, design phase and EoL phase.

8.2 RECOMMENDATIONS FURTHER RESEARCH

The design for disassembly assessment, focuses on limited criteria and it can be interesting to study additional criteria. Scores of these can be determined by taking into account the on field practices.

The scope of this research is limited to specific components and it can be interesting to see how the projects might score differently based on the inclusion of more components such as the signaling systems and rolling stock. As seen during the calculations for the GHG, steel plays an important role in its contribution and including more components of either steel or concrete could possibly change the preferential weight of each component.

Currently, implementation of secondary materials is prioritised over new virgin materials and components to close material loops. It can be interesting to study the trade-offs between implementing secondary materials for shorter lifespans due to their secondary nature or new materials and components for a large lifespan and thus reducing material demand.

This method focuses on the technological side of the EMF butterfly diagram. Although, focus of CE also includes biological cycles, further research can be extended to include such cycles.

The panel size can be expanded to include more perspectives. Involvement of different stakeholders can also help in identifying perspectives based on their roles. Possibilities of having different priorities of indicators based on the role of the stakeholder can provide interesting insights.

8.3 RECOMMENDATIONS FOR PRACTICE

Circularity has gained a large amount of traction since its inception. The building sector has been successful in implementing CE ideologies to a much greater extent than the infrastructure sector. One of the many reasons for this difference is due to the lack of awareness of CE within the railway sector. During interviews and the case studies, it was observed that often stakeholders are unaware of the exact extent and principles of CE. To overcome the majority of barriers discussed in this research, it is necessary for organisations to garner sufficient knowledge regarding CE. To offer circular solutions, it is necessary for organisations to completely understand the far-reaching impacts and opportunities of CE before diving into the technical intricacies.

Large infrastructure projects are often complex and require the coordination and coherence of multiple stakeholders and organisations. To successfully implement circular solutions, early involvement of different stakeholders and contractors from the initial phases is necessary. Circular solutions are not the responsibility or the capacity of an individual stakeholder, but rather a collective effort. The current tendering and procurement processes lack such involvement of different stakeholders which hampers the chances of implementing innovative and circular solutions. Modifications to such processes by including knowledge partners and contractors in the early phases can help better formulation of the requirements that can encompass more circular principles than current practice.

Changes to design methods and formation of the design documents is also necessary to sufficiently design modular solutions and transfer information for future life cycles. While analysing the documents for the case studies, specifically for the design phase, it was observed that little attention was given to specifying the details about connections and joints. In order to assess the design for disassembly aspect, change in formulating such documents is also necessary. Aspects such as separation damage, connection tool, etc if incorporated in these documents can accelerate the assessment and at the same time provide sufficient data for future projects. If such details of components are known while designing new projects, this data can be used to assess the applicability of these components based on the current and disassembled conditions.

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APPENDICIES

A – INTERVIEW TEMPLATE

Interviewee introduction and role within the organisation is to be understood.

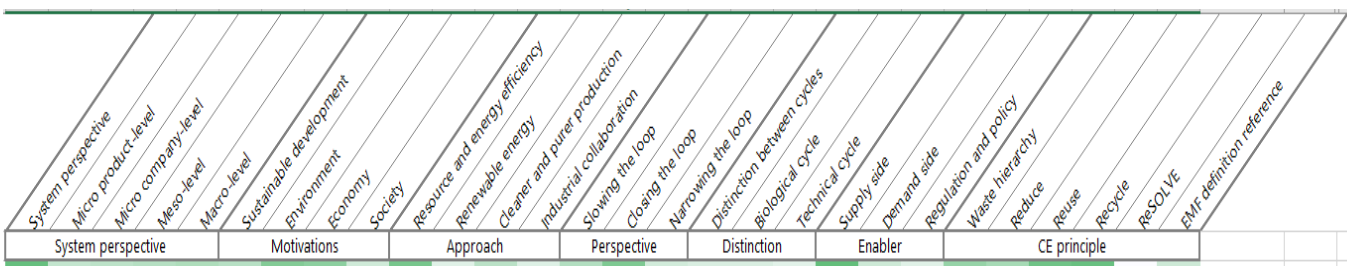
If any specific project is to be discussed, then -

- **Project specific**
- Can you give a brief description of the project?
- What was your role in the project?
- Did the project have any aspects of CE involved?
- If yes, which? / if no, why not?
- Which aspect of CE was the spearhead of the project?
- To what extent was CE given importance over costs, time and other factors OR Which other factors were prioritised over CE?

- **General CE related**
- What is your definition of CE?
- How would you describe the level of awareness in terms of CE in a) the organisation b) in the field of infrastructure sector?
- What is the current state for CE in railways in general?
- Is there vagueness regarding the boundaries of CE and sustainability?
- What do you think are the factors that hinder the application of CE in the railway industry?
    - Technological
    - Economical/financial/market
    - Governmental
    - Organisational
    - Supply chain
    - Environmental
    - CE Definition/framework
- What are the enablers for CE in railway industry? (Gov. policies, client requirements, technical knowledge, etc)
- What do you think are the indicators for CE implementation for railway infrastructure?
- What framework, if at all is used to measure the extent of CE for railway infrastructure?
- If framework for CE doesn't exist, on what basis is CE being judged for railways?
- Do you think the sector is prepared on all fronts for implementing CE? (Regulatory, Innovatory, financial, compatibility, etc)
- Which life cycle phase of the project has the highest impact in the implementation (acceleration if already being implemented) of CE and why?
- According to the system breakdown structure for the scope, which aspects have the maximum potential for CE strategies and which has the least?

B - BACKGROUND INFORMATION REGARDING THE DEFINITION TOOLKIT

The definition tool that is used in this research, was originally developed by Arntzenius (2020) for the purpose of completing his Master thesis. The author of this research has merely added new definitions into this tool and has used this tool to aid his own research work, after seeking permission from its original developer. The definition tool presents itself in the form of an Excel sheet containing 3 tabs, 'Instructions', 'Input and Results', 'Definitions'. The 'Input and Results' tab consists of all the defined dimension that can be selected by the user, in order to obtain all the definitions from the tool sample which consist or mention aspects of the required dimensions. The dimensions were defined based on an extensive literature study, which along with the extensive explanation of the tool itself, are explained in the Master thesis report. Depending on the different criteria provided in the tool, all the definitions matching these criterias are given. In order to fit the definition for this research, the criteria was selected by keeping in mind the defined scope.



Following were the selection of dimensions made in the first round:

- System perspective - Since the focus lies on products within the railway infrastructure, the input was given to micro product level.
- Motivations – reflecting on the definitions provided in this category, the "environment dimension, defined as – results into higher conservation of natural resources" seemed to fit well with the scope as the focus is material loops.
- Approach – Resource efficiency, since we focus on material loops and exclude energy and environmental impacts
- Perspective – "slowing the loop and closing the loop" definitions fit well. "narrowing the loops" definition fits well but looking at the explanation of it in the report, which states "indicating material efficiency during production" resulted in omitting this aspect since the production of material does not lie in the scope of this research.
- Distinction – our focus is on technical cycles.
- Enablers – all, because we don't focus on any particular stakeholder.
- CE principles – waste hierarchy.

C – CALCULATION OF WEIGHTS FOR PROCURMENT PHASE INDICATOR

Table 30: Weights for procurement phase indicators

INDICATORS	Very Important	Important	Moderately Important	Of Little Importance	No Importance	Not sure	Indicator Score (IS)	final weight	Final weight (%)
The scope of circular economy is clearly defined by the client	4	8	1	1	0	0	43	0.053	5.28%
Incentives are provided for circular solutions	3	6	2	1	0	2	35	0.043	4.29%
Circular criteria does not conflict with other award criteria for tenders (For eg. Maximum maintenance free period along with demand for higher lifespan is required)	2	5	4	0	0	3	31	0.038	3.80%
Functional requirements (Performance based requirements) are specified over technical requirements for components/materials	4	5	1	1	0	3	34	0.042	4.17%
If technical requirements are specified, they should be in line with circular economy principles	4	9	0	0	0	0	43	0.053	5.28%
There is a collaboration between the client and contractor to successfully implement circular ideologies from the initial phases of the project	10	3	1	0	0	0	51	0.063	6.26%
Suppliers and stakeholders are involved through market dialogue to promote circular public procurement	2	7	3	0	0	2	35	0.043	4.29%
Suppliers can challenge the criteria if they see opportunities to improve circularity	6	5	3	0	0	0	45	0.055	5.52%
Networks and organisations are used as knowledge partners while drafting tenders (For eg, involvement of organisations such as TNO, PIANOo, EMF or universities)	1	1	5	1	0	6	18	0.022	2.21%
Involved organisations (Contractors, sub-contractors, designers, advisors, etc) need to have certain experience with circular solutions	0	10	3	1	0	0	37	0.045	4.54%
Design for disassembly/demountability/modularity is implemented	4	7	2	0	0	1	41	0.050	5.03%
A specialised design team in design for disassembly/demountability/modularity is involved	2	3	4	1	0	4	26	0.032	3.19%
Eligibility requirements are set up for the design (for disassembly) team in terms of competence and experience	0	5	4	0	0	5	23	0.028	2.82%
Deconstruction team/organisation is included in the consortium from the design phase	1	4	4	1	0	3	25	0.031	3.07%
Requirements are specified for using Reused/Refurbished/Remanufactured/Recycled (Secondary materials) or products as a certain fraction or as a whole*	3	7	2	0	0	2	37	0.045	4.54%
Off the shelf (standardized/ traditional) purchasing is reduced OR circular off the shelf products are required (as means to promote innovative solutions)*	2	5	4	0	0	3	31	0.038	3.80%
There is a "Rethink" in ownership where public organisations do not purchase products but instead implement pay per use contracts or performance based contracts	1	4	6	1	0	2	29	0.036	3.56%
Requirements are specified for circular packaging of materials/products*	3	5	5	0	0	1	37	0.045	4.54%
Requirements are specified for utilising nearby secondary material flows of components/materials	0	8	4	0	0	2	32	0.039	3.93%
Extensive maintenance and repair agreements are included to ensure maximum lifespan extension of components*	5	6	3	0	0	0	44	0.054	5.40%
Requirements are specified for a longer guarantee period along with easily available spare parts during the operation phase*	2	8	3	0	0	1	38	0.047	4.66%
End of Life scenarios of the components are required to be planned out during the tender*	4	7	3	0	0	0	43	0.053	5.28%
Requirements to develop and maintain material passports to better assess the applicability of the material/component for its subsequent life cycles	3	7	2	0	0	2	37	0.045	4.54%

D – CALCULATION OF CRONBACH'S ALPHA

Table 31: Cronbach's alpha calculation

Respondents	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16	Q17	Q18	Q19	Q20	Q21	Q22	Q23	Q24	Q25	TOTAL
1	3	3	0	0	3	3	3	2	2	3	3	2	3	2	3	0	2	4	3	2	3	3	4	3	3	62
2	3	0	3	3	3	3	0	3	0	2	3	0	0	0	2	0	0	0	2	3	3	0	4	3	0	40
3	3	4	3	4	3	4	3	4	2	3	4	3	2	4	3	2	2	4	3	3	4	3	3	4	4	81
4	3	2	3	4	3	4	3	3	0	3	2	3	2	1	3	4	2	1	2	2	2	3	2	2	2	61
5	3	4	2	4	4	4	3	4	3	2	3	2	3	3	4	3	2	3	2	3	4	3	4	3	3	78
6	3	3	3	1	3	4	2	2	0	3	3	0	0	0	3	3	0	0	2	0	4	4	0	2	0	45
7	4	3	0	0	4	4	3	4	4	3	0	0	0	0	0	3	3	0	0	0	3	3	0	3	3	47
8	1	1	4	4	3	4	4	4	1	3	3	3	2	0	4	3	1	1	4	3	4	2	3	4	4	70
9	4	0	4	3	3	4	0	4	0	3	4	0	0	3	3	4	3	3	3	3	4	3	4	2	3	67
10	3	3	2	3	3	3	2	3	0	1	3	1	3	0	3	0	2	3	4	2	3	4	3	3	3	60
11	4	3	2	3	3	4	3	3	2	2	4	4	3	3	3	2	3	2	3	2	2	3	3	4	3	73
12	3	3	3	2	4	2	2	2	2	3	3	2	2	2	2	3	2	3	3	3	3	2	2	3	2	63
13	2	4	0	0	4	4	4	4	0	3	2	4	0	3	0	2	3	0	2	3	3	3	4	4	4	62
14	4	2	2	3	3	4	3	3	0	3	4	2	3	2	4	2	4	3	4	3	2	2	2	3	3	70
variance	0.64	1.68	1.74	2.24	0.2	0.37	1.39	0.6	1.69	0.37	1.07	1.98	1.66	1.94	1.52	1.74	1.21	2.21	1.09	1.06	0.55	0.92	1.78	0.49	1.52	134.74

$$\alpha = \frac{K}{K-1}\left[1 - \frac{\sum s^2 y}{s^2 x}\right]$$

K	25
s2y	31.658
s2x	134.74
α	0.80

E - DETERMINATION OF THE WEIGHTS FOR SEPARATION DAMAGE INDEX (AHP)

Step 1: Create a comparison matrix

- In this step, a *n x n* comparison matrix is created, where n is the number of indicators/criteria whose weights are to be determined. Each indicator is compared with all the other indicators in pairs and is rated accordingly on a scale of 1 to 9. For example, if an indicator A has a very strong importance as compared to indicator B, then it gets a value of 7. In case of B being very strongly important than A, A gets a value of 1/7. The scale and its description can be found in table 15. Since the research has more than one respondent, each of which individually complete a pairwise matrix, the final pairwise matrix is calculated by taking a geometrical average of all matrices (Goepel, 2013).

Table 32: Intensity of importance for AHP (Source: (Nardo, Saisana , Saltelli, Tarantola , & Giovannini, 2005))

Intensity of importance	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience slightly favours one indicator over the other
5	Strong importance	Experience strongly favours one indicator over the other
7	Very strong importance	One indicator is very strongly favoured over the other and the dominant nature is demonstrated in practice
9	Extreme importance	The evidence favours one indicator over the other in the highest possible affirmation
2,4,6,8 can be used to expressed intermediate values		

Final pairwise comparison matrix A - $\begin{bmatrix} a_1 & b_1 & \dots & x_1 \\ \vdots & \vdots & \dots & \vdots \\ a_n & b_n & \dots & x_n \end{bmatrix}$

Table 33: Pairwise comparison matrix

	Fully Reusable	Minor Damage	Non – reusable	Extensive Damage	Destructive Separation
Fully Reusable	1	3	6	7	9
Minor Damage	1/3	1	3	4	6
Non – reusable	1/6	1/3	1	3	4
Extensive Damage	1/7	1/4	1/3	1	3
Destructive Separation	1/9	1/6	1/4	1/3	1
	1.787	4.75	9.583	15.33	23

Step 2: Normalised pairwise comparison matrix

- Once the final comparison matrix is computed, it is then normalised by dividing each element in a column by the total sum of that column.

Normalised pairwise comparison matrix - $\begin{bmatrix} a_{norm1} & b_{norm1} & \cdots & x_{norm\,1} \\ \vdots & \vdots & \ldots & \vdots \\ a_{norm\,n} & b_{norm\,n} & \cdots & x_{norm\,n} \end{bmatrix}$

Where,

$$a_{norm\,1} = \frac{a_1}{a_{sum}} \qquad \text{equation (3)}$$

$$a_{sum} = \sum_{i=1}^{i=n} a_i \qquad \text{equation (4)}$$

Step 3: Determination of criteria weights

- The final scores for the indicators are then determined by using equation (5)

$$w_1 = \frac{a_{norm\,1} + b_{norm\,1} + \ldots + x_{norm\,1}}{n} \qquad \text{equation (5)}$$

Normalised pair wise matrix

Table 34: Normalised pairwise matrix

	Fully Reusable	Minor Damage	Non – reusable	Extensive Damage	Destructive Damage	Sum	Weight
Full Reusable	0.560	0.632	0.522	0.457	0.391	2.561	0.512
Minor Damage	0.187	0.211	0.313	0.261	0.261	1.232	0.246
Non – reusable	0.112	0.070	0.104	0.196	0.174	0.656	0.131
Extensive Damage	0.080	0.053	0.035	0.065	0.130	0.363	0.072
Destructive Separation	0.062	0.035	0.026	0.022	0.043	0.189	0.038
	1.000	*1.000*	*1.000*	*1.000*	*1.000*	5.000	

Step 4: Consistency verification

- The final aim of the consistency check is to determine the consistency index based on the eigenvalues. Determination method of eigenvalues is shown in the subsequent steps.
  i. Firstly, the non-normalised comparison matrix is multiplied by the criteria weights to obtain the matrix B

$$B = \begin{bmatrix} a_{v1} & b_{v1} & \dots & x_{v1} \\ \vdots & \vdots & \dots & \vdots \\ a_{vn} & b_{vn} & \dots & x_{vn} \end{bmatrix}$$

Where, $a_{v1} = w_1 * a_1$ equation (6)

  ii. The weighted sum values are calculated for each row by adding up all the rows of the matrix B

$$w_{s1} = a_{v1} + b_{v1} \dots \dots \dots + x_{v1}$$ equation (7)

  iii. The weighted sum values for all the rows are then divided by the corresponding criteria weights

$$\lambda_{max} = \frac{\frac{w_{s1}}{w_1} + \frac{w_{s2}}{w_2} \dots\dots\dots\dots + \frac{w_{sn}}{w_n}}{n}$$ equation (8)

  iv. The consistency index can then be calculated by using the equation 9

$$\text{Consistency Index (CI)} = \frac{\lambda_{\max} - n}{n - 1} \qquad \text{equation (9)}$$

v. From the consistency index and the random index, the consistency ratio can be calculated from the equation 10. Random index is an average value of CI for random matrices and for this study, the standard values defined by Alonso & Lamata , (2006) are used.

Consistency Ratio (CR) = Consistency index / random index equation (10)

On solving step 4 of the above approach, the consistency index was found to be 7%, which was lesser than the allowable threshold of 10%. The weights obtained as can be seen in table 18 sum their total to 1. Comparing these weights with that of the other indices, there is an inconsistency regarding their extreme values. Fully reusable as per its definition should get a value of 1 as it is completely circular whereas for destructive separation should be zero. In order to maintain the consistency of all the indices, these weights were normalized using the min-max method where the final weights of this index was calculated based on the equation (11)

$$W_f = \frac{w_i - w_{max}}{w_{max} - w_{min}}\ ;\ i = 1,2....5 \qquad \text{equation (11)}$$

F – CALCULATION OF GREEN HOUSE GAS EMISSIONS

The basic track structure that has originally been defined in chapter 4 is hereafter analysed for the greenhouse gas emissions in order to assign appropriate importance in the final measurement of the scope of circularity.

Substructure

GHG emissions for the construction and maintenance of the subgrade layer as well as the earthworks to dig cutting or to fill embankments are determined

- **Properties**
  - 40 cm thick
  - Density of gravel-sand of 2.80 t/m^3
  - 60 years lifespan
  - No data for the maintenance materials of the formation layer, therefore it was omitted
  - Emission factors were taken of gravel-sand

Table 35: Quantities of formation layer (Source: (Schmied & Mottschall, 2013))

	unit	Erection expenditure		Maintenance attitude	A total of
		per km	*per km and a*	*per km and a*	*per km and a*
1-track line					
- New line	t	9,632	160.5	0.0	160.5
- Other routes	t	7,392	123.2	0.0	123.2
2-track routes					
- New lines	t	14,896	248.3	0.0	248.3
- Other routes	t	12,320	205.3	0.0	205.3

- To calculate the CO_2 t/km/annually, the value of 2 route track per km/annually is multiplied with the respective emission factor from table 18.

Superstructure: RAILS

After the analysis of the substructure, the focus is then shifted to the superstructure which according to the scope of this research consists of the rails, sleepers and ballast. The track type of slab track is also considered for this research and hence the appropriate components of these will also be looked at.

Rails within Europe are manufactured from mild steel by undertaking the process of oxygen blowing and for the calculations based in this report, values relating to the "steel converter" are used for calculating the equivalent emission. For the ballast and slab track, according to the report by Schmied & Mottschall (2013), the commonly used rails are S54 rails, UIC 60, and S49.

For calculation purposes, the service life of these rails is considered to be 30 years with a maintenance effort of approximately 0.5m of rail per single track kilometer. The total weight of the tracks considering all these aspects (per km per year) are given in the table 43.

Table 36: Rail profiles and their weights per meter (Source: (Schmied & Mottschall, 2013))

	unit	P 49	P. 54	UIC 60
cross-section	mm^2	6297	6947	7686
Steel per rail	kg / m	49.43	54.54	60.34
Steel - single-track route	t / track km	98.86	109.08	120.68
Steel - double-track route	t / track km	197.72	218.16	241.36

Table 37: Steel quantities for rails (Source: (Schmied & Mottschall, 2013))

Rail type	unit	Erection expenditure		Maintenance attitude	A total of
		per km	*per km and a*	*per km and a*	*per km and a*
1-track line					
- Rail S 49	t	98.9	3.30	0.02	3.32
- Rail S 54	t	109.1	3.64	0.03	3.66
- UIC 60 rail	t	120.7	4.02	0.03	4.05
2-track routes					
- Rail S 49	t	197.7	6.59	0.05	6.64
- Rail S 54	t	218.2	7.27	0.05	7.33
- UIC 60 rail	t	241.4	8.05	0.06	8.11

Superstructure: SLEEPERS

Different types of sleepers are considered for their assessment, namely, wooden, steel and concrete sleepers. According to Schmied & Mottschall, (2013), in Germany, the majority of the sleeper population was dominated by concrete sleepers which accounted for around 75%, followed by wooden sleeper (around 16%) and steel sleepers accounting for the lowest amount (for around 7%). The annual replacement requirement is assumed to be one sleeper per 2 km of a single track.

While calculating the GHG emissions, the values assigned to the reinforcing steel are used for the reinforcement steel in the concrete sleepers and “steel from the converter” for steel sleepers is used.

- **Details of concrete sleepers**
  - **Type:** B70 (Prestressed concrete single block sleepers)
  - **Dimensions:** 2.60 m long with sleeper spacing of 60cm and weighing 280 kgs. 2.5% of this weight is owing to the presence of the reinforcing steel (approx. 7kg/sleeper)
  - **Volume of concrete:** 114 litres which eventually leads to 910 tonnes of concrete ((or 380 m^3 of concrete) and 23.3 tonnes of reinforcing steel **per double track kilometre**.
  - **Lifespan:** 35 years

- **Wooden sleepers**
  - **Type:** Hardwood such as oak and beech (Mostly beech)
  - **Dimension:** 2.60 m long (0.225 m^3) weighing 153kg/sleeper. To increase the durability of these sleepers, they are infused with tar oil (14 kg of tar oil/sleeper). Sleeper spacing of 60 cm. This results in a total of 750 m^3 of beech wood and 46.8 tonnes of tar oil per double track km.
  - **Lifespan:** 30 years
- **Steel sleepers (7% of the tracks)**
  - **Type:** Y steel sleepers
  - **Dimension:** these sleepers weigh around 143 kg. the total requirement thus results 229.7 tonnes for a double track per km.
  - **Lifespan:** 30 years

Table 38: Quantities of different types of sleepers(Source: (Schmied & Mottschall, 2013))

Threshold type	unit	Erection expenditure		Maintenance attitude	A total of
		per km	*per km and a*	*per km and a*	*per km and a*
1-track line					
- concrete sleeper					
concrete	m^3	190.0	5.43	0.06	5.49
Reinforcing steel	t	11.7	0.33	0.00	0.34
- wooden sleeper					
Beech wood	m^3	375.0	12.50	0.11	12.61
Impregnation oil	t	23.4	0.78	0.01	0.79
- steel sleeper					
Steel, converter	t	118.9	3.96	0.05	4.02
2-track routes					
- concrete sleeper					
concrete	m^3	380.0	10.86	0.11	10.97
steel	t	23.3	0.67	0.01	0.67
- wooden sleeper					
Wood	m^3	750.0	25.00	0.23	25.23
Impregnation oil	t	46.8	1.56	0.01	1.57
- steel sleeper					
steel	t	237.8	7.93	0.11	8.04

Ballast

The amount of ballast required depends on the type of sleepers used and it was observed that the amount of ballast needed, decreased from concrete sleepers to wooden sleepers to steel sleepers.

- **Details:** the overall thickness of the ballast layer was considered to be 30cm, with the material density of 1.65 t/m^3. The lifespan of the ballast was assumed to be 15 years with a maintenance requirement of (tamping and cleaning) 0.1% replacement of the ballast mass per year.

- The emission factor chosen for this layer was that of the "crushed gravel, from the mine".

Table 39: Quantities of ballast (Source: (Schmied & Mottschall, 2013))

Threshold type	unit	Erection expenditure		Maintenance attitude	A total of
		per km	*per km and a*	*per km and a*	*per km and a*
1-track line					
- concrete sleepers	t	3,573	238.2	3.6	241.8
- wooden sleepers	t	3,030	202.0	3.0	205.1
- steel sleepers	t	2,319	154.6	2.3	156.9
2-track routes					
- concrete sleepers	t	7,099	473.3	7.1	480.4
- wooden sleepers	t	6.141	409.4	6.1	415.5
- steel sleepers	t	4,907	327.1	4.9	332.0

Slab track

Construction method: the concrete support layer can be designed as a trough in which the grid is fixed with concrete sleepers and poured with concrete. In another system the concrete sleepers are built into and fixed in the concrete base layer with the help of frames.

- **Details:** service life of 60 years. For the maintenance of slab tracks, 1/3rd % of the total installed slab track quantity was assumed.

Table 40: Quantities for slab track (Source: (Schmied & Mottschall, 2013))

Threshold type	unit	Erection expenditure		Maintenance attitude	A total of
		per km	*per km and a*	*per km and a*	*per km and a*
1-track line					
- Concrete	m^3	1,132	18.9	3.3	22.2
- Reinforcing steel	t	66	1.1	0.2	1.3
2-track routes					
- Concrete	m^3	2,264	37.7	6.6	44.4
- Reinforcing steel	t	133	2.2	0.4	2.6

Overhead lines (catenary, contact wires and droppers)

- **Contact wires:**
- **Details:** the most commonly used cross sectional areas of contact wires are of 80mm^2, 100 mm^2 and 120 mm^2 that are made up copper, copper silver alloy (CuAg0.1) and copper-magnesium alloy (CuAg0.5). The kilometre weight of wires with a cross sectional area of 100 mm^2 and 120 mm^2 is 0.9t and 1.1t respectively. The annual maintenance amounts to around 1/3% of the material inventory of the overhead lines. The weights calculated in

the reference report for the contact wires also includes the catenary wires hence while calculating the GHG emissions, the final factor obtained is divided into two equal weights and assigned to contact wire and catenary. This has been specifically done due to the absence of details mentioned about them separately and in order to maintain continuity and consistency of data. The minor contribution of these overhead line wires to the overall GHG emissions also led to this approximation.

- **Emission factor used:** contact wires consists of very pure copper due to which the emission factor used from table 18 is that relating to primary copper. The droppers are usually made up of bronze.
- **Lifespan: 7 years** for contact wires and catenary
  - **20 years** for droppers

Table 41: Quantities of OHLE (Source: (Schmied & Mottschall, 2013))

	unit	Erection expenditure		Maintenance attitude	A total of
		per km	*per km and a*	*per km and a*	*per km and a*
HGS - double track (Re 330)					
- copper	t	2.1	0.30	0.01	0.31
- bronze	t	2.5	0.12	0.01	0.13
ABS - double track (Re 200/250)					
- copper	t	2.0	0.20	0.01	0.20
- bronze	t	1.3	0.07	0.00	0.07
Remaining routes - two-pronged					
- copper	t	1.8	0.09	0.01	0.09
- bronze	t	1.1	0.05	0.00	0.06

G – DETERMINATION OF WEIGHTS FOR THE DIFFERENT LIFE CYCLE PHASES (AHP)

The tables below show the individual respondents' pairwise comparison matrices which are later combined into a single matrix by taking its geometric mean (table 40)

Table 42: Pairwise comparison matrix for respondent 11

	Procurement phase	Design phase	End of life phase
Procurement phase	1	0.2	0.2
Design phase	5	1	1
End of life phase	5	1	1

Consistency ration – 0%

Table 43:Pairwise comparison matrix for respondent 7

	Procurement phase	Design phase	End of life phase
Procurement phase	1	0.33	3
Design phase	3	1	4
End of life phase	0.33	0.25	1

Consistency ratio - 9.9%

Table 44: Pairwise comparison matrix for respondent 2

	Procurement phase	Design phase	End of life phase
Procurement phase	1	0.5	7
Design phase	2	1	8
End of life phase	0.14	0.13	1

Consistency ratio – 4.7%

Table 45: Pairwise comparison matrix for respondent 4

	Procurement phase	Design phase	End of life phase
Procurement phase	1	0.33	1
Design phase	3	1	3
End of life phase	1	0.33	1

Consistency ratio – 0%

Table 46: Pairwise comparison matrix for respondent 6

	Procurement phase	Design phase	End of life phase
Procurement phase	1	7	5
Design phase	0.14	1	1
End of life phase	0.2	1	1

Consistency ratio – 2.1%

Table 47: Pairwise comparison matrix (geometric average)

	Procurement phase	Design phase	End of life phase
Procurement phase	1	0.6	1.84
Design phase	1.67	1	2.49
End of life phase	0.54	0.40	1

Consistency ratio- 0.5%