Critical Raw Materials in optical telecommunication, introducing strategies for a resilient supply chain

A dynamic material flow analysis of CRMs in fibre optical equipment

Msc. thesis Industial Ecology
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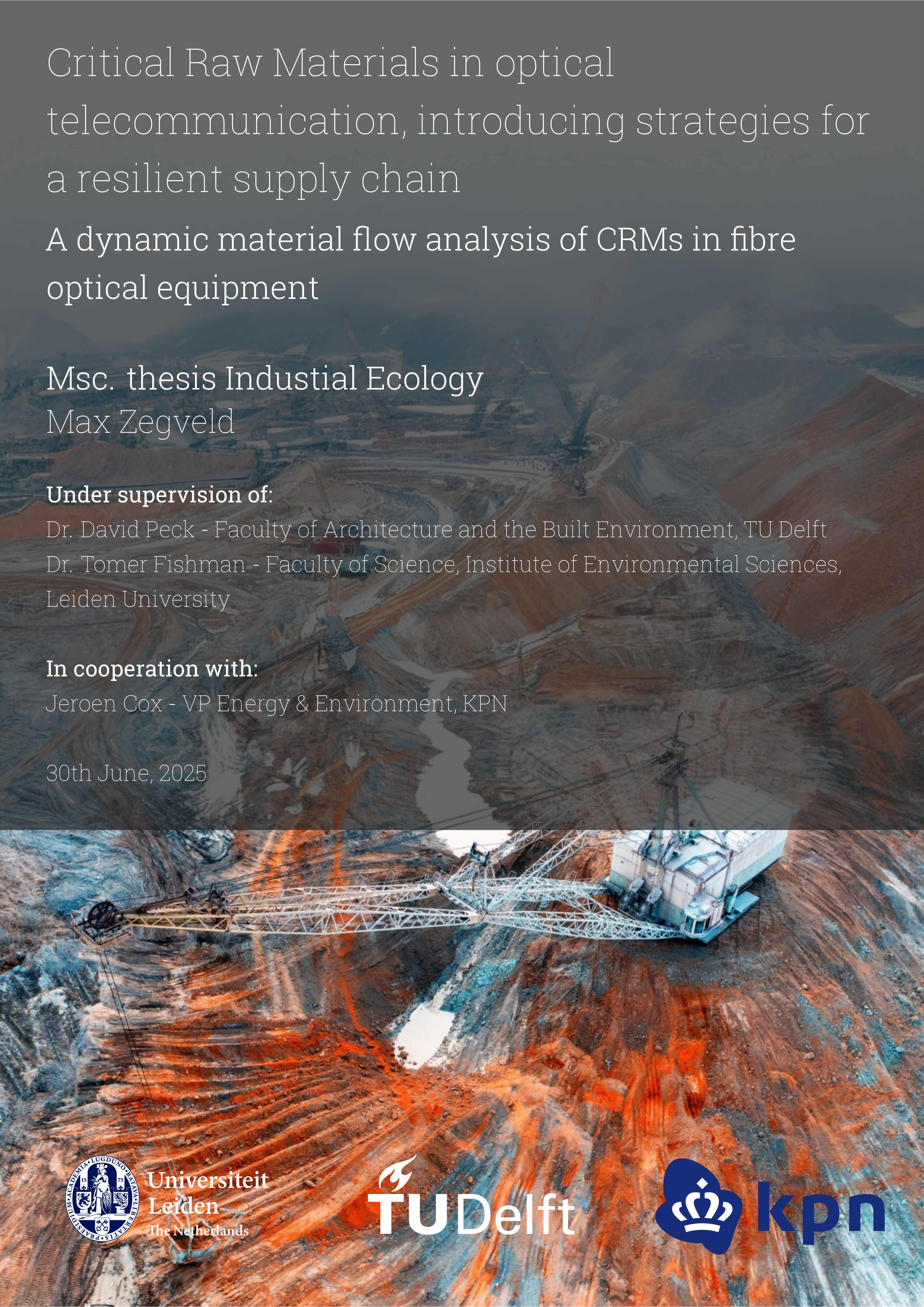

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Abstract

This study addresses a research gap in understanding how telecommunications companies can become more resilient by examining organisation level flows of critical raw materials (CRMs) in optical transport network (OTN) equipment. While previous research has quantified CRM stocks and flows in consumer electronics, the material dynamic behaviour of fibre optical equipment, specifically amplifiers and transponders remain under investigated. In particular, there is little quantitative and time dependent analysis of how CRMs embedded in fibre optical equipment circulate within the network of KPN. This gap raises the following research question:

What strategies can KPN implement in their operations to secure a resilient supply chain of critical raw materials embedded in optical transport network equipment?

To answer this question, a dynamic material flow analysis (dMFA) was developed for amplifiers and transponder deployed by KPN in the Netherlands over the period 2024–2045. First, internal desk research and expert consultation with optical network architects provided insight into equipment lifespans, failures, and the build-up of the network. Next, data from original equipment manufacturers (OEMs) and similar case studies quantified the CRM contents, leading to mapping of 16 CRMs: erbium, bismuth, thulium, germanium, praseodymium, silicon, antimony, boron, magnesium, manganese, nickel, palladium, ruthenium, silicon, strontium, tantalum, titanium, tungsten and yttrium. These inputs enabled the integration of a stock driven dMFA model projecting annual primary CRM inflows, stocks, and outflows. Four scenarios were modelled to address uncertainty: (1) business as usual, (2) AI driven growth, (3) a circular and sustainable economy and (4) technology & innovation representing a hybrid scenario combining moderate growth with circular interventions. A Monte Carlo sensitivity analysis assessed the extended uncertainty for stock accumulation and the impact of the selected parameters.

Results indicate that, under high growth scenarios, demand for key CRMs in amplifiers and transponder printed circuit boards rises increasingly fast, with a stable period between 2033 and 2038 due to capacity doubling and a continued exponential growth after 2038 resulting in a demand increase between factor 9 and 14 for the low and high scenario respectively. Possible leading to issues in the future as competing sectors such as solar photovoltaics, wind turbines and electrolysers are also expected to grow rapidly in the EU and globally. With primary use rates indicating that higher recycling yields still cannot account for the demand increase periods. Whereas experimentation of low, medium and configurations of circular economy strategies have shown that individual strategies cannot reduce more than 30% of primary material demand in 2045. A combined strategy however, resulted in higher savings, while expected savings amount to higher reductions due to the dampening of lifetime extension on recycling and reusing practices. Combining literature surrounding the feasibility of resilience strategies on a firm level with the temporal and magnitude of the strategies led to managerial implications for KPN. With proposed short term (2025 - 2033) strategies focusing on reduction and lifetime extending strategies, whereas medium term (2033 - 2038) strategies emphasize recycling and reusing of equipment. With long term (2038 - onwards) strategies aimed at reducing material needs. However, the study also shows the high dependency of KPN on supplier product design choices and the limited control on upstream influence.

In order to further enhance the study, it is firstly recommended to investigated to conduct a more thorough stakeholder analysis to get a better understanding of the power and interests of the relevant players in the value chain. In addition to an extension of the economic importance criteria tailored to telecom companies and an investigation on methods to integrate higher data efficiency across the optical transport network. With a final recommended study surrounding the upscaling of the equipment to magnify the impact of the fibre optic sector on CRM demand beyond the Netherlands.

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Throughout the writing of this report, there are a number of people I would like to thank for their help during the process.

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I would further like to thank David and Tomer for guiding the thesis process from the start of the study from the thesis preparation course until the finalisation phase. The feedback I received from you during the meetings allowed me to improve the quality of the study significantly. Besides the formal meetings, I also really enjoyed conversations sometimes ranging to completely different topics with David, which was a very welcome change.

Lastly, I would like to thank Hélène, my family and friends for their constant support during, but also before the completion of my studies.

Contents

List of Figures

List of Tables

List of abbreviations

(d)MFA	(dynamic) Material Flow Analysis
BAU	Business As Usual
CAGR	Compound Annual Growth Rate
CE	Circular Economy
CRM	Critical Raw Material
EDFA	Erbium-doped Fibre Amplifier
EV	Eletric Vehicle
FTTP	Fibre To The Premises
GPP	Green Public Procurement
HCF	Hollow-core Optical Fibres
HREE	Heavy Rare Earth Element
ILA	In-line Amplifier
LREE	Light Rare Earth Element
MSA	Material Systems Analysis
MTBF	Mean Time Between Failures
OEM	Original Equipment Manufacturer
OTN	Optical Transport Network
PCB	Printed Circuit Board
PGM	Platinum Group Metals
PIC	Photonic Integrated Circuit
PV	Photovoltaics
REE	Rare Earth Element
ROADM	Reconfigurable Optical Add/Drop Multiplexers
SMF	Single-mode Optical Fibres
SOA	Semiconductor Optical Amplfier
SRM	Strategic Raw Material
VHCN	Very High Capacity Network
WDM	Wavelength Division Multiplexing
WEEE	Waste Electric and Electronic Equipment

1

Introduction

Critical raw materials (CRMs) have a major role in modern telecommunication infrastructure due to their unique properties, these vary from having high conductivity, magnetism or thermal stability. These materials are categorized within multiple groups with different criticalities and properties, including platinum group metals (PGMs) and rare earth elements (REEs). With applications being essential for manufacturing of semiconductors, antennas and other technologies which are widely used for telecommunications, with demand possibly increasing through innovations of emerging technologies. However, having an increased reliance on CRMs poses significant challenges for supply disruptions and consequent technological development implications.

The European Union currently relies heavily on imports for their CRM supply with significant shares sourced from a limited number of countries, including China, Russia and the US, this dependency exposes the EU to disruptions in supply due to geopolitical tensions (European Commission, 2023). In particular, fibre-optic infrastructure is expanding at a rapid rate and increasingly dependent on CRMs, although it receives less attention from a material perspective than end-user products such as mobile devices. Compared to mobile devices, replacement rate of the network infrastructure is lower, however, cumulative CRM stock build-up is significant and concentrated at fixed (known) locations. This characteristics makes these infrastructures a key point of leverage for improving resilience from the operational level of a telecom service provider. The environmental impact of extraction and processing of CRMs often include environmental damaging practices such as habitat destruction, water contamination and substantial emissions, with recycling practices of some CRMs resulting in even more energy and subsequent emissions (Perossa et al., 2024).

From a technological perspective, it can be seen that innovations in telecommunications for new generations of mobile network as well as early stages of quantum communications could increase demand for specific CRMs (Jakovcic et al., 2019). Consequently if supply disruptions for these materials come into effect, technological progress might be hindered if resilience strategies are not employed in a higher degree.

To address EU's increasing dependency resulting from growing material demand in telecommunications, the Critical Raw Materials Act aims to reduce dependency of CRMs through increased domestic extraction, processing and recycling combined with shifts of a maximum of 65% of annual consumption coming from a single third country (Hool et al., 2023). However, complex compositions and high dispersions of CRMs in electronic components make recycling challenging (Righetti & Rizos, 2024), whereas annual consumption of several CRMs is currently imported from a limited number of suppliers increasing EU's vulnerability. Furthermore, firm level practice and EU policy are disconnected in their integration of circular economy strategies, requiring an investigation of resilience strategy effectiveness for KPN and specifically from an emerging technology perspective. Thus, the following research question has been formulated:

What strategies can KPN implement in their operations to secure a resilient supply chain of critical raw materials embedded in optical transport network equipment?

Understanding the characteristics of material flows of CRMs in emerging telecommunication products at firm level is crucial from multiple perspectives. Scientifically, this study investigates developments of material flows that are crucial in the telecommunication sector and offers insights into resilience strategies from a company perspective. From a social perspective, CRM supply chain involves diverse stakeholders across different levels within the supply chain, from extraction to end-of-life treatment, as well as policymakers that are engaged in setting up governance frameworks for the increasing implications of CRM dependency and social equity. Taking an industrial ecologist perspective into account, the findings of the study integrates the interaction of scientific and social aspects mentioned above. This property of CRMs in telecommunication is further underlined in that materials depletion from the ecosphere and artificially manufactured into the technosphere, which is our communication infrastructure and its corresponding machinery, connecting ecology with industry in the system boundary.

2

Problem statement

The problem statement introduces the theoretical background of critical raw materials, establishing the base for the subsequent research gap. The following research objective and questions are then presented to address the research gap, in which the chapter concludes with an outline of the study.

2.1. Theoretical background

Deployment of critical raw materials in emerging technologies

CRMs play an important role in the telecommunications sector because of their role in manufacturing components such as semiconductors, batteries, or infrastructural equipment. These materials are irreplaceable for technological applications due to their unique properties as stated by van Gaalen and Slootweg (2024). The classification of critical materials is based on the characterization of a high risk of supply disruption and a high economic importance as defined by European Commission (2014). Examples of current telecommunications infrastructure include the use of erbium in optical amplifiers and aggregated groups of multiple raw materials such as Light Rare Earth Elements (LREEs) consisting of neodymium, which can be found as permanent magnets in antennas (Bobba et al., 2020). With emerging technologies in telecommunications expected to require even more LREEs for development of rare-earth doped crystals implemented in quantum communication, for instance (Pathak, 2013).

The integration of innovations such as emerging telecom technologies show a deployment pattern in the form of socio-technical transitions, in which the Multi-Level Perspective explains how radical innovations emerge in protected 'niches' before it breaks through and reshapes established regimes (Geels, 2004). The governance of these transitions involves multiple policy instruments, activities enabling network-building and supporting measures such as subsidies that can accelerate diffusion of the technology (Smith et al., 2005). In the context of emerging telecommunications, such as next-generation optics, experiments are not only technical but also social arenas consisting of regulators, firms and research institutions each with different perceptions (Smith et al., 2005). However, these existing studies are predominantly qualitative with a focus on energy systems, instead of quantitatively evaluating how these niches shift the firm-level material flows over time in the context of social-institutional dimensions.

Critical raw material supply risks

Regarding the materials in the emerging technology in a socio-technical context, the significance of the materials can be seen to go beyond their technological applications. Since currently, 15 of the total 27 materials designated as CRMs as of 2020 are based on import for 95%, whereas the most important suppliers are China followed by the USA, Russia, Brazil, and Nigeria depending on specific materials (Gaub & Boswinkel, 2020). This dependence creates considerable risks when disrupted for the EU supply chain which is reinforced by three factors: evolution of technological innovations, CRM production being concentrated in a few countries, including fragile states, and finally, the increasing geopoliticization of international trade, illustrated by ongoing tensions between China and the US in recent years (Gaub & Boswinkel, 2020). Within data transmission networks specifically, components with high supply risk for EU include fibre cables and printed circuit boards (PCBs), with 65% of the production capacity primarily situated in Taiwan and China and only 4% coming from the EU (Carrara et al., 2023).

Circular Economy strategy challenges

In response to these challenges, the European Union has emphasized the importance of addressing CRM supplying issues in the economy through the introduction of the Critical Raw Materials Act (CRMA) in 2023, with the intention to reduce their dependence on CRMs and stimulate a sustainable playing field for EU's value chains (Hool et al., 2023). Among the proposed strategies is the incorporation of effective recycling and recovery strategies within a circular economy framework. However, currently a third of all CRMs face significant constraints in recycling efforts, with precious metals used in electronics in particular, since they are distributed in complex alloys making efficient recycling technically challenging and economically unfeasible (van Gaalen & Slootweg, 2024). In addition, Ueberschaar (2017) states that the recycling process could result in unintended removal of toxic elements or valuable materials. With a study by Golroudbary et al., 2019 also taking energy consumption and emissions into account, concluding that lithium recovery from batteries using current technologies leads to more emission and energy usage than primary production. Another approach in overcoming supply disruptions and decrease demand for certain critical materials is through substitution (Pavel et al., 2016). In which four different strategies could be implemented: substance-for-substance (direct substitution), service-for-product (ownership substitution), process-for-process (alternative need shift) and new-technology-for-substance (complete technology substitution) (Goddin, 2020), each element is addressed in more detail in paragraph 8.2.3.

However, difficulties in substitution have been presented due to alterations on performance of a metal as a result of direct substitution (Mouloudi & Samuel, 2022). As demonstrated in literature, the most effective substitutes are those derived in the same metal group as Platinum Group Metals (Graedel et al., 2015) and rare earth elements (REEs) (Ayres & Peiró, 2013). However, substituting these elements leads to the same supplying problems, making it challenging to substitute one material directly for another while maintaining the same level of performance. Therefore, it could be interesting to reduce the used quantity instead, as shown for LREEs (Omodara et al., 2019) and Neodymium and Praseodymium within magnets (Pavel et al., 2017).

The concepts mentioned above are intertwined on multiple levels. With telecommunication technologies relying heavily on CRMs, in addition to having a supply chain that is vulnerable to geographic placement and geopolitical factors and lastly combined with possible demand increases for optical data transmission in the future. Furthermore, it was found that policy frameworks proposed by governmental bodies such as the EU are restricted in their effectiveness. Since substitution and recycling are widely recommended across literature as resilience strategies, practical feasibility is constrained by trade-offs in performance (Mouloudi & Samuel, 2022), lower economic viability from miniaturized components (Xia et al., 2024) and occasional higher emissions from recycling (Golroudbary et al., 2019) compared to primary production. Thus, current literature often fails to account for the techno-economic limitations considering the circular strategies with real-world industry constraints, highlighting the importance of firm-specific approaches going beyond EU regulations.

2.2. Research gap

Based on existing literature, studies have explored material flow analysis (MFA) of electronic equipment for everyday use such as mobile phones, laptops and desktops in the past (Thiébaud et al., 2018).

Although this is less readily available for current telecommunication products, whereas material flows of emerging technologies have not been mapped and analysed yet. Islam and Huda (2019) state in their knowledge gap review, that future research show opportunities in performing product level MFA studies by implementing time series for the lifespan of products. This is further addressed as innovation cycles of electronic equipment are generally fast paced, while prices of new devices tend to decrease, resulting in short product life-cycles and higher sales (Prakash et al., 2016). This trend creates research opportunities into the effect of lifetime extension and whether it might counteract since there is less inflow into the circular economy. The conducted study will integrate the effect of dynamic lifetime distributions for emerging technologies considering the non-static nature of in- and outflow into the system and its consequent strategy for a telecommunication company.

Furthermore, the techno-economic uncertainties of CRM flows at company-level networks are seldom explored. While national MFA studies exist, their results are too arbitrary to inform decision-making at the company level, especially dealing with equipment specific material composition, use-phase stock accumulation and end-of-life scenarios. At the same time, circular economy strategies proposed by the EU under the Critical Raw Materials Act, primarily target international governance and policy, overlooking strategies suited for the value chain of private sectors. As a result, current approaches are inadequate for firms striving to reduce CRM dependencies in a practical manner (Lapko et al., 2016). Therefore, company-level strategies adjusted to resource-specific and internal capabilities of companies becomes apparent (Mouloudi & Samuel, 2022).

2.3. Research objective and research questions

2.3.1. Research objective

The study aims to address the knowledge gaps identified in the literature review by quantifying the composition and volumes of CRMs embedded in emerging telecommunication technologies, with a particular focus on the network infrastructure of KPN. This research project combines data with dynamic material flow analysis in order to project future CRM stock and consequent primary CRM demand development under different scenarios and circular economy strategies, by means of changing input parameters of the model, such as recycling yield and lifetime extension practices. Ultimately providing insights into how primary CRM demand evolves over time and informing how a telecommunication operator such as KPN can contribute to a more resilient and sustainable supply chain by implementing organization level strategies. By combining the quantitive modelling results to the broader strategic context of the telecom sector, this study investigates how KPN, positioned as an operator and buyer of equipment can or cannot act as a leverage point in the CRM value chain.

2.3.2. Research scope

To achieve the stated objective, this research is structured as a scientific systems study that applies dynamic material flow analysis (dMFA) to quantify the temporal development of critical raw materials embedded in fibre optical equipment. The focus is placed on amplifiers and transponders deployed within the Optical Transport Network (OTN) of KPN, based on their critical role in network performance and anticipated growth in deployment.

The material scope is restricted to the list of critical raw materials designated by the European Union in 2023, excluding non-critical or bulk materials that fall outside the EU's criticality criteria. These CRMs are selected not only for their technological function but also their supply risk and strategic importance.

The geographical scope of the study is set to the Netherlands, reflecting KPN's national operations, while the temporal model spans from 2024 to 2045 to capture multiple equipment lifecycles and long-term material trends. Within this defined system boundary, CRM stocks and flows are modelled under various future development scenarios.

The model is however, restricted to the optical part of the data transmission network in telecommunications, consequently excluding wireless network components and end-user devices such as mobile phones. Due to proprietary constraints and lack of data, material breakdowns for the amplifiers and transponders were in part approximated based on OEM supplied mass data and similar case studies. With modelling results affected by assumptions such as average equipment lifetimes while excluding disrupting technology developments which could be foreseen in the future. These assumptions limit the model's accuracy for long-term forecasting but allows scenario based insights on material dependency and mitigating strategies.

Besides modelling material behaviour according the material and geographical scope. This study aims to translate the scientific findings into actionable strategies for the organization. In this context, KPN is assessed as a stakeholder situated within a complex supply chain, whose influence is determined by relationships with surrounding stakeholders such original equipment manufacturers (OEMs), recyclers, and policymakers. While the report is grounded in scientific modelling of empirical data, the study is also intended to inform strategic decisions within KPN. In addition, although the case is focused on KPN, the methodological framework can be adapted for telecom providers in other EU member countries if material flow data is available. Conclusively, the primary audience includes both academic researchers and decision makers in (material) sustainability domains in the value chain.

2.3.3. Research questions

Based on the different aspects of the research gap and the consequent research objective, the following main research question has been established:

What strategies can KPN implement in their operations to secure a resilient supply chain of critical raw materials embedded in optical transport network equipment?

The main research question will be supported by the following sub-research questions:

- What is the composition of critical raw materials in fibre optic equipment integrated in the optical transport network?
- How does primary critical raw material demand develop through optical transport network expansion?
- What resilience strategies can KPN implement considering the impact of circular economy measures on primary critical raw material demand?

These questions aim to provide both a system-level understanding of CRM flows and corresponding strategies adjusted to KPN's operational context. Aligning with the Industrial Ecology discipline by addressing sustainability problems while considering technological infrastructures, material flows and decision-making at an organization level.

2.4. Outline of the study

The structure of the report is as follows: chapter 1 introduced the research topic, while chapter 2 described the theoretical background based on existing literature surrounding the topic, and the research gap and research questions originating from the theoretical background. In response to the formulated research questions, chapter 3 explains how the research methodology is structured to answer the research questions and what the inherent limitations of the methods are. Chapter 4 aims to address the first sub-research question by introducing the fibre optical technology and the collection and interpretation of the critical raw materials within the selected equipment. As the present study employs a quantitative model for the dynamic material flow analysis, prior to introducing the results from sub-questions 2 & 3, chapter 5 is introduced to explain the model methodology including the different parameters and selected scenarios. After introduction of the conceptual model, chapter 6 addresses sub-question 2 and presents the results of how CRM demands develop according to the scenarios for the selected equipment. Chapters 7 and 8 aim at answering sub-question 3 with chapter 7 describing the quantitative impact of individual and compound circular economy strategies on primary material demand. Whereas chapter 8 subsequently goes in-depth on what the implications of the strategies are at organizational level. Chapter 9 consist of a discussion surrounding the conducted research as well as the limitations of the study and recommendations for future research. Finally, chapter 10 provides a conclusion of the report's findings for the research questions.

3

Research methods

The research approach to answering the research questions is divided into three subsequent phases, with each phase building upon the findings of the previous stage, the structure can be seen in figure 3.1 and elaborated further in the paragraph below. The subsequent sections describe the used methods, the operationalization of data and explains how limitations are addressed for each phase.

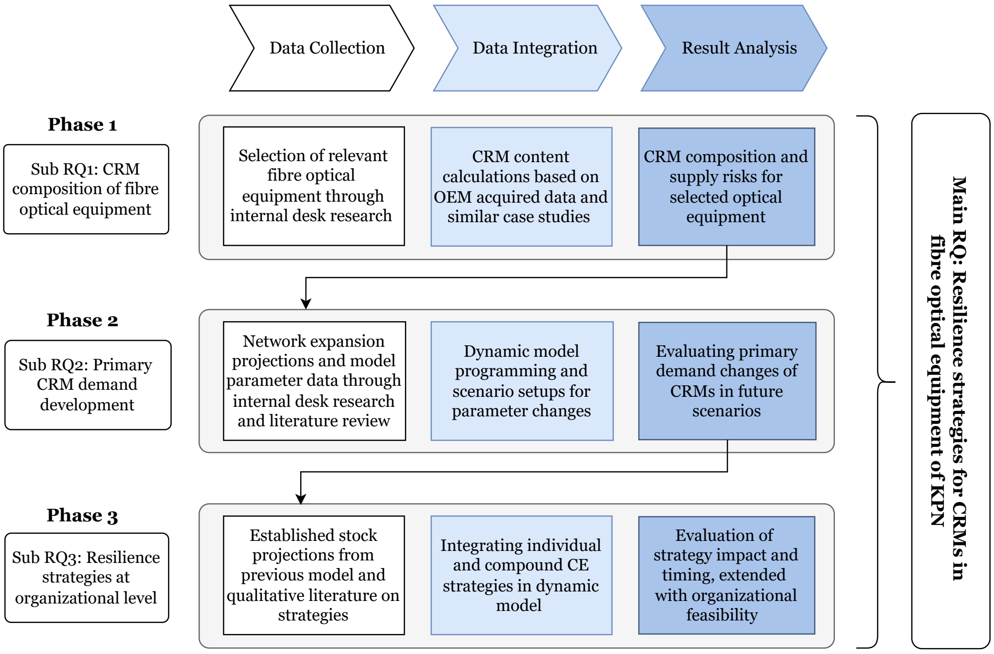


Figure 3.1: Research approach according to each phase

The initial phase involves the investigating how the overall network infrastructure is build-up and which equipment is required for the optical transport network in particular. This is followed up with retrieving the critical raw materials necessary within the selected equipment and their assessment from a static perspective in terms of concentration and supply risks. The second stage of the research consists of investigating the expansion of the OTN in the past generation and the projected growth of the system in the current generation. In addition, this stage involves establishing four different scenarios. The purpose of these scenarios is to evaluate the effect of the relevant exogenous parameters on the system and to account for uncertainties in future developments. This stage results in a projection of how the identified CRMs from stage 1 grows in its demand from the initial start in 2025 until 2045 and how this corresponds to demand growth in other sectors. The third and final phase incorporates the stock projections from stage 2 and assesses the impact of various individual and compound circular economy strategies on primary material demand. Consequently, resilience strategies at organizational level are presented, based upon the quantitative results and extend with literature.

3.1. Critical raw material composition of fibre optical equipment

Identification of relevant equipment in data transmission network

The first step in answering sub-research question 1 included (internal) desk research to determine the context of the relevant equipment in the network. Desk research was selected as it includes expanding on data which already has been collected and processed before (Moore, 2018). Thus, data available within the company was collected to review which part of the network is part of emerging technology within telecommunications and is expected to be integral and prone to growth in the future. Collection of this data came through regular contact with an internal network architect specialised in the optical transport network, through the application of unstructured interviews with main findings reported in the appendix. In addition to interviews, scientific literature has been explored to determine the functionality of each part of equipment within the optical transport network. As a result of combining available literature and personal communication with the network architect, transponders and amplifiers were selected to focus on further during this research.

CRM composition determination

After scoping the equipment focus to two products, the critical raw material content had to be determined. As exact material composition of transponders and amplifiers were not readily available, the study was limited to include existing data for amplifiers from a previous research conducted by Flik (2021) and transformed to the amplifier mass for this case study as shown in the appendix. Regarding transponders, overall critical raw material structure was not readily available, with an exception of the PCB assembly mass supplied by the original equipment manufacturer. To supplement the initial gap on PCB data, empirical data from literature had been assessed to compare waste PCBs in other appliances, as shown in the table and evaluate on (waste) PCBs and its inherent differences in results due to data availability and time scope. After careful internal desk research within the OEM, calculations of the concentration of CRMs in PCBs were provided and transformed to element fractions in terms of compounds, this is elaborated further in paragraph 4.2.2. However, it should be noted that extracting pure element mass from compounds such as ceramics and minerals does pose limitations as it disregards the characteristics and functionality differences between the original compounds, with silicon dioxide for instance, originating from a mineral and ceramic as seen in the table.

Assessment of CRM mass percentage compared to supply risk

Finally, the identified CRM composition as mass percentages of total material weight of amplifiers and transponder PCBs have been compared to the supply risk indicator scores derived from the EU 2023 criticality assessment Grohol and Veeh (2023) found in figure 4.4. The two dimensions have been plotted to identify not only the role of high volume CRMs, but to critically show the associated supply risks subject to the established variables from EU's criticality methodology illustrated in figure 4.3. As a result, the diagrams aim to show possible classifications for telecommunications companies according to the quadrant the materials are situated. Whereas materials situated in the top right quadrant represent a combination of high absolute amount of material combined with a high supply risk, whereas materials found in the bottom left quadrant represent lower volumes and smaller supply risks.

3.2. Primary critical raw material demand development

The paragraphs below describe the overall approach for the second research question, whereas the exact operationalization of the model variables is elaborated in more detail in chapter 5, after the results from phase 1 in chapter 4.

(Prospective) dynamic MFA consideration

The second phase of the research involved the building the dynamic material flow analysis model for the identified CRMs in amplifiers and PCBs in transponders from the initial phase. As the aim of the research question was to determine how the primary CRM demand develops in the future as a result of network expansion, dynamic MFA was applied as it is considered a valuable tool for the corresponding goal of evaluating resource management in supply chains over time (Zaghdaoui et al., 2017). This is further addressed by Klinglmair et al. (2017), stating that static MFA is limited in its representation of dynamic changes for different moments in time. However, dynamic MFA is coupled with constraints when there is a lack of relevant data for flows of lifecycle stages (Ziemann et al., 2013). This gap in available data is further underlined as the model comprises of a prospective dMFA, in which model results, or future stocks in this case, is estimated based on a number of exogenous parameters driving the required stock. This approach, however, has to be regarded with significant uncertainty due to factors such as price changes in the future (Deetman, 2024).

Modelling uncertainties

In order to evaluate the model's capacity to cope with uncertainty of the model behaviour in the future, four scenarios are introduced with varying parameters followed up with a Monte Carlo validation procedure. This enables the calibration of the output measured at the end point of the model scope, in addition to the output measured during each year for a significant amount of different runs (1000). As outlined in paragraphs 6.5.2 and 6.5.1, the research compared the sensitivity of the accumulated primary demand of materials and the material stock for each corresponding year.

Data collection & operationalization

The build-up of a stock-driven model was based on internal desk research to retrieve the projected links on the OTN, as shown in the table in the appendix and as bottom-up modelling of demand is suitable for undefined scenarios (Deetman, 2024). In addition, other parameters such as recycling yields and very high capacity network connections were derived from literature and EU based reporting in combination with internal desk research of equipment capacity for instance. The equations used with stock-driven dynamic MFA models are reported in the appendix, which describes the foundation of the model for: inflow, outflow, net addition to stock and recycling and reusing parameters. Furthermore, the complete modelling source code for the amplifier and transponder models are reported in the appendices.

The second research question concludes by gathering insights into how primary demand of the identified CRMs accumulate over time based on different scenario's modelled to visualize the effect of varying parameters.

3.3. Resilience strategies at organizational level

Quantitative analysis of individual & compound circular economy strategies impact

The last phase and corresponding sub-research question aims at modelling and evaluating the impact of different circular economy (CE) measures on the aggregated primary material demand of the equipment. The CE strategies examined include reuse at product level through redeployment, recycling of embedded material, reduction of material intensity and lifetime extension (Fontana et al., 2021). The proposed CE strategies were then modelled via three levels of configurations to evaluate their impact on primary demand, as further addressed in table 7.1, with the complete reported model code found in the appendix. As a result primary demand reductions and lost outflows could be assessed using a dynamic perspective, so to assess how the measures act from a temporal scope as well as in its magnitude, so the cumulative reduction of primary CRM demand. This evaluation of the individual strategies enabled a comparative analysis between the strategies, however, in reality (inter)national policy but also firms strive to combine multiple strategies. Therefore, consequent compound effect of strategies are analysed on their net savings of CRMs compared to the expected savings when summing the impact of individual strategies.

Qualitative analysis of organization level strategies

Besides the quantitative analysis of the strategies, it is important to address whether the strategies are feasible from the perspective of a telecommunication company and to identify which specific strategies for lifetime extension, recycling, reusing, reduction and alternative strategies can be integrated in the current and future operations of KPN. This analysis was conducted by reviewing scientific literature on organizational and higher level strategies combined with internal desk research supported by experts on the technical and sustainable specifications for the OTN as reported in the appendix. Ultimately, the analysis combines the temporal and magnitude of the findings from the quantitative analysis with the qualitative analysis to introduce a short, medium and long term strategy roadmap from the perspective of a telecommunication company, with the corresponding constraints connected to the circular economy strategies.

4

Critical Raw Materials in optical telecommunication technology

This chapter is dedicated to answering the first sub-question through the subsequent sections: introduction of the build-up of the current infrastructure of telecommunications, followed up with an assessment of fibre optical equipment, and finalised with an identification of the CRMs and what their supply risk implications are.

4.1. Emerging fibre optic technologies in telecommunications

4.1.1. General data transmission network build-up

Within telecommunications, there is a distinction between the means of communications as wireless and grid bound networks are considered different separate technologies and compose of other critical raw materials (Carrara et al., 2023). The infrastructure consists of wireless mobile networks supported by antennas distributed through the Netherlands enabling data exchanges via waves to client devices within range of the antennas. In addition to mobile networks, fixed networks are in place to enable data exchange via connected fibre cables, offering efficient and higher volumes of data communication. The fixed network is essentially organised in a layered network, in which the bottom layer is defined as the backbone, consisting of fibre optic cables connected to optical switching equipment at the nodes (Wong, 2021). The optical equipment in the core network is the main focus of this study, as the replacement of the older generation of equipment has a rollout period in the coming years and is integral for high bandwidth data transmission within the Netherlands.

4.1.2. Optical transmission network

The OTN layer is designed to efficiently transport data over long distances using optical signals, significantly reducing latency and enhancing capacity compared to traditional electrical signalling via copper. The network is structured to support multiple channels simultaneously through Wavelength Division Multiplexing (WDM), where each channel is transmitted at a unique wavelength, maximizing the bandwidth of a single optical fibre. The OTN is organized in a redundant architecture where nodes typically comprise of shelves which carry cards transforming signals and are interconnected via optical links. A characteristic of this meshed structure is its reliability, as redundancy is embedded in the design to ensure that if a failure occurs at a specific node or link, traffic can be rerouted through alternate paths without significant downtime. The overall layout of the network, as illustrated in figure 4.1 below, features a series of interconnected components exchanging data across fibre cables between client routers A and B. The following paragraphs will delve deeper into the function and materials involved in each of these components (Internal desk research, 2025).

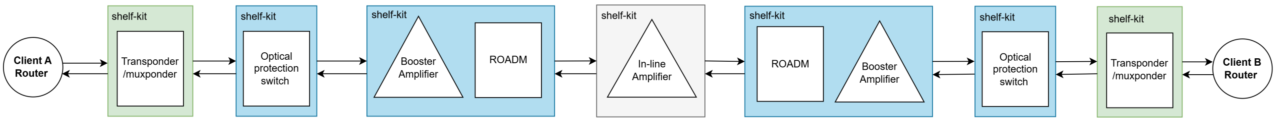


Figure 4.1: Line-model of optical transport network

4.1.3. Photonic service switch shelves

In the optical transport network, photonic service switch shelves act as modular enclosures designed to house multiple cards that are essential for the conversion and management of optical and electrical signals. These shelves are integrated into the network's physical infrastructure, supporting cards such as transponders, muxponders, ROADMs, and amplifiers, further elaborated in the following paragraphs. The switch shelves establish point-to-point communication between the corresponding channels of the card slots (Tu et al., 2019). The shelves vary in size, typically consisting of configurations that support eight or sixteen slots for different cards, depending on the requirements of the specific network application. As the slots have blank spots for additional cards, shelves are less prone to require additional units as the network grows. The materials used in the construction of the shelves are primarily stainless steel for the casing, supported by aluminium and copper which is also incorporated in the internal PCBs that offer electrical connectivity and support computing functions of the equipment.

4.1.4. Signal conversion equipment

The supporting cards which are housed in the shelves have different applications for transforming light particles within data transmission via optical fibre cables. Figure 4.2 shows an overview of the different equipment and their functionality within the network. The following paragraphs shows more in-depth technological properties.

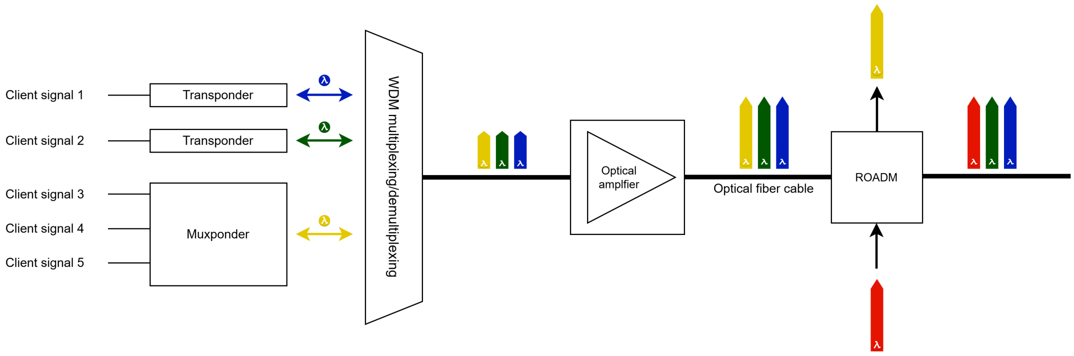


Figure 4.2: Optical signal conversion equipment

Transponders & muxponders

Transponders and muxponders are components in the optical transport network that enable the conversion of client data into the core network, facilitating long-range transmission. Transponders convert low-speed optical signals from clients into electrical signals and back into high-speed optical signals using WDM, a technique that assigns different wavelengths (λ), or light colours to different 'grey' data streams, allowing multiple optical channels to be transmitted simultaneously over a single optical fibre (Mukherjee et al., 2020). This enables the efficient use of the available bandwidth, increasing the overall capacity of the fibre network.

Muxponders, serve a similar function, as its a combination of a transponder and multiplexer, in which multiplexing translates to combining multiple client services into a single wavelength (Mukherjee et al., 2020), the difference can be seen in figure 4.2. This multiplexing increases the efficiency of the system by combining various lower-order signals into a higher-order signal, thereby improving the network's overall throughput. The data capacity of the equipment is characterized by the information rate arriving at the client side, for example, a 400 Gbps transponder can receive ten 40 Gbps signals or four 100 Gbps signals (Mukherjee et al., 2020). Consequently, if data traffic is projected to grow, both transponder and muxponders housed in the specified shelves should be increasingly deployed according to future needs.

ROADMs

Reconfigurable optical add/drop multiplexers (ROADM) are complementary to the WDM multiplexing utilized by the transponders and muxponders, whereas ROADMs are able to add or drop wavelengths and enables switching between multiple optical fibres (Garrich et al., 2015). The boards support the simplification of deploying advanced optical networks, although the installed base does not require comparable expansion of installation as the transponders/muxponders and amplifiers to support data growth.

4.1.5. Signal amplification equipment

Amplifiers

Amplifiers ensure the regeneration of signal power of the optical signals over long distances (Mukherjee et al., 2020). The inherent challenge in optical transmission is signal attenuation, where light signals weaken due to long distance transport, in which attenuation (in dB) increases linearly with distance (Rani et al., 2022). Amplifiers are strategically placed in two key areas within the network: as booster amplifiers at the initial stages of signal transmission, often before the ROADMs, and as in-line amplifiers (ILAs) at intervals along the transmission path to restore the signal strength. These amplifiers are designed to amplify the optical signal directly, without the need for converting it into an electrical signal first, thus maintaining efficiency of the optical transport.

The construction of amplifiers involves various materials, including stainless steel and aluminium, which make up a significant portion of the device's mass in the form of casing, although their criticality is considered insignificant according to the EU in 2023 (Grohol & Veeh, 2023). Instead, the core of the amplifying technology consist of erbium-doped fibre amplifiers (EDFAs), which contain small quantities of erbium ions that, when stimulated by incoming light, emit additional photons and thus amplify the signal on the C-band or the 1520 to 1565 nm wavelength range (Mukherjee et al., 2020). Besides erbium and casing material, other identified CRMs include bismuth, thulium, germanium, germanium, praseodymium and silicon metal as reported by Flik (2021) and adapted in table **??**. Expansion of the network capacity consequently requires additional amplifiers to ensure signal intensity.

4.1.6. Printed circuit board assemblies

The installed base of equipment within the optical transport network relies on PCBs for computing functionality. Data on the absolute mass of PCB assemblies can be found in the appendix, this resembles the aggregated components, although individual volumes of elements have to be determined. Since assembly design is function-dependent, some equipment requires substantial computing power, necessitating more complex PCBs while passive components may not require PCB assemblies at all.

Historical data on PCB waste indicates significant fluctuations, largely due to the rapid evolution of circuit board design. Current waste streams may still reflect circuit boards manufactured 10 to 20 years ago, making accurate assessments challenging. Additionally, determining the material content of newly manufactured PCBs and projecting the composition of future circuit boards remain difficult tasks. These challenges are further compounded by the emergence of new technologies, such as photonic integrated circuits (PICs), which may alter PCB material contents based on transmission of data via optics, instead of electrical signals, requiring indium phosphide compounds to detect light at wavelengths between 1310 and 1550 nm (Zhao et al., 2019). Furthermore, waste PCBs in electronic equipment shows trends in smaller mass contribution according to total product weight, with PCBs in professional IT equipment (UNU key 0307) decreasing from roughly 12% in 1995 to roughly 7% in 2015 (Wagner et al., 2021). Whereas Ueberschaar (2017) reports miniaturization trends in electronic components, with tantalum used in capacitors potentially decreasing for instance. Explorations of material intensity developments and its effect on CRM waste flows will be conducted in chapter 5 and 6.

4.2. CRM selection

4.2.1. Criticality assessment EU 2023

The selection of critical raw materials in the EU in 2023 is assessed based on the dimensions supply risk and economic importance, as seen in figure 4.3. The dimensions have been scored on a number of factors to determine the degree of risk and importance. With the risk of supply being calculated by a formula including input variables: global supply, EU domestic production, import reliance, end-of-life recycling input rate and the substitution index related to supply risk (Blengini, Blagoeva, et al., 2017). The substitution index is consequently derived from a combination of substitute production, substitute criticality and substitute co-production (Blengini, Blagoeva, et al., 2017), emphasizing the challenge of substitution as alternative materials could originate from previous EU criticality risk or possibly future additions.

Economic importance is determined by a multiplication of the share of end use of a material, the sector's value added and the substitution index of a raw material related to economic importance (Blengini, Blagoeva, et al., 2017), with share of end use of a raw material and value added being dependent on the corresponding sector based on NACE Rev. 2 classification. Thus economic importance could differ for the operations of telecom parties in the EU, depending on supplying manufacturing sectors. This classification will be taken into account in the discussion of criticality for the specific case study.

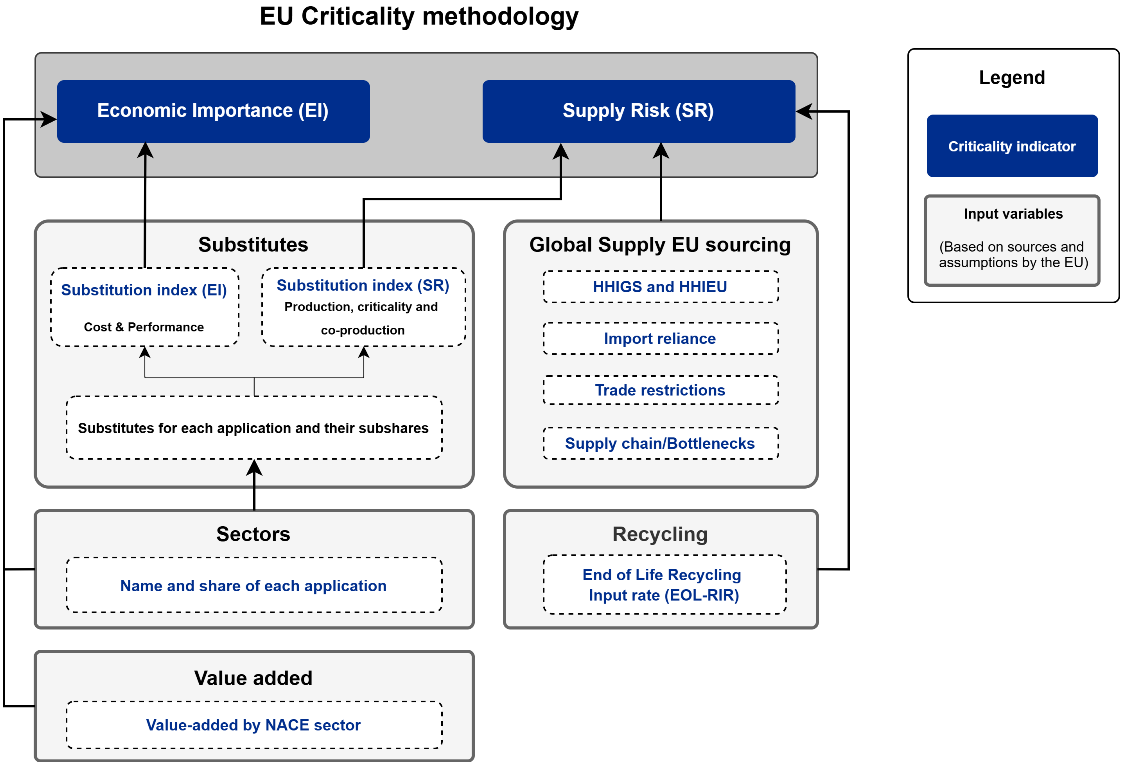


Figure 4.3: Criticality methodology EU (European Commission, 2017)

Drawing upon the input variables introduced above, the following economic importance and supply risk indicator results can be found for each critical raw material in figure 4.4 below. In which a material is classified as critical if the supply risk and economic importance indicators exceed a threshold of respectively 1.0 and 2.8. However, exceptions are in place for copper and nickel due to their classification as Strategic Raw Material (SRM), which serves as an additional category in the CRMA (Hool et al., 2023). As stated by Espinoza (2023), a material is considered as SRM if it essential for EU's future transition goals and strategic sectors, such as aerospace and defence. SRMs are distinguished by a high level of expected demand growth, difficulties in significant production increases and a low level of reserves in comparison to current production levels (Espinoza, 2023).

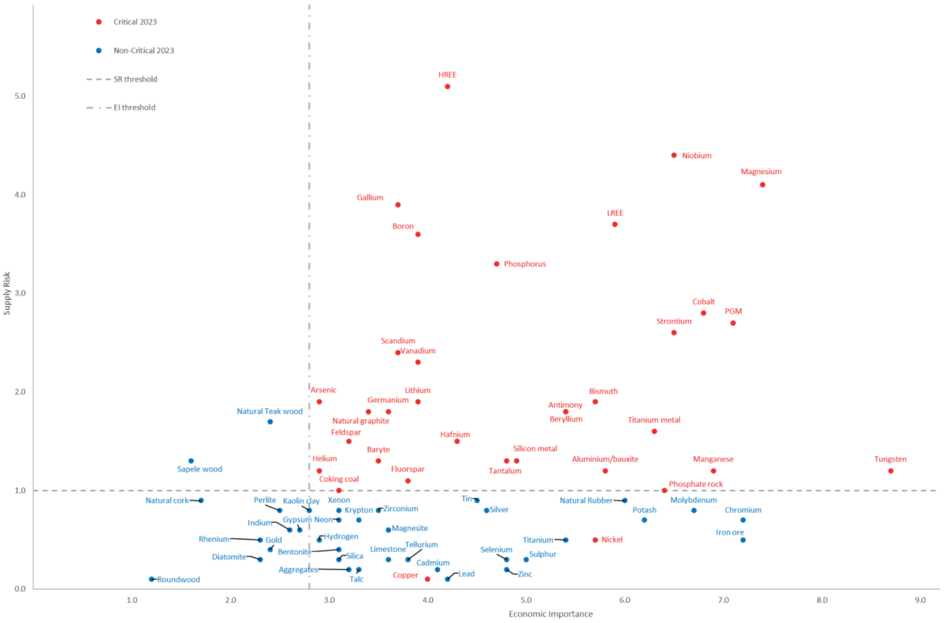


Figure 4.4: Results of the EU 2023 criticality assessment (Grohol & Veeh, 2023)

4.2.2. CRMs in printed circuit boards

Several studies have explored the identification of the material content of PCBs. Analysing the content of electronic waste consisting PCB assemblies shows significant differences in CRM composition, with the ProSUM project taking a timescope of 1995-2015 for its waste flows, resulting in values as seen in the appendix derived from Wagner et al. (2021). However, empirical data from the study conducted by Xia et al. (2024), using a timescope of 2009-2013, reported in the right column of the table in the appendix, concludes that PCBs consist of relative substantial amounts of silicon, whereas silicon is not present in the results of ProSUM project. Thus, PCB contents presents itself with difficulties in defining what the exact CRM composition is at a certain moment in time, with even higher uncertainties for emerging technologies in the near future.

Nonetheless, extraction of the material content of PCBs in transponders have been provided by the supplier. The aggregated list of CRMs embedded in PCBs within currently deployed OTN equipment consists of 14 raw materials obtained by internal research from the supplying firm (Supplier, 2025). These metals, minerals and ceramics are grouped in the table in the appendix. Whereas transformation to the element fraction of the compound, by excluding the bounded oxygen element mass, has been reported in the table in the appendix.

This transformation has been achieved by calculation of the element molar mass compared to the compound molar mass. For instance, silicon dioxide, which is characterized by high electric resistivity and is thus widely employed in the semiconductor industry, follows an oxidation chemical reaction of (Lin, 2008):

$$\mathrm{Si}_s + \mathrm{O}_2 = \mathrm{SiO}_s$$

Where:

- Si (molar mass of 28.0855 g/mol)
- O_2 (molar mass of $2 \cdot 15.999 = 31.998$ g/mol)

Resulting in an elemental fraction of Si from the total compound mass of :

$$100 \cdot \frac{28.0855}{(28.0855 + 31.998)} \approx 46.74\%$$

These grouped materials account for 0.63% of the total mass of the PCB, as most of the material consists of weight from the circuit board itself, with respectively 41.4% glass, 42.3% plastics and 14.5% copper and the remaining materials accounting for the passive components, including capacitors, resistors, inductors, oscillators and connectors (Supplier, 2025).

4.3. CRM overview

The identified critical raw materials can be seen in the periodic table of elements as illustrated in figure 4.5 below. Whereas silicon and bismuth are both identified in amplifiers besides PCBs found in transponders. At the second to last row at the bottom of the periodic table are the lanthanides, also characterized as the light and heavy rare earth elements within the EU (Hool et al., 2023). In which the light rare earth elements contained in amplifiers consists of praseodymium, with heavy rare earth elements contained in PCBs in transponders consisting of erbium, thulium and yttrium. These elements do not occur in their elemental metal form such as the other elements, but instead they are bound with a variety of host materials which have nearly identical ion sizes requiring selective and costly separation (Talan & Huang, 2022).

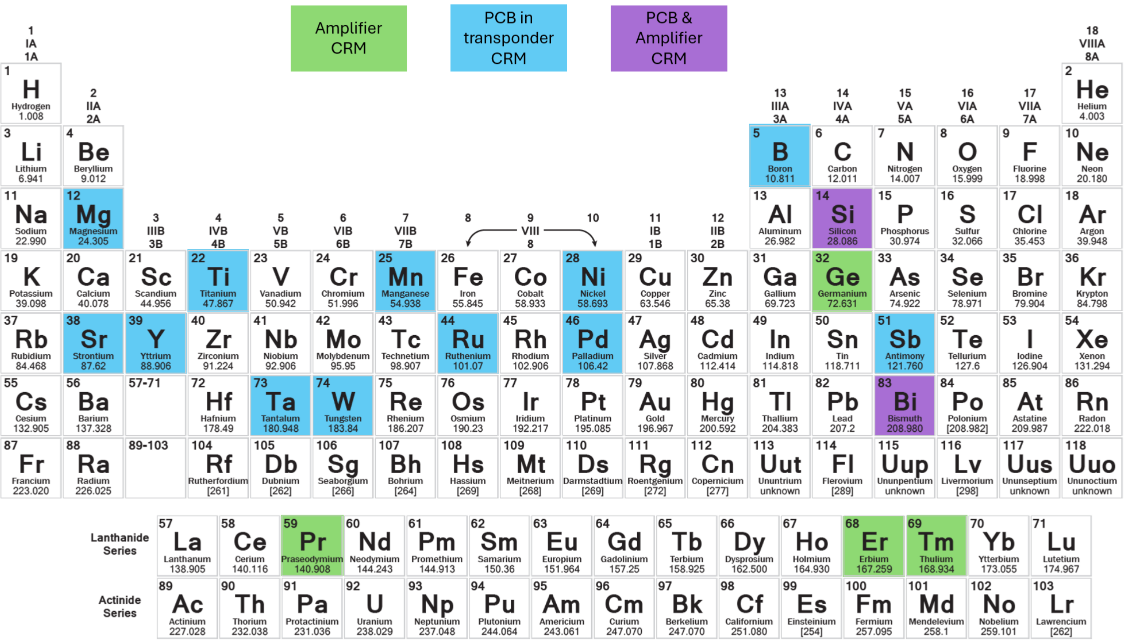


Figure 4.5: CRMs contained in transponders & amplifiers

4.3.1. Supply risk and mass percentage of CRMs in amplifiers

The following diagram 4.6, shows the relationship of the concentration of CRMs in amplifiers as identified in the appendix as opposed to the supply risk of materials in the EU in 2023 (Grohol & Veeh, 2023). This figure illustrates that silicon is the most abundant material found in amplifiers, consisting of more than x% of the total weight, whereas the other materials are present in magnitude between x% for germanium and x% for praseodymium. However, supplying risks show that silicon metal has the lowest supplying risk of the contained materials due to sourcing from France and Norway (Grohol & Veeh, 2023). While sourcing of HREEs: erbium and thulium is currently relying 100% on import (Grohol & Veeh, 2023), although their concentration comprises of approximately x%.

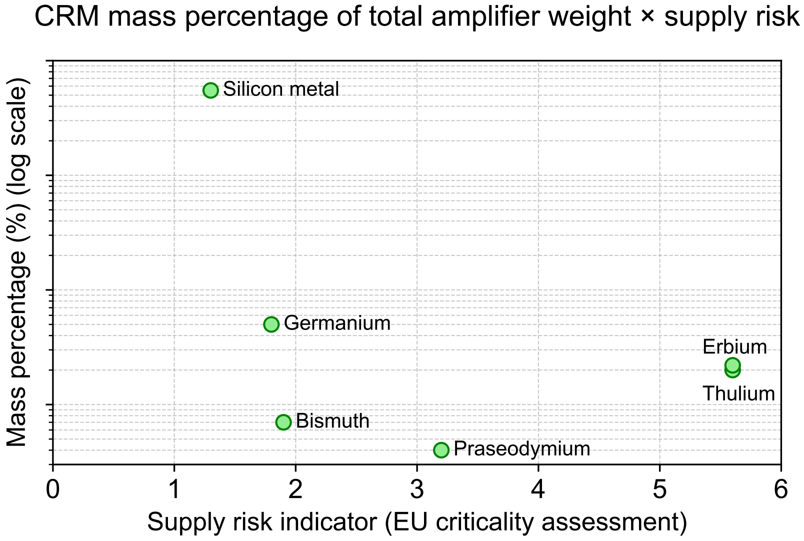


Figure 4.6: Supply risk and CRM mass percentage of total amplifier weight

4.3.2. Supply risk and mass percentage of CRMs in PCBs integrated in transponders

The concentration of CRMs in PCBs embedded in transponders are less abundant compared to the material content in amplifiers. As seen in figure 4.7 below, the highest concentrations can be found in silicon metal and nickel, with respective concentrations of approximately and x% and x%. However, supplying risks for these materials are relatively low compared to the other contained materials, with nickel and titanium situated underneath the supply risk threshold of 1.0 proposed by the EU (Grohol & Veeh, 2023). Whereas magnesium can be seen with the highest supply risk combined with a concentration in the upper half of the diagram, considering the scale of the graph, this amounts to roughly x% of the total mass of the PCB. The high supply risk of magnesium is due to an import reliance of 100%, combined with sourcing of primarily China (94%) and 1% from Israel (Grohol & Veeh, 2023). On the other hand, tungsten is present in the lowest concentration and has a relative minor supplying risk, with nickel and titanium only having lower supplying risks.

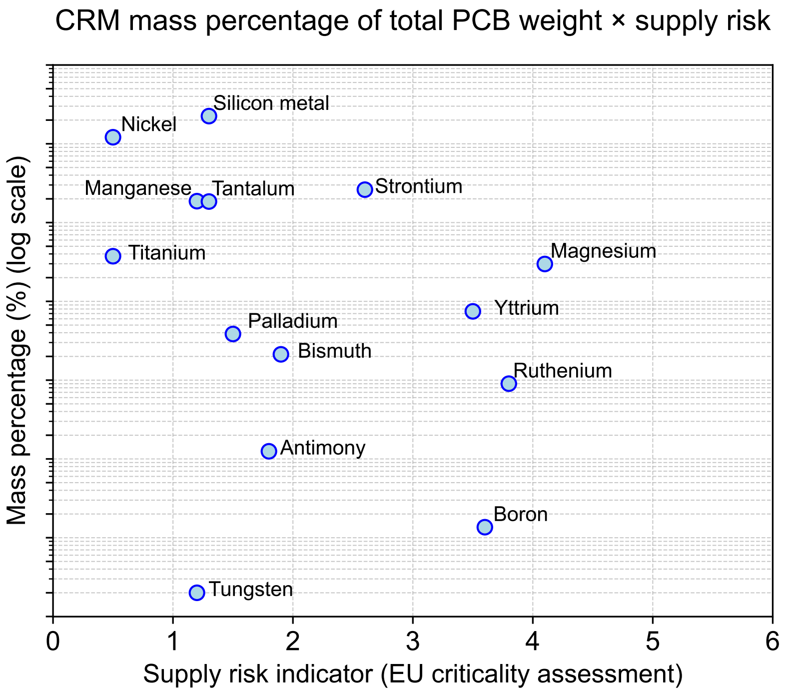


Figure 4.7: Supply risk and CRM mass percentage of total transponder PCB weight

5

Model methodology

The ensuing chapter starts with outlining the considerations for selecting the geographical and temporal scope of the model. In the following section, the chapter provides a more detailed elaboration on the parameters relevant within the system boundary as well as presenting the mathematical equations of how they are incorporated. Subsequently, four scenarios are introduced to address the uncertainties surrounding the future output of the model with a concluding remark on how links on the OTN are currently projected compared to the previous generation of equipment.

5.1. Build-up of model

5.1.1. Model geographical & temporal scope

For the modelling of the dynamic material flow analysis, the scope must be further defined. As mentioned in the research approach, the geographical scope is set in the Netherlands, as the equipment is implemented into the infrastructure within the Netherlands. While limiting the geographical scope to the Netherlands is also chosen due to data availability on the infrastructure of KPN. This scope indicates that feedback loops for reusing and recycling practices flows back into inflows of the equipment and material stock within the system boundary as can be seen in paragraph 5.1.2.

This specific process represents a step within the complete life cycle of the equipment, as seen in figure 5.1 below, metals generally follow a life cycle which subsequently consist of mining, raw material production, manufacturing, use and waste management. In this system, materials primarily flow from mining until end-of-life, with the main recycling flow coming from waste management back into raw material production. As dynamic MFA aims at addressing the accumulation of certain materials within a time frame of multiple years, the focus is set during the use phase of the equipment. This process step represents the accumulation of metals according to its lifetime whereas the other process steps such as manufacturing product does not build up stock over multiple years, instead showing a continuous flow with short periods in each transforming step. The timescope represents two generations of optical transport network, from the initial installation established in 2016, until an interval of 8 years from the start of the second generation of equipment installed in 2024. Enabling the analysis of two outflow patterns based on the respective generation of technology in the moment in time.

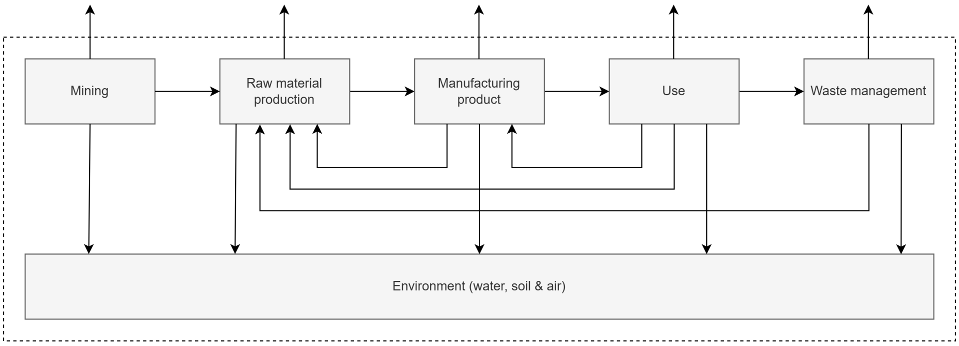


Figure 5.1: System overview of metal life cycle from extraction to end-of-life

5.1.2. Model system overview

An overview of all relevant variables affecting product and material stock accumulation can be seen in figure 5.2. Main output of the model outside the system boundary consists of the CRM criticality, by retrieving the exact primary demand of specific CRMs during the time frame of the model. Within the system, output is defined for two dimensions. With the main process consisting of inflows, stock-buildup and decommissioning at the end-of-life of optical transport equipment. Based on installed equipment at corresponding moments in time, CRM flows are deduced by multiplication with CRM intensity for each equipment type. Besides CRM intensity, flows at product and material level are influenced by multiple exogenous and intermediate variables characterized by the flows of information represented by the dashed arrows. The following paragraphs elaborate further on the exact considerations for the input parameters.

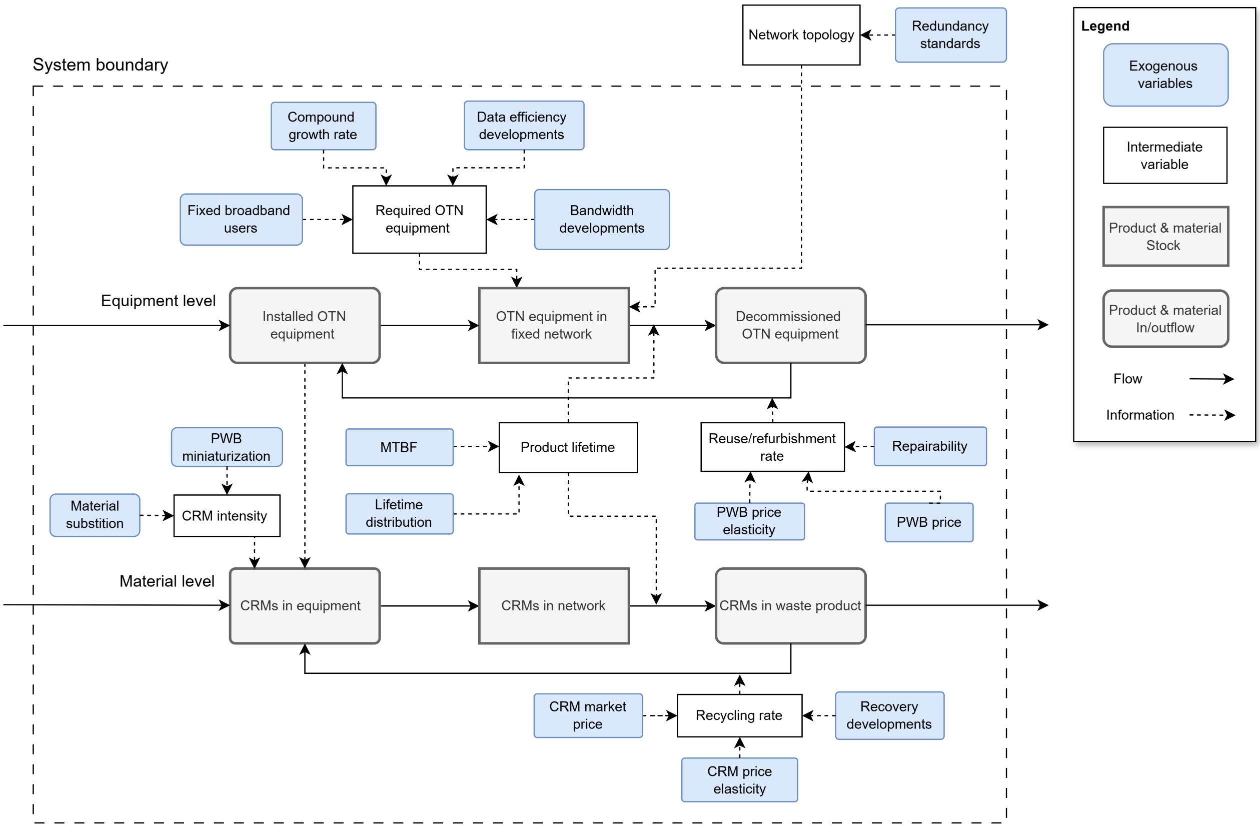


Figure 5.2: OTN Model system overview

5.1.3. Model variables

Product lifetime

Lifetime of network equipment is set at an average of 7 years according to (NTIA, 2024), with high dispersion of the life cycle depending on the function and layer of the network equipment. With a study from Ciscato and Fabbi (2016) making a distinction of the useful life time of core switching and routing products between 5 and 7 years. For software and active optic electronics, the expected life time seems to reach between 6 to 10 years, although Optical Passive Infrastructure consisting of fibres, cables and connectivity instruments has an expected life time of 50 years (FTTH Council Europe, 2020).

The useful life time of network equipment has been split into four determining factors: market innovation, vendor end-of-life policies, operating life and operating costs. With the operating life being related to the product's mean time between failures (MTBF), which is based on a curve predicting the level of failure in the product, and is designed to be greater than roughly 11 years (Ciscato & Fabbi, 2016). From the most recently installed equipment, MTBF data has been gathered for optical shelves, amplifiers, and ROADM equipment, except for transponder units. With data reported in the table in the appendix. Albeit life cycles in practice regularly do not meet the MTBF due to the impact of external factors, whereas empirical data from the last generation of OTN equipment installed from 2016 onwards as seen in the table in the appendix, showing failures and corresponding replacement patterns starting from 2022.

As such, considerations for the lifetime parameters have been made reflecting the expected lifetime between 6 and 10 years from (FTTH Council Europe, 2020) combined with empirical data on the timescope of failures from previous equipment. This is integrated in the model via shape parameter β reflecting the failure time (Müller et al., 2014). In which $\beta > 1$ represents increasing failure rate which is common in aging equipment such as optical equipment. With $\beta = 0$ simulating constant failure, or exponential distribution and $\beta < 0$ simulating decreasing failure rate over time, which corresponds least with the selected technology. The location parameter Γ values has no reported empirical data for optical equipment and is set at 0 for the model (Müller et al., 2014). Whereas scale parameter α, reflecting the tail and more frequent failures valued at roughly 7 years depending on the scenario (Müller et al., 2014).

To address the uncertainties of exact lifetimes, as the current equipment has only recently been installed, multiple setups for the lifetime distribution of the equipment will be used, further explained in paragraph 5.1.5 and visualised in figure 5.4.

Data traffic growth rate

The internet data bandwidth can be predicted using Nielsen's law. This law states that available bandwidth for high-end users grows 50% annually, with a regression line of 0.99 R^2, explaining 99% of variability of data (Adaramola et al., 2024). The bandwidth growth formula is modelled as:

$$B(t) = B_0 \times (\text{CAGR})^t$$

Where:

- $B(t)$ = Bandwidth at time t
- B_0 = Current bandwidth
- $CAGR$ = Compound annual growth rate

However, the compound annual growth rate presented with Nielsen's law is specified for a minority of high-end users in society, requiring empirically reported data for average data growth rate regarding consumers on the Dutch telecom market. With research conducted by Little et al. (2018) showing a more reserved outlook on data consumption forecast of average users by a compound annual growth rate of 1.21 for fixed data consumption in the Netherlands in GB/home/month.

Optical data bandwidth developments

Besides growth of data traffic, maximum data bandwidth across optical transmission networks have evolved non-linear as well, with each iteration enabling the transmission of higher bandwidths of data. Initially, capacity consisted of 10 Gbps, with advancements made towards 100 Gbps and eventually 400 Gbps (Sun et al., 2015). Current capacity developments surrounding photonics shows that 800 Gbps transferred across each link is possible, corresponding with respective ethernet growth rates amounting to 200 GbE, 400 GbE, 800 GbE and possibly 1,6 TbE in the future (Pedro et al., 2020). However, uncertainties surrounding doubling of capacity per iteration have to be taken into account when modelling for long term developments. For instance, advancements in computing power of integrated chips in PCBs is diminishing by its physical properties, as downscaling of transistors becomes increasingly difficult in addition with power dissipation, which requires proper heat management (Urhobo & Ugwuegbulam, 2024). Regarding the time scope of capacity switching from 400 to 800 Gbps, expectations for doubling the network capacity are set to be necessary from around 2033 onwards (Network architect, 2025).

Network topology

Telecom operators design the network with a certain topology, or nodal degree, to enhance connectivity between nodes. The topology consist of redundant links for each node to redirect data traffic via an alternative route during failures or fibre cuts (Personal Communication, 2025). This redundancy is integrated by connecting at least two pathways per (core) node. Thus, anticipating future network topology, the network must support these extra pathways and consequent additional equipment such as amplifiers and transponders. The current generation of the optical network connects each of the 4 core locations with each other via routes consisting of multiple links expected to grow depending on service needs. The projected growth of links can be found in the table in the appendix. However, in an optical network, there is a trade off consisting of minimizing bandwidth usage, by reducing wavelengths and consequent required equipment, competing with delay of data transmission, where shortest propagation routes are preferred although resulting in more equipment needed (Kavian et al., 2009). Thus, network design and corresponding mesh density could be greatly influenced by the prioritization of bandwidth usage or latency by the operator in the future.

Fixed broadband users

Coverage of fixed broadband connections within the Netherlands is expected to gradually reach its limits of 99.6% by 2030 for very high capacity network (VHCN) (European Commission, 2024b). VHCN coverage describe broadband networks capable of delivering at least 1 Gbps and in which coverage is based on different indicators, consisting of fibre to the premises (FTTP) and 5G connections, showing fixed and wireless data transmissions. The overall trend of VHCN connections shows that in 2022 already 97.8% is covered whereas the subset FTTP, or fibre connections to households, reflects a logistic curve of respectively 35.6% in 2020, 51.9% in 2021, 63.4% in 2022 and from 2023 onwards reaching the plateau from 97.8% to possibly 99.6% in 2030 (European Commission, 2024b). With 5G infrastructure already surpassing maximum coverage of 100 %in the Netherlands in 2023 (European Commission, 2024b). As FTTP and 5G connections are a subset of the VHCN coverage, FTTP and 5G coverage are excluded from calculating total fixed broadband users as it would induce double counting.

Consequently, taking VHCN, and indirectly FTTP and 5G into account, the effect of total connections on required equipment installations is expectedly less significant than the data traffic progression, as connectivity has almost reached the plateau. Exact data surrounding VHCN and FTTP coverage can be found in the table in the appendix.

Reuse/refurbishment rate
Taking the system boundary into account, reuse and refurbishing of equipment is only relevant if the equipment is redeployed within their own OTN infrastructure of the telecom operator. If equipment were to be sold via a secondary party in a foreign country, embedded CRMs will be lost within the system. Currently, reuse of 'older' generations of photonic equipment is not integrated on a large scale. However, refurbishing of products shows potential for products used in other categories, since lifetime in many electronics extends beyond end use period, although it is replaced based on added performance or functionality of newer iterations.

Refurbishing of the equipment in turn is affected by the exogenous variables 'repairability' and 'PCB price', whereas repairability describes design principles of the equipment, if manufacturers designed the product to be modular and in more detail if individual components on PCBs can be repaired or replaced if necessary. The PCB price affects reuse, as it serves an integral purpose within the OTN equipment and lower pricing decreases incentive to refurbish or reuse older equipment to a state where the equipment can be re-deployed. The PCB price depends on the elasticity of demand change as a result of price changes, with elasticity values > 1 corresponding to increasing reuse rates of PCBs as demand decreases by a higher percentage change than price growth. The formula for price elasticity, modified for PCBs is stated as:

$$\varepsilon = \frac{\text{\% change in recovery rate}}{\text{\% change in PCB price}} = \frac{\Delta R/R}{\Delta P/P}$$

Where:

- ε = price elasticity
- ΔR = Recovery change
- R = Current recovery
- ΔP = Price change
- P = Current price

Currently there is a lack of data on refurbishing and reuse practices, as well as price elasticity for future flows, this sensitivity will be tested using multiple scenario's, introduced in paragraph 5.1.5.

CRM intensity
The CRM intensity describes the composition of CRMs related to the specific equipment used in the OTN. Regarding amplifying equipment, total erbium inflows can be calculated by multiplying the aggregated amplifier inflows with the erbium density within the product. Besides product-specific CRMs such as erbium, almost all optical equipment consist of printed circuit board assemblies with variations of components such as capacitors and layers. Using available dimensions of the assemblies, CRM intensity of PCBs can be calculated. Within this variable, changes for CRM intensity can occur based on trends in PCB miniaturization of components implemented in the PCBs.

Recycling rate
Recycling rates differ for each element. With increasing yields based on recycling developments. However, recycling in practice is not only dependent on the technological capabilities to retrieve elements from end products. As reported in the study of CRMs in PCBs (time scope from 2009 to 2013) by Xia et al. (2024), market prices affect the frequency of metals worth retrieving. With precious metals gold and silver and PGMs: platinum and palladium, positioned at the high end of the Sherwood plot as seen in figure 5.3 below. Indicating that only materials above the curve are of interest for recyclers, excluding bulk materials with lower prices or low mass combined with high prices. However, recycling is further

limited due to miniaturization trends as seen in PCBs for tantalum for instance (Ueberschaar, 2017), showing a misalignment between manufacturer and recycler interest.

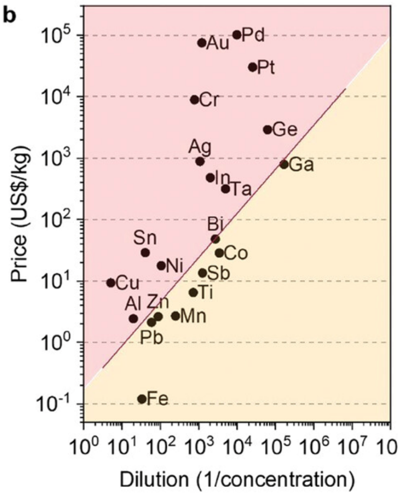


Figure 5.3: Sherwood plot (Xia et al., 2024)

Recycling of CRMs embedded in the OTN equipment also comes with difficulties surrounding circularity of inflow and outflow, as there could be a disparity of where manufacturers import raw materials and where recovered materials from the equipment end up on, especially taking illegal retail markets for raw materials into account. For simplicity, the model uses an 'ideal' recycling loop of material outflow into inflow, complementary to the primary inflow of materials. With estimations on recycling potential of PCBs being set at 22% by the equipment manufacturer (Supplier, 2025). With additional comments on the possibility of recycling yield to be higher, especially for bulk materials embedded in the casing, so for steel and aluminium as reported in chapter 5. However, the denser and finely scaled the elements in PCBs are, the more effort is required challenging future recycling yields if costs outgrows revenue of recovery for waste processing organisations.

The price effect of CRMs on the recycling rate is also dependent on the elasticity of demand change as a result of increasing or decreasing price, whereas empirical studies have shown that steel and aluminium elasticity is reported at -0.2, indicating that increasing the metal price with 10% leads to a demand reduction of 2% (Söderholm & Ekvall, 2020), opening possibilities for secondary supply. Recycling potential of individual CRMs for baseline values have been extracted from the study on critical raw materials for the EU (Grohol & Veeh, 2023) and reported in table **??**. With current legal obligations not focusing on the recovery of CRMs, although the proposed CRM Regulation will be aimed at collective governing of CRMs, possibly increasing recovery yield (Turunen & Suikkanen, 2024).

5.1.4. Intermediate variables calculation

The variables described above consist of intermediate and exogenous variables, with intermediate variables depending on the input of the exogenous variables. These exogenous variables will be varied according to each scenario, described in paragraph 5.1.5. The intermediate variables are calculated based on the following formulas:

Required OTN equipment

The required OTN equipment based on the minimum data bandwidth in scenario s and year t is defined as:

$$\text{OTN demand}_{t,s} = \frac{\text{VHCN}_{t,s} \cdot (1 - E^{s}_{\text{data},t}) \cdot B_{t,s}}{\text{Bandwidth dev}_{t}}$$

Where:

- OTN demand$_{t,s}$: OTN demand (#) in scenario s at year t
- VHCN$_t$: Very high connection coverage (%)
- $E^s_{\text{data},t}$: Scenario-dependent data efficiency factor (baseline = 0, improved scenarios > 0)
- B$_{t,s}$: Scenario-dependent data traffic growth (Gbps) in scenario s at year t
- Bandwidth dev$_{t,s}$: Bandwidth development (Gbps) at year t

Critical Raw Material (CRM) Intensity

CRM intensity per unit in scenario s at year t is:

$$\text{CRM}_{\text{intensity},t,s} = \text{PCB}_{\text{assembly}} \cdot \text{CRM}_{\text{base intensity}} \cdot f^s_{\text{miniaturization},t}$$

Where:

- CRM$_{\text{base intensity}}$: Baseline CRM intensity (kg CRM/ kg PCB)
- PCB$_{\text{assembly}}$: PCB assembly mass (kg/unit)
- $f^s_{\text{miniaturization},t}$: Scenario factor (BAU = 1.0, improvement < 1, decline > 1)

Reuse and Refurbishment Rate

Reuse and refurbishment rate for scenario s at year t is:

$$R_{\text{reuse},t,s} = R^{\text{BAU}}_{\text{reuse},t} \cdot f^s_{\text{repairability},t} \cdot \left(f^s_{\text{PCB-price},t}\right)^{\varepsilon^s_{PCB,t}}$$

Where:

- $R^{\text{BAU}}_{\text{reuse},t}$: Baseline reuse/refurbishment rate (0.15)
- $f^s_{\text{repairability},t}$: Scenario factor for repairability (BAU = 1.0, easier repairs > 1, harder repairs < 1)
- $f^s_{\text{PCB-price},t}$: Scenario factor representing the influence of PCB price (BAU = 1.0, higher price > 1, lower price < 1)
- $\varepsilon^s_{\text{PCB},t}$: PCB price elasticity (BAU = 1.0, highly responsive > 1, weak response < 1)

Recycling Rate

CRM recycling rate in scenario s at year t is given by:

$$R_{\text{recycling},t,s} = R^{\text{BAU}}_{\text{recycling},t} \cdot f^s_{\text{recovery-developments},t} \cdot \left(f^s_{\text{CRM-market-price},t}\right)^{\varepsilon^s_{CRM,t}}$$

Where:

- $R^{\text{BAU}}_{\text{recycling},t}$: Baseline recycling rate (according to CRM derived from the table in the appendix)
- $f^s_{\text{CRM-market-price},t}$: Scenario factor due to CRM market price (BAU = 1.0, higher market price > 1)
- $f^s_{\text{recovery-developments},t}$: Scenario factor due to recovery technology (BAU = 1.0, better technology > 1)
- $\varepsilon^s_{\text{CRM},t}$: CRM price elasticity (BAU = 1.0, highly responsive > 1, weak response < 1)

5.1.5. Variable parameter scenarios

As mentioned in previous paragraphs on exogenous variables, parameters for several variables is lacking or possibly developing dynamically in the future in terms of technological, political or economic shifts. Considering the dynamic characteristics of the variables, the following scenarios are introduced to test the sensitivity of results based on the following varying parameters:

Business as usual (BAU)

The BAU scenario describes the development of OTN stock based on current empirical data. On the equipment level of the model, this scenario reflects similar trends of the previous generation of OTN equipment, with most failures appearing after 8 years of using the equipment. Refurbishing of the equipment is selected at a baseline of 15% of the total outflow during the timescope, supported through periodic maintenance. In terms of recycling yields, recycling practices employ the same technology as current recovery through a combination of pyrometallurgy and hydrometallurgy. In which pyrometallurgy utilizes high temperatures up to 1200 degrees Celsius for precious metals, whereas hydrometallurgy uses a chemical solution to recover the other metals from PCBs (Tolusso et al., 2024). The subsequent recycling rates are shown in the table in the appendix. In terms of CRM intensity, density of materials within PCBs is stable, using the reported material content as described in the table in the appendix

High AI-driven data growth

The data growth scenario, driven by increased integration of artificial intelligence in the Dutch society, mainly differentiates itself from the BAU scenario by requiring significantly higher amounts of data bandwidth transport on the OTN. As described by (Carrara et al., 2023), 'big data' is becoming mainstream, with industrial change fuelled by data-driven technologies such as AI, but also including advanced robotics and Internet of things. At equipment level, this is integrated by varying the compound annual growth rate of data traffic upwards, in terms of data efficiency and bandwidth development, capacity increase is conducted in the same order from 400 to 800 GBps while data efficiency measures are not present, as it is not the prioritization of developing the economy. While reuse/refurbishing rates will stay low due to replacement of decommissioned equipment with state of the art equipment capable of the highest performance and capacity. From a material level, CRM intensity will be driven by substituting new elements needed for next-generation computing to enable high performance of OTN equipment, such as indium phosphide present in photonic integrated chips (Zhao et al., 2019). Lifetimes are shortened with more failures at an earlier stage due to increased wear through maximization of the existing capacity on the net. With reduced PCB prices as the scenario comes with rapid innovation steps for PCBs, making outflowing and older PCB assemblies less attractive to reuse compared to buying new assemblies. CRM market price as well as price elasticity are reduced due to respectively increased extraction leading to lower prices and less responsive elasticity as the primary goal is satisfying AI implementation expansion.

Sustainable and circular economy

The sustainable and circular economy scenario is classified as a timeline with an emphasis on minimizing the environmental impact of the equipment, as well as driving circular economy practices to reduce dependency of certain CRMs identified with a high supply risk by the EU. This is driven by a lower compound annual growth rate, as end-users are shaving down on their data use as well as increased data efficiency through caching of data packets at regional locations. In terms of CRM intensity, this scenario introduces regulations from EU level that minimizes additional use of CRMs in electronics developed within the EU, while requiring manufacturers to expand the digital product passports. The product lifetime is extended to an extra two years and designed to fail at later moments compared to the baseline. Regarding reusing and recycling, this scenario is characterized by higher responsiveness to price changes, making recycling and reusing more viable options compared to using primary materials for manufacturing. Furthermore, recovery developments are highly affected and subsidized by the EU to increase the recycling yield and making steps to reach the 25% recycling goal set within the critical raw materials act of the EU (Hool et al., 2023).

Technology & innovation breakthrough

The last scenario emphasizes breakthrough in innovation and technology, characterized by a higher growth rate of data to meet the low latency and high throughput required in an increasing IT based economy. Upgrade cycles of equipment is slightly shorter than BAU scenarios to support implementation of the latest and up to standard iteration of OTN equipment in its infrastructure, integrated through shorter lifetime distributions. Regarding the material intensity of the equipment, this scenario is defined by a decreased footprint of overall material requirements, due to more efficient material use. While reuse/refurbishing within the system boundary is slightly decreased, as a result of a lower PCB price elasticity, since newer technology requirements generally outweigh price increase effects. Similar trends of pricing effects of equipments can be seen in the material market pricing and price elasticity as with AI driven data growth, in which extraction of primary material is motived with minimal rebound effects of demand through price increases. Although recovery developments are stimulated with innovating technology, reducing energy requirements to separate materials in waste streams.

Parameter changes according to scenario

The scenarios described above are integrated into variables variations in the form of scenario factors as seen in table 5.1 below. The values are relative to the business as usual scenario which serves as baseline model setup. With exact (growth) rates and annual data points, such as fixed broadband user shares per year, reported in the appendix. Regarding fixed broadband users, the factors are 1.0 for each scenario, since fixed broadband users shows stable progression with little deviation according to the table in the appendix . Whereas the parameter redundancy standards is excluded from the system boundary.

Table 5.1: Parameter changes relative to BAU scenario

Model variables		$f^{scenario}$			
Intermediate variable	**Exogenous parameter**	**BAU**	**AI driven growth**	**Sustainable & circular**	**Tech & innovation**
Required OTN equipment	Fixed Broadband users	1.0	1.0	1.0	1.0
	Data efficiency	0.0	0.0	0.1	0.2
	Bandwidth dev.	1.0	1.0	1.0	1.0
	CAGR	1.21	1.25	1.21	1.23
CRM intensity	PCB miniaturization	1.0	1.05	0.95	0.97
Product lifetime	Weibull shape	2.0	1.8	2.5	2.0
	Weibull scale	7.0	6.0	9.0	6.0
Reuse rate	Repairability	1.0	1.0	1.2	1.0
	PCB price	1.0	0.9	1.05	1.0
	PCB price elasticity	1.0	1.0	1.1	0.9
Recycling rate	CRM market price	1.0	0.9	1.05	0.95
	Recovery dev.	1.0	1.1	1.25	1.1
	CRM price elasticity	1.0	0.95	1.1	0.9

Lifetime distributions

The different product lifetime parameters as presented in table 5.1, when integrated into the weibull distribution results in the following survival probability curves of figure 5.4 below. The graph shows the chance of survival in time that the equipment is functional, in which survival chance diminishes the longer it is operational. With the scale parameter accounting for lifetime and the shape adjusting to earlier or later failures as described in paragraph 5.1.3. The curves reflect the effects simulated with the scenarios, since the sustainable and circular economy is shifted to the right as a result of the extended scale, with a decreased steepness of the drop according to the increased shape. Whereas the technology and innovation scenario is shifted to the left of the BAU scenario, producing earlier failures through the reduced scale, and shape for the AI-driven growth, generating shorter throughput out of the installed stock.

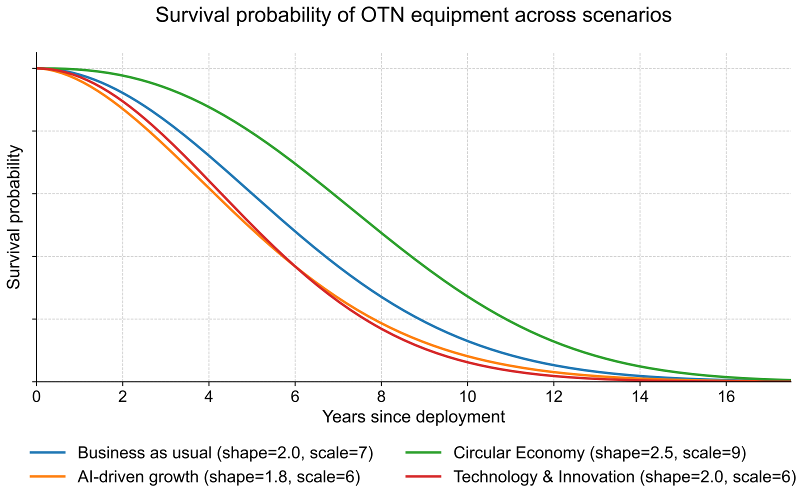
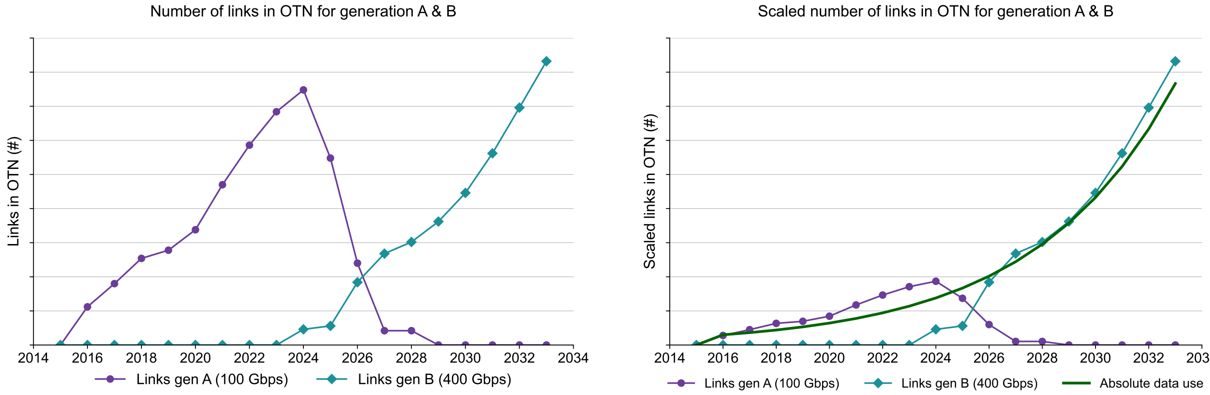


Figure 5.4: Survival probability curves

5.2. Current OTN link forecast

Based on personal communication with the optical network architect (2025), projections could be made on the number of links within the optical transport network supporting data transmission between the core locations. The number of links is a derivative of the network capacity, supporting the traffic of client channels from core location A to B and vice versa. As described in paragraph 5.1.3, the capacity on these links in the previous generation was equal to 100 Gbps per link, with advancements made toward 400 and possible 800 Gbps in the future (Optical network architect, 2025). Calculating the total physical number of links based on internal desk research shows a linear graph rising from 2016 until 2024, with a full replacement of the equipment with the second generation of OTN equipment as seen in figure 5.5a below. When multiplying the number of links according to the capacity of each generation, figure 5.5b reflects generation B with a bandwidth of 400 Gbps compared to 100 Gbps from generation A, while taking the absolute data use into account. The absolute data use prediction is based on the compound growth rate of 1.21 with a 'current' bandwidth value (60 Gbps) starting from 2016 to approximate link forecasting as closely as possible with the compound annual growth rate.

Although, the forecasts made for the number of links should be regarded with its limitations due to isolating data use growth as the only decisive factor. As direct transformation of the links disregards maintenance and failures due to lifetime characteristics of the equipment. Figure 5.5 can, however, be regarded as a starting point of the trend of OTN capacity growth correlated with data traffic growth. With a general linear growth of amplifying equipment and transponders of roughly 0.5 compared to the number of links in between the locations (Optical network architect, 2025).



(a) Number of links on OTN

(b) Scaled link capacity on OTN compared to data growth

Figure 5.5: Physical links on OTN network and scaled links compared to growth rate data traffic

6

Primary CRM demand development for amplifiers & transponders

The following sections describe the results for critical raw material development in amplifier and transponders from generation B equipment, in which the capacity of the equipment transitions from 400 to 800 Gbps from 2033 onwards. Subsequently, outputs are evaluated according to the selected scenarios and further tested on their uncertainties through a sensitivity analysis.

6.1. Results amplifier model

6.1.1. Amplifier demand development

Amplifier demand shows similar growth to transponder equipment, as it is driven by the same annual data growth, as seen for each scenario in figure 6.1. Differences can however be seen within the early years of installation, as amplifiers initially are installed at x units, compared to the initial number of transponders installed in the optical transport network which currently holds x units. When extrapolating the data to 2033, internal research has projected that the required equipment reaches around x optical amplifiers compared to x optical transponders. Stating that while the current installed base of amplifying equipment is higher, the demand curves converge and stabilize between 2024 and 2033 after which they increase by the same annual rate due to the equation of 'OTN demand' as introduced in paragraph 5.1.4 reflecting the demand growth. During this period, the plateau is forced due to doubling of capacity, resulting in halving of the per unit demand, before increasing when data growth catches up. Suggesting that with the the CAGR of each scenario, equipment demand could be met with capacity increase from 400 to 800 Gbps until around 2038 after which demand grows non-linearly.

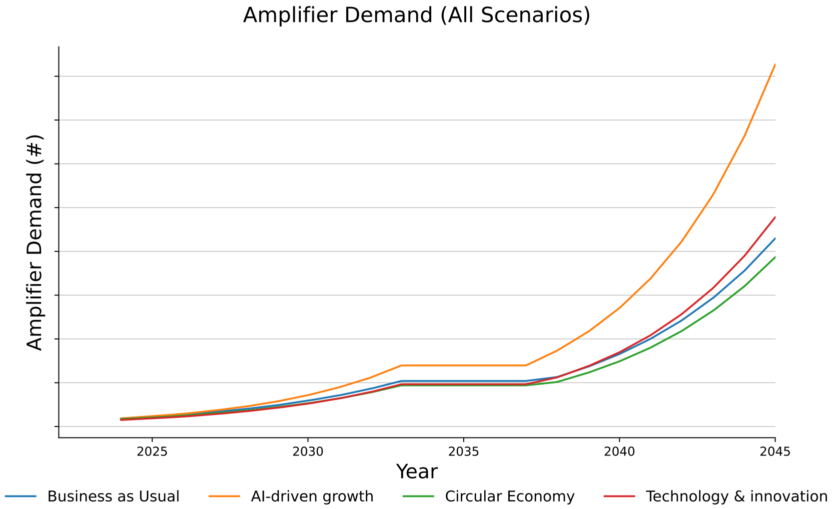


Figure 6.1: Amplifier demand development

6.2. Reuse rate for amplifiers

Calculating the circular use rate of amplifiers, according to the equation as noted in the appendix. Results in the share of reused equipment according to the point in time as seen in figure 6.2 below, using a baseline reuse rate of x. Most noticeably, the base reuse rate of x is only reached during the equilibrium between 2033 and 2038 when the stock is maintained at the same level for the technology & innovation and Business as Usual scenarios. With Circular Economy showing most fluctuations through higher factors surrounding repairability combined with PCB price and elasticity. Its delaying effect shows the increased shape and scale parameters of the lifetime distribution, delaying the reusable outflow. With overall reuse strategy being the most effective during stable stock periods, with rising demand of equipment resulting higher primary material use for each upcoming year of inflow.

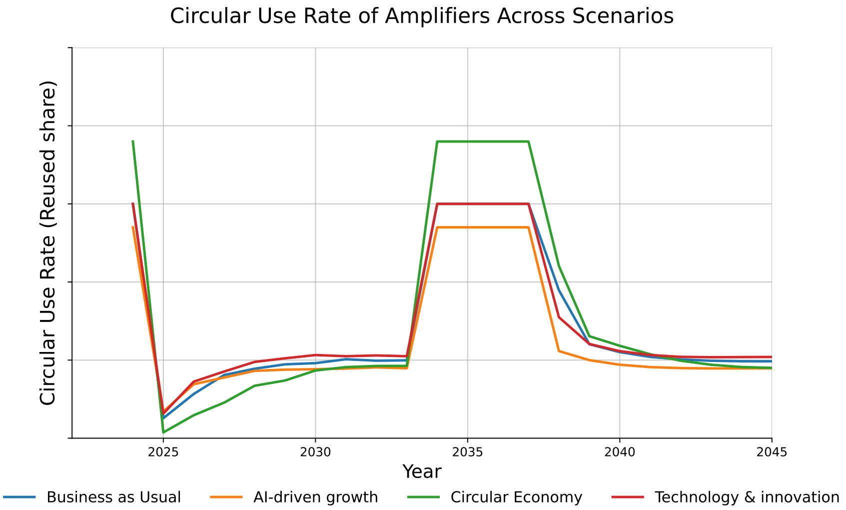
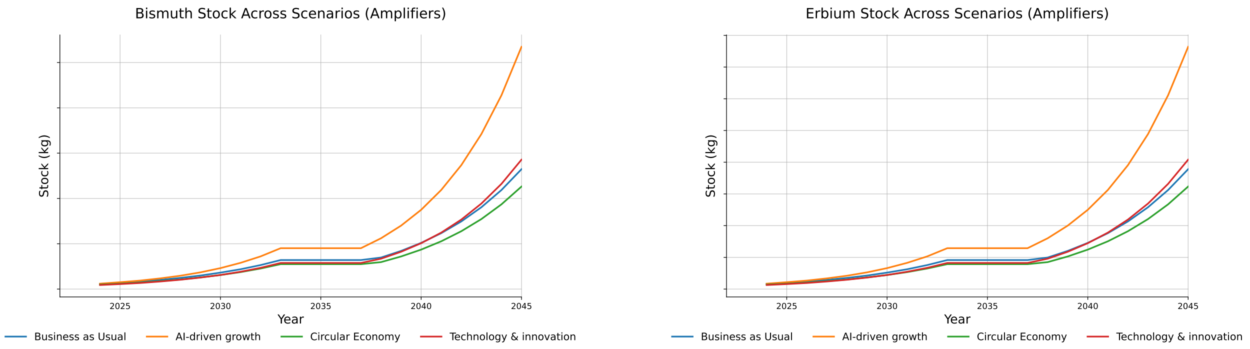


Figure 6.2: Circular use rate of amplifiers

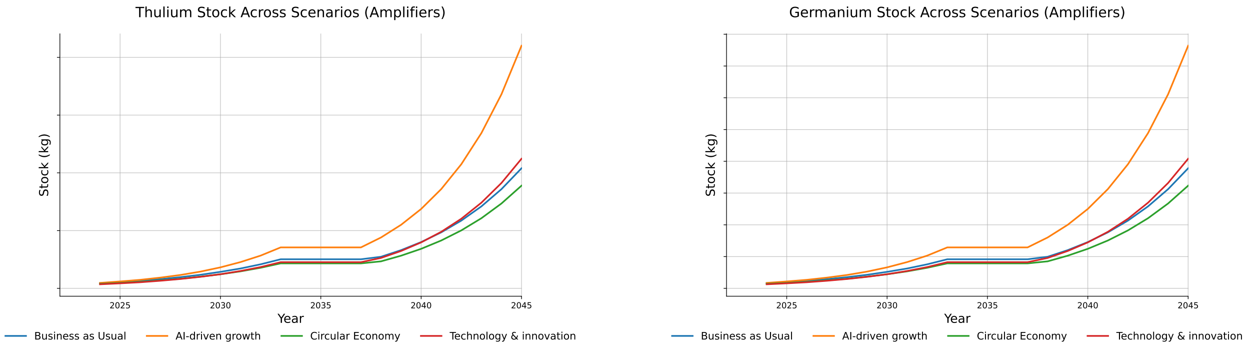
6.2.1. CRMs in amplifier development

Consequent CRMs embedded in the amplifying equipment, based on the reported mass from the table in the appendix, results in the following stock development curves as seen beneath in figure 6.3. Whereas significant accumulation of silicon stock is projected in figure 6.3f, having a bandwidth between x kg accumulated for a circular economy scenario up to x kg for the high data growth driven by AI demand scenario. In which the other material contents are less abundant in their presence in the overall stock. Praseodymium results in a total stock in the order of around x kg in a circular economy scenario compared to roughly x kg within the AI-driven growth scenario. With diverging stocks behaving this way based on the different annual data growth rates in addition to different material intensity rates for each scenario, in which AI driven growth has both a high CAGR (1.25) and higher CRM intensity rate (1.05). While the technology and innovation scenario has a higher CAGR (1.23) than the business as usual scenario, but material content is reduced with (x%). Cumulative primary demand of each CRM in 2045 is reported in the appendix, showing the difference between the scenarios for primary demand according to the total stock. In which the total primary demand exceeds the required stock for each scenario, albeit with different ranges.



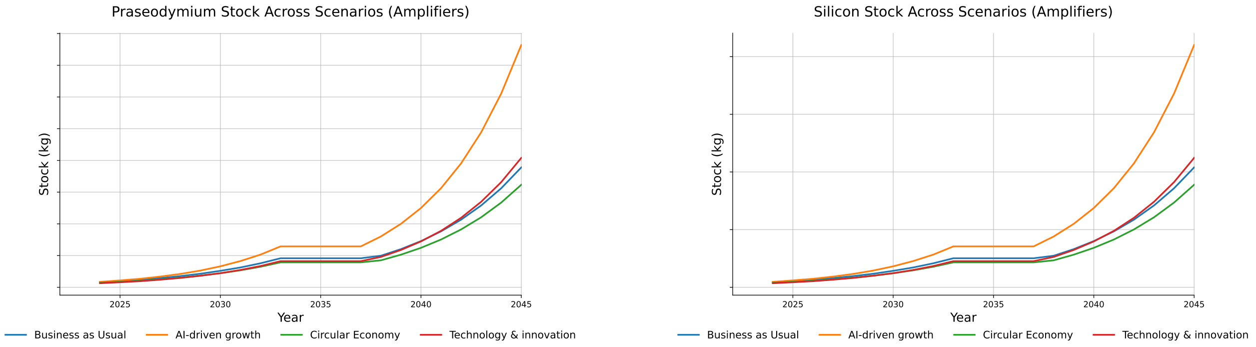
(a) Bismuth stock development

(b) Erbium stock development



(c) Thulium stock development

(d) Germanium stock development



(e) Praseodymium stock development

(f) Silicon stock development

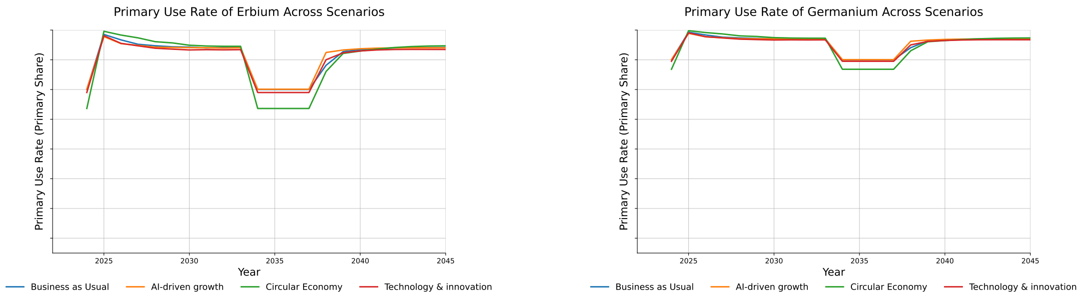
Figure 6.3: CRM stock development across scenarios for amplifier equipment

6.2.2. Primary use rate of CRMs in amplifiers

As a result of integrating a reuse baseline of x% and recycling input rates provided in the table in the appendix, the following plots in figure 6.4 as seen below, show the primary CRM demand rate for each year. So the annual inflow rate of novel material as a share compared to the total annual inflow rate, using the corresponding recycling rate of each CRM. Silicon and bismuth are excluded as they have a recycling rate of 0%, with respective primary inflow rates resulting in 100% during the complete modelling period.

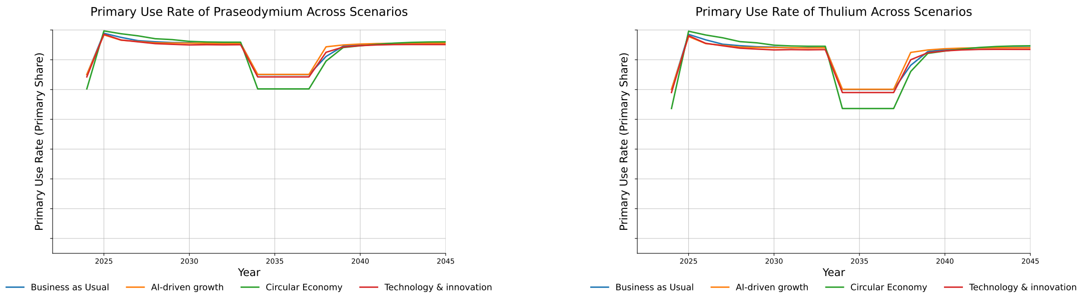
The results show that as a result of low recycling rates, primary material inflow is above x% for each scenario and for each identified CRM, with only a slight decrease during the stable stock when equipment capacity is increased from 400 Gbps to 800 Gbps. This is a result of the sudden inflow stop in 2033, while outflow continues arriving at the end of life time and produces recycle inflows. Whereas the initial jump from 2024 to 2025 reflects the installed base starting at a non-zero value, requiring 100% primary CRM inflow with no outflow available.

Between the scenarios, circular economy recovery improvements show higher yields and consequently reduced primary material use during the plateau period. Conversely the stock expansion periods between 2024 and 2033, and from approximately 2039 onwards, demonstrate comparable or higher primary use rates in comparison to the other scenarios. Indicating that primary use may be slightly reduced by lifetime-extending measures. As seen for the circular economy scenario, characterised by Weibull parameters at a scale of 9, combined with a shape of 2.5. Suggesting that the probability of a product reaching the outflow stream is subject to delay, necessitating the inflow of primary material in the early years of the model.



(a) Primary use rate of Erbium

(b) Primary use rate of Germanium



(c) Primary use rate of Praseodymium

(d) Primary use rate of Thulium

Figure 6.4: Primary use rate of CRMs in amplifiers

In addition to the primary use rate representing the share of primary material inflow, the accumulated total primary demand compared to the final year stock is reported in the appendix. Showing similar trends between the identified CRMs, with a broad range between the total primary demand from the outlying scenarios. For instance, silicon has a total primary material demand of x kg in terms of the sustainable and circular economy scenario, whereas the high output scenario for AI-driven growth results in total primary material demand of x in 2045. Moreover, the gap between the final year stock and the total primary demand reflects the efficiency of the scenario setup. With AI-driven growth showing the relatively largest gap between stock and the required primary material demand, whereas the sustainable and circular economy scenario results in a stock and primary material demand with the smallest difference.

6.2.3. Primary CRM demand growth in amplifiers

The results above shows the material flows at each point in time, however, if the primary material demand is aggregated over multiple years, the following total primary CRM demands can be seen for 2030 and 2045 in table 6.1. The results also show the growth factor between 2030 and 2045, in which each CRM seems to have similar growth rates of roughly 14.2 for the AI driven data growth scenario and a lower bound of around 9.3 for the circular and sustainable scenario.

Table 6.1: Cumulative CRM primary demand in amplifiers in 2030 and 2045, with growth factors (GF) for high (AI driven) and low (Circular Economy) demand scenarios

	High demand scenario			**Low demand scenario**		
CRM	AI 2030 (kg)	AI 2045 (kg)	AI GF	CE 2030 (kg)	CE 2045 (kg)	CE GF
Erbium			14.2			9.36
Bismuth			14.2			9.33
Thulium			14.2			9.36
Germanium			14.2			9.35
Praseodymium			14.2			9.35
Silicon			14.2			9.33

6.3. Results transponder model

In essence, the transponder model is an equivalent of the amplifier model, with consequent stock and flow trends following the same pattern. With the main difference regarding the calculation of the material content of the equipment, whereas the material content of the amplifier was determined of the complete product, transponder material content could only be deduced from the PCB content. Resulting in an extra transforming multiplication of the PCB mass with the element fraction in the PCB. Furthermore, the different CRMs embedded in the PCBs consist of a variety of recycling input rates as reported in the table in the appendix, affecting the in- and outflows of the elements.

6.3.1. Annual stock cohort development transponders

In order to comprehend the evolution of the transponder stock, it is interesting to look at the classification of the cohorts in each year. The cohorts describe the inflow in a given year, where the life expectancy of the cohort around the average life expectancy according to the Weibull distribution starts to flow out around 7 years for the business as usual scenario. The width of the cohort signifies the inflow quantity, which becomes progressively narrower over time to illustrate the residual value. As demonstrated in figure 6.5, from 2036 onward, the inflow from the initial cohort becomes negligible, necessitating the light green inflow to maintain the stock at a constant level. Given the substantial growth required from 2040 onwards, the cohorts become progressively wider at the initial moment they flow into the system to meet demand requirements. Indicating that high growth periods, especially after 2040, increasingly relies on primary inflows rather than older existing stock from previous cohorts. Thus limiting the effect of reuse and recycling measures.

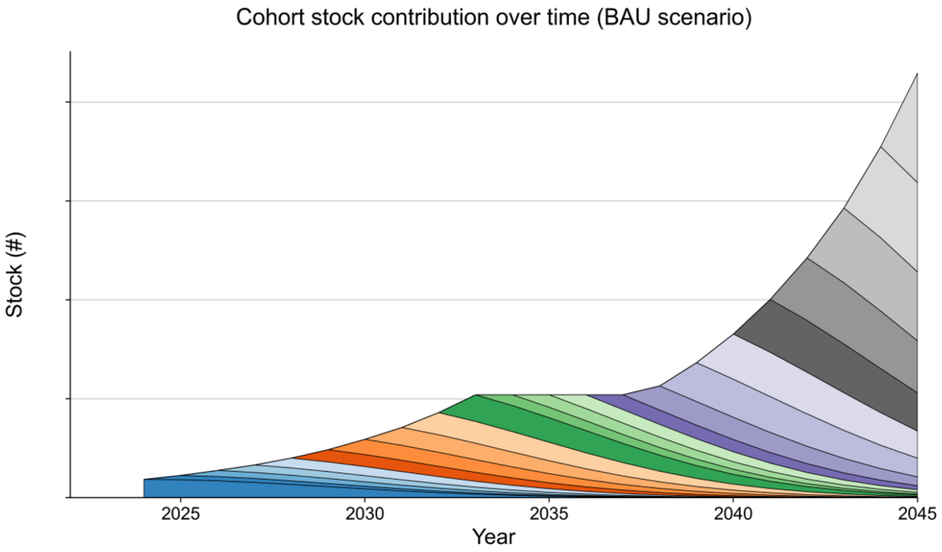
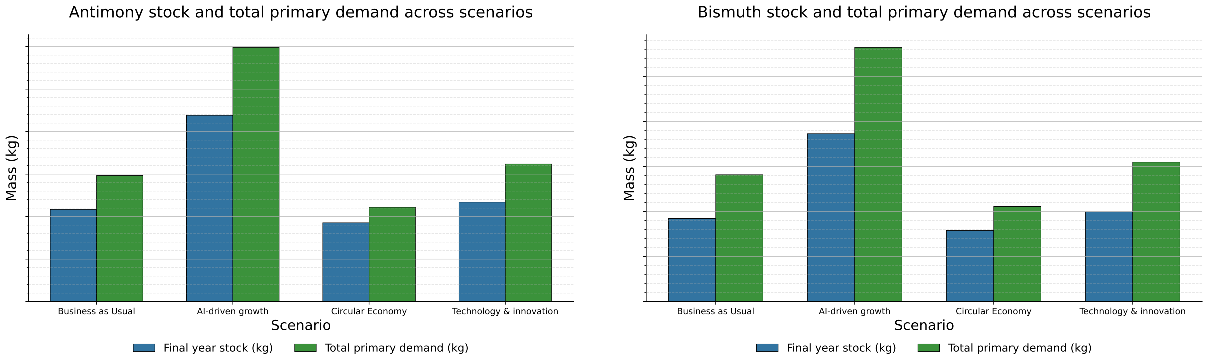


Figure 6.5: Annual cohort contribution to transponder stock

6.3.2. Primary CRM demand accumulation within transponders

Total primary CRM demand has been calculated and plotted in the appendix for each CRM in 2045, in which the stock and primary demand has been compared next to each other. It can be derived that the general trend of the total primary demand exceeds the stock required in the final year for each CRM, similar to the amplifier model. This is also the case for CRMs with higher end-of-life recycling input rates such as tungsten (42%) and antimony (28%), although the total primary demand is slightly closer to the total stock. For instance, antimony indicates a quantity of x kg for the BAU scenario, in comparison to x kg for the sustainable and circular scenario. In contrast, bismuth results in x kg for the BAU scenario, in comparison to x kg for the sustainable and circular scenario. Illustrating the relatively higher demand related to the final stock in 2045. This can be attributed to antimony being modelled according to a baseline end of life recycling rate of 28%, with bismuth corresponding to 0%, as shown in figure 6.6 below.



(a) Total primary demand and final stock antimony

(b) Total primary demand and final stock bismuth

Figure 6.6: Total primary demand compared to final stock for antimony and bismuth

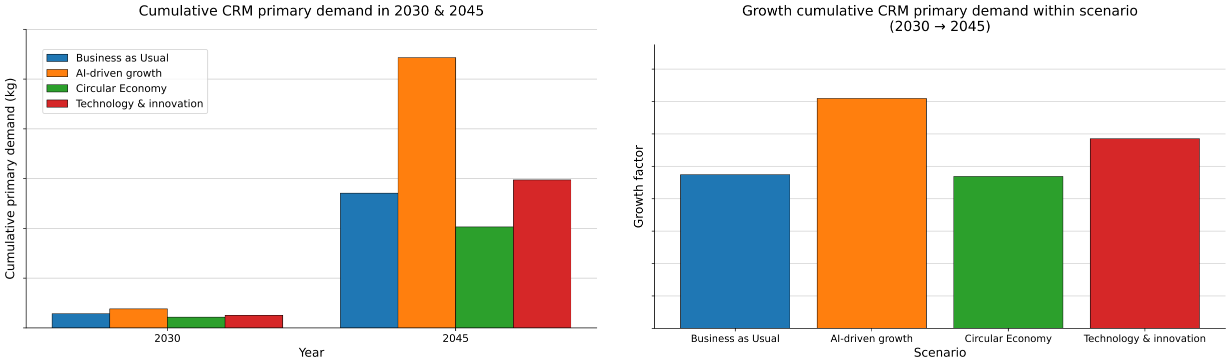
6.3.3. Primary CRM demand growth in transponders

Total primary CRM growth in transponders

In addition to the individual primary demand development in 2045, as illustrated in the previous paragraph, the collective growth of CRMs in PCBs in transponders can be regarded as a reflection of an overall trend. With figure 6.7a below, showing the cumulative primary material demand in 2030 and

2045, with figure 6.7b next to it, demonstrating the relative growth within the scenarios from 2030 to 2045. It can be deduced that cumulative demand in 2030 between the scenarios is relatively similar and does not exceed more than x kg for all scenarios. However, as demonstrated by the growth pattern in figure 6.7b, the difference between the scenarios is magnified by 2045. With the scenarios with higher initial values in 2030, growing even more in 2045. Nonetheless, the growth in total stock of primary CRM demand is at least a minimum of ninefold for the circular and sustainable economy and exceeding fourteenfold for the AI-driven growth scenario.

Given that the total stock of transponders and amplifiers show similar growth patterns between 2030 and 2045, this primary material growth factor can also be used to analyse CRMs in amplifiers.



(a) Cumulative CRM primary demand in 2030 & 2045

(b) Cumulative primary CRM demand growth 2030 to 2045

Figure 6.7: Cumulative primary CRM demand growth in 2030 and 2045 according to scenario

Individual primary CRM growth in transponders

Consequent individual primary CRMs growth factors are similar to the developments in amplifiers as the stock build-up follows the same trend, as shown in table 6.2 below. With growth factors within the AI driven scenario also being roughly 14.2 and the circular and sustainable economy resulting in a growth factor of approximately 9.35. The growth factor of the individual CRMs is higher than collective values from figure 6.7, as the individual primary inflows summed to 2045 is dominated by the later years due to the exponential growth rate through the CAGR. In which the cumulative sums amplify the ratio at the endpoint of the model.

Table 6.2: Cumulative CRM primary demand in amplifiers in 2030 and 2045, with growth factors (GF) for high (AI driven) and low (Circular Economy) demand scenarios

	High demand scenario			Low demand scenario		
CRM	AI 2030 (g)	AI 2045 (g)	AI GF	CE 2030 (g)	CE 2045 (g)	CE GF
Antimony			14.4			9.59
Bismuth			14.2			9.33
Boron			14.2			9.34
Magnesium			14.2			9.44
Nickel			14.3			9.47
Palladium			14.2			9.41
Ruthenium			14.2			9.41
Silicon			14.2			9.33
Strontium			14.2			9.33
Tantalum			14.2			9.33
Titanium			14.3			9.50
Tungsten			14.5			9.75
Yttrium			14.2			9.36
Manganese			14.2			9.40

6.4. Material demand growth from competing sectors

As developments in other sectors drive CRM demand as well, the growth factors from the transponder and amplifier models can be compared to evaluate whether competition and possible supplying constraints can be seen. The following studies have made projections according to overall demand in the EU, as well as sector specific growth rates for short (2030) and long terms (2050):

- With overall REE demand driven by dysprosium, neodymium and praseodymium growing with factor 5-6 by 2050 (Carrara et al., 2023).
  - Most notably, praseodymium magnets (in a compound with neodymium) specifically grows with factor 30 from 2030 to 2050 (for the high demand scenario) as a result of the green transition to electric motors for e-mobility and wind turbines (Bobba et al., 2020).
- Furthermore, nickel demand, in the form of battery grade used in high-purity batteries increases by factor 10 in the EU from 2030 to 2050, also as a consequence of e-mobility growth (Bobba et al., 2020).
- On the other hand, silicon metal demand in the EU is expected to decrease by a factor of approximately 0.8 between 2020 and 2050 (Carrara et al., 2023).

As demand projections are not available for the other embedded CRMs, global demand trends have been assessed as they also drive competitiveness on the short and longer term, such as:

- Increasing global manganese demand in clean energy with factor 4 between 2030 and 2050, as a result of their wide use in EV batteries and steel components in wind turbines (International Energy Agency, 2024).
- With silicon metal showing opposite growing demand trends compared to EU projections, in which solar photovoltaics (PV) and electric vehicles are projected to increase by factor 1.5 between 2030

and 2050 (International Energy Agency, 2024).

- Whereas palladium demand is currently 80% represented by its application in internal combustion engines and emission catalysts. However, it is expected to structurally decline as a result of the growth in electric vehicle (EV) production as a substitute (International Energy Agency, 2024).
- Although within PGMs, ruthenium is projected to consistently increase due to demand growth within membrane electrodes such as hydrogen electrolysers (International Energy Agency, 2024).
- Regarding antimony, bismuth, tantalum, tungsten and boron, relative slow uptake is projected until 2035 (U.S. Department of Energy, 2023), with long term projections by (International Energy Agency, 2024) resulting in a relative small demand increase of factor 1.3 up to 1.5.
- The HREEs, erbium, thulium and yttrium are forecast to roughly grow with a factor between 2 and 2.4 for 2020 volumes compared to 2050, with U.S. Department of Energy (2023) trajectory showing growth of 2.4 while International Energy Agency (2024) projects a doubling in a net-zero scenario.
- With germanium and titanium demand projected to grow with approximately factor 1.5 between 2020 and 2050 through its application in respective fibre optics and electrolysers for green hydrogen (U.S. Department of Energy, 2023).
- Strontium, considered a niche material used in electrolyser ceramics is projected to grow rapidly with factor 20 between 2020 and 2035 after which it reaches an equilibrium according to (International Energy Agency, 2024).
- Lastly, magnesium is forecast to double by 2050 through its application as lightweight bodywork of EVs (International Energy Agency, 2024), with short term projection until 2035 forecasting an increase of around 1.6 (U.S. Department of Energy, 2023).

Demand projections in the EU and global on the long and short term shows that the growth factor found from the rise of transponders and amplifiers between 2030 and 2045 is well above most projections on the EU and global scale. In which praseodymium and nickel however, shows equally high demand projections due to upscaling of e-mobility and wind turbine in the EU, while global manganese demand also shows considerable projected growth through its use in the same sectors.

6.5. Sensitivity analysis amplifier & transponder model

The sensitivity of the model has been tested using two output indicators: the stock of CRMs shows the sensitivity at each point in time of the model, while the change in primary demand reflects the model output at the last point in time, which is the cumulative primary material demand in 2045. The parameter changes have been set at +20% and -20% from the baseline parameter setup.

6.5.1. CRM stock development sensitivity

Firstly, the development of the CRM stock, in this instance for nickel stock, is presented in figure 6.8, illustrating the result of 1000 runs using a Monte Carlo simulation setup. The uncertainties are represented by Bayesian likelihood distributions which assign normalized probability densities over all plausible values through the use of Monte-Carlo simulations (Bornhöft et al., 2016). In the Monte Carlo sensitivity analysis runs, the stock at each point in time is selected as the dependent variable and is repeatedly evaluated over the large sample size of 1000 unique runs. While nickel has been selected as the representing CRM in this analysis, the general trend of the stock development is equal for each CRM, only differentiating in the fractions of total stock present in the equipment.

The fan chart with the percentile distributions is illustrated in figure 6.8 below, concluding that as the model progresses, the uncertainty boundaries become wider, simulating the increasing uncertainty associated with projecting stock in the future. This diverging motion underlines the extended effect of the scenarios as seen in the previous paragraphs and questions whether results at later points in the model are statistically significant, requiring a sensitivity analysis of total output as presented in the following paragraph.

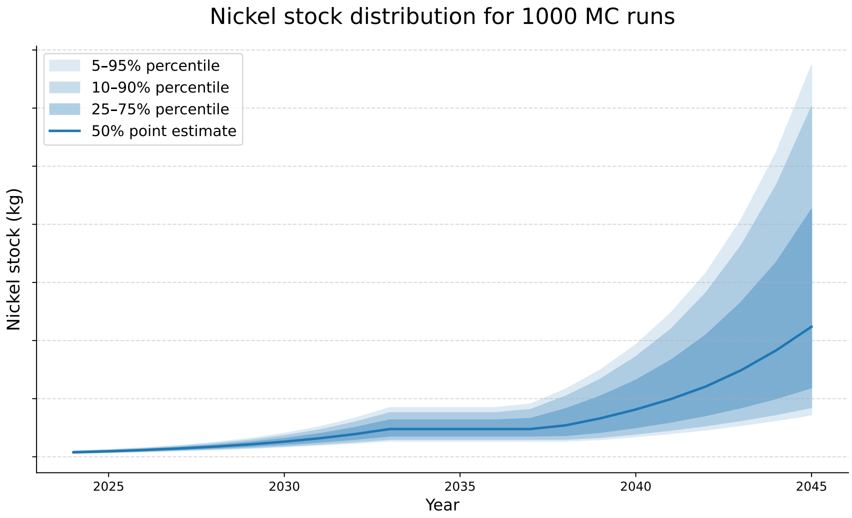


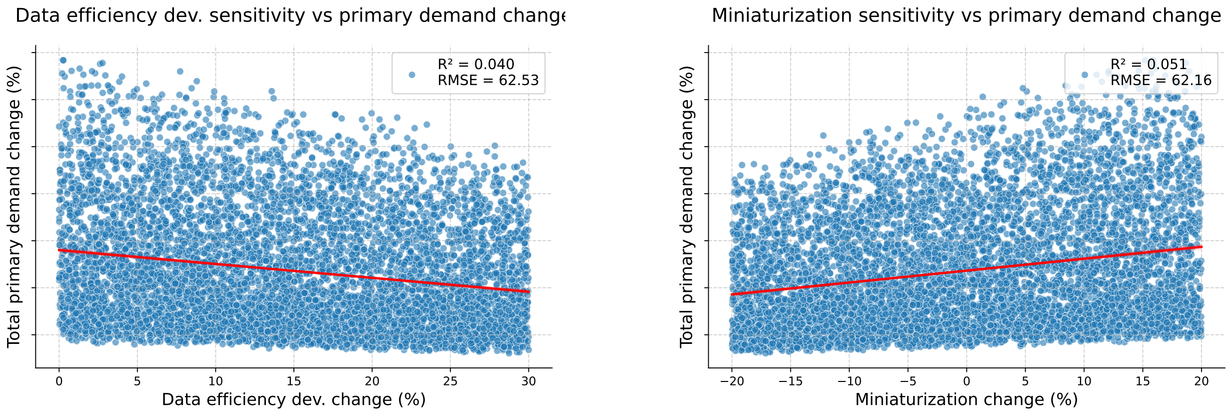
Figure 6.8: Stock distribution for Monte Carlo simulation runs

6.5.2. Primary demand change sensitivity

A sensitivity analysis has been conducted to test the sensitivity of the exogenous parameters used in the model and to extend the boundaries of the scenarios, as the scenarios represent only 4 different setups. Within each, of 7500 runs total, all parameters are assigned a random number between -20% and +20% of the baseline parameter value across the total modelling period from 2024 to 2045 to simulate a substantial combination of parameters, with the exception of the compound annual growth rate of data traffic. As the CAGR consists of a year-on-year growth, its effect results in exponential changes, thus the parameter change for this case is limited from roughly -6% to +7%, corresponding to shifts between a growth rate of 2.15 and 2.30.

The most significant linear correlation between parameter changes and the subsequent change in primary demand comes from miniaturisation and data efficiency developments as shown in figure 6.9b and 6.9a below, which show a R_2, or explain the variance in total primary demand change with respectively 0.046 and 0.038. Whereas the sensitivity results of the other parameters can be found in the appendix.

Although variability values are above zero for data efficiency developments and miniaturization parameters, the root mean square error is relatively high, both just above 60, resulting in low predictive power of the regression, as a 60%-points spread from the regression of total primary demand change can be found. Taking into account that a sample size of 100 or above the error distribution should result in reliable results with standard deviation within 5% (Chai & Draxler, 2014).



(a) Sensitivity of data efficiency development

(b) Miniaturization sensitivity

Figure 6.9: Sensitivity of miniaturization

The sensitivity analysis of the CAGR results in the most significant and narrow distribution of primary demand change according shifts in CAGR input parameters, however its regression is shown as linear, even though its transformation follows a exponential growth, limiting the reliability of the regression line and R_2 value. It can be concluded from the Monte Carlo simulation runs that data traffic growth via the compound annual growth rate has a significantly greater impact on the primary demand compared to the other parameters. As can be seen from the corresponding scatter plot and regression line visualised in figure 6.10, with the highest reported R_2 and lowest reported root mean square error.

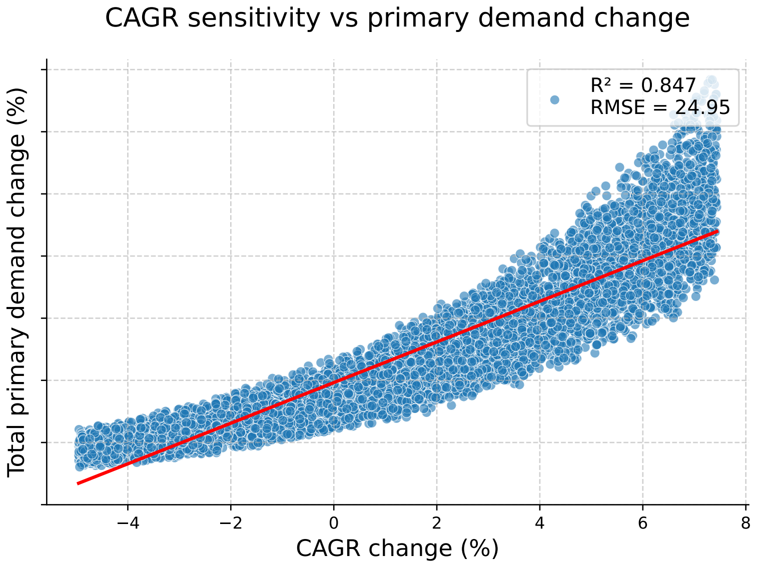


Figure 6.10: Sensitivity of compound annual growth rate

A more thorough discussion of the sensitivity results can be found in paragraph 9.2.1. Elaborating further on why the model behaves according to the outputs shown above and to identify its limitations.

7

Resilience strategies based on circular economy measures impact

Based on the model framework of the previous chapter, circular economy strategies are tested on its individual effect on primary demand changes for CRMs. Since transponders and amplifiers are determined using the same exogenous parameters affecting demand, resulting in similar growth patterns after 2033, they are grouped as general OTN equipment. Although absolute stocks differ slightly, the timing of the peaks and troughs is identical, driven by the same independent variable setups.

In the upcoming sections, CE strategies will be tested upon effectiveness through the primary material use rate. To normalize results, product flows and material flows are scaled to a ratio of 1 : 1 to enable comparison of general progression of flows, without going into the specific development of each CRM. By treating a kilogram of product inflow and a kilogram of material inflow as identical units, it can be derived which lever delivers the steepest drop in primary material demand during each point in time and accumulated at the end of the model. However, this means that it must be considered that each product which can be reused consists of multiple embedded CRMs within the PCBs in transponders and the CRMs embedded in amplifiers which in turn can have specific recycling rates according to the specific material as presented in the table in the appendix.

7.1. CE strategies configurations setup

The different runs of each CE strategy is presented in table 7.1 below. Whereas during every run, only one CE strategy is adjusted, over 3 setups to isolate its effect on the primary material use rate of CRM inflows, totalling 12 output runs. Baseline values have been set at a lifetime shape of 2 and scale of 7 years, with stock values based on the trends seen in the business as usual scenario for the equipment. This enables comparison of each individual strategy according to the specific case study of transponders and amplifiers installed in the fixed network for telecommunications. Whereas the range of the strategies for each configuration have been selected to represent increases in a realistic order. Since full CRM reduction is only possible with substitution of the whole product or all its integrated materials. Whereas reusing close to 100% would in practice mean that you have an endless loop, even though electronics eventually need to be replaced due to deterioration. In which deterioration is classified in two forms, with relative deterioration describing the state in which a product is no longer used due to replacement with a new product and absolute deterioration describing reaching end-of-life due to the product not being able to be repaired or not worth repairing (Okumura, 2022).

Table 7.1: Model run configurations

Configuration name	Shape	Scale (years)	Reuse rate	Recycling rate	CRM reduction
Baseline 7y	2.0	7	0.00	0.00	1.00
Lifetime 9y	2.0	9	0.00	0.00	1.00
Lifetime 11y	2.0	11	0.00	0.00	1.00
Lifetime 15y	2.0	15	0.00	0.00	1.00
Reuse 20%	2.0	7	0.20	0.00	1.00
Reuse 40%	2.0	7	0.40	0.00	1.00
Reuse 60%	2.0	7	0.60	0.00	1.00
Recycle 20%	2.0	7	0.00	0.20	1.00
Recycle 40%	2.0	7	0.00	0.40	1.00
Recycle 60%	2.0	7	0.00	0.60	1.00
CRM Reduction 10%	2.0	7	0.00	0.00	0.90
CRM Reduction 20%	2.0	7	0.00	0.00	0.80
CRM Reduction 30%	2.0	7	0.00	0.00	0.70

7.2. CE strategy results

7.2.1. CE strategies results according to low/medium/high configurations

The low, medium and high configurations are characterized by the first, second and third tier of each configuration. So with lifetime extension from 7 to 9 years being the first and lowest tier, 11 years representing the medium configuration and 15 years representing the highest configuration to test each CE strategy effect. Enabling the relative comparison of each individual configuration with the baseline and each other. Whereas recycling and reusing practices show same primary material inflow effect as reused product flows save primary product inflow in the same degree as recycling saves primary material inflow, as seen in the equations defined in the appendix.

Between each configuration, two patterns can be deduced: these consist of the timing and magnitude of the impact. In the low configuration shown in figure 7.1 below, the lifetime extension from 7 to 9 years is projected to result in substantial savings of primary material inflow during the stabilization of equipment between 2033 and 2038. This can be attributed to the role of the Weibull scale parameter in delaying outflows. Specifically, driving the reuse potential during the plateau window, characterized by static demand. In comparison, the CRM material intensity reduction of 10% only overtakes the lifetime extension near 2038, because prior to 2038, annual inflows remain relatively low, thus resulting in minor absolute benefits derived from 10% reduction. With recycling/reuse strategies at 20% resulting in flat and the relative lowest impact on primary material inflow, as it only captures a fraction of the outflows from product and corresponding material level, which remains low until the surge after 2038.

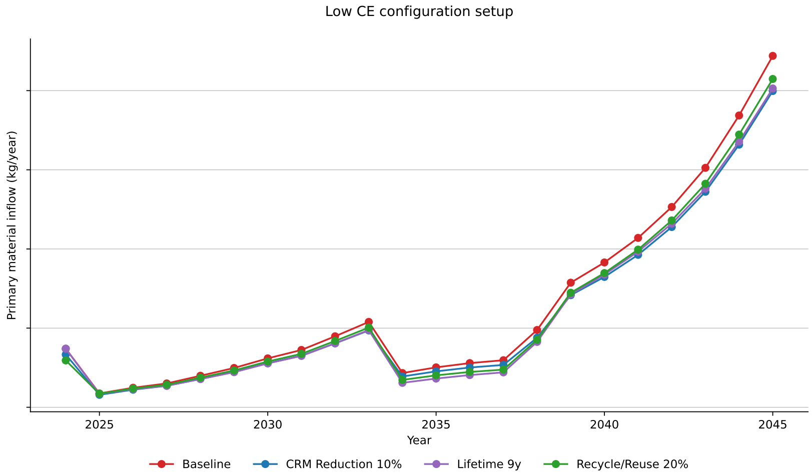


Figure 7.1: Low CE configuration output

In the medium configuration setup as seen in figure 7.2 below, extending lifetime to 11 years, yields diminishing marginal returns, resulting in around a 5 kg/year inflow reduction in 2045 compared to lifetime extension to 9 years. Whereas a CRM reduction increase to 20% clearly differentiates the primary material inflow in the high-growth tail part of the model. Demonstrating that design for lightweight is more than linearly effective at reducing yearly material inflow. Furthermore, it is interesting to note that a 40% reuse/recycling is almost equivalent to the lifetime extension of 11 years, emphasizing that pushing recovery beyond 40% yields roughly the same outcome to adding two more years to the product use phase.

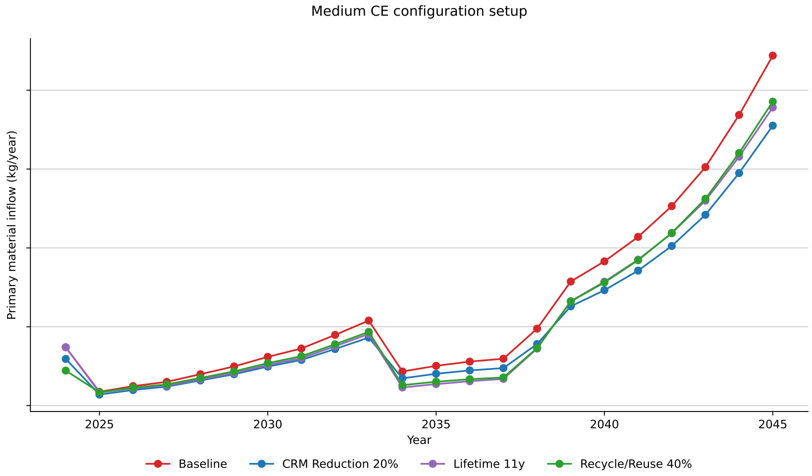


Figure 7.2: Medium CE configuration output

In the high configuration shown below in figure 7.3, CRM reduction of 30% increasingly diverges from the baseline at the demand growth periods and has relatively the most significant impact compared to the other strategies. However, the slight increase in primary inflow during the stable phase between 2033 and 2037 for all strategies understates that doubling of equipment capacity still forces the base load of primary material in each year, albeit reaching almost zero during the plateau phase for the recycling/reusing of equipment and material at 60%. Indicating that a combined approach of lifetime extension and reusing/recycling could be most promising during flat periods, while miniaturization strategies is especially effective at saving primary material yearly inflow when growth of the total stock is resumed.

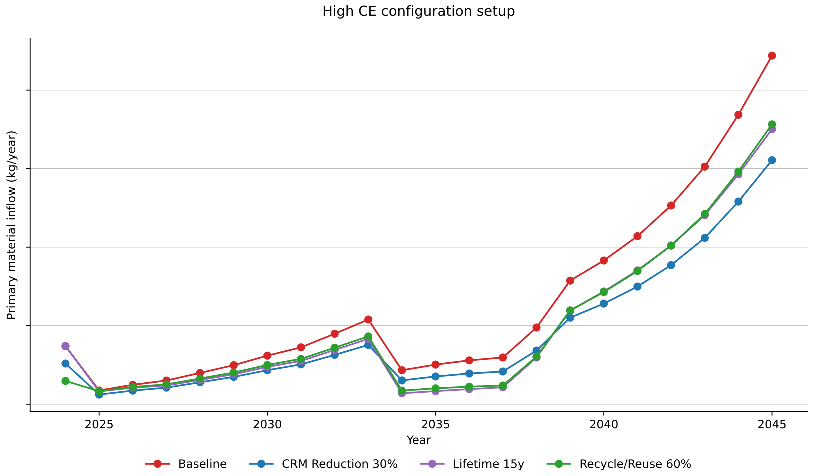
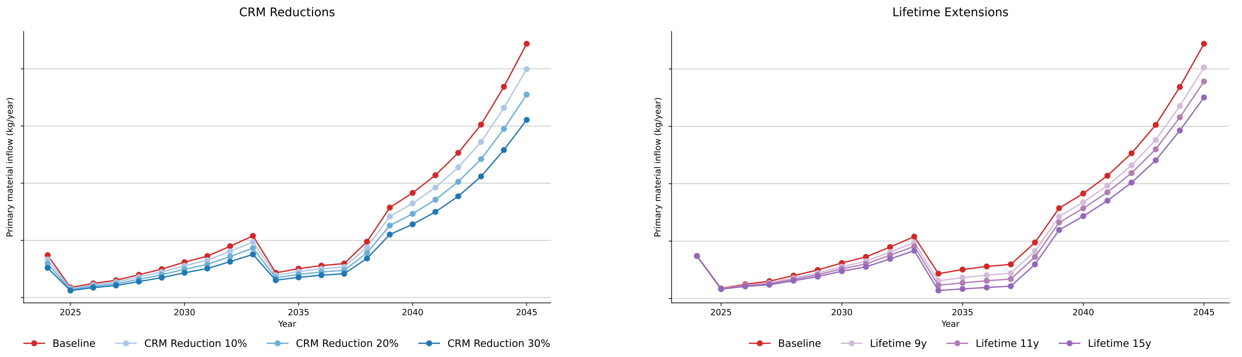


Figure 7.3: High CE configuration output

7.2.2. Results within each CE strategy

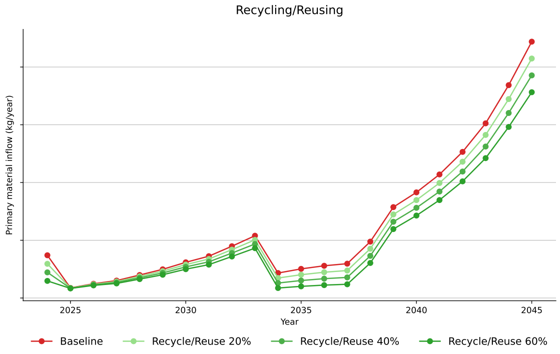
When analysing the individual CE strategies for each configuration, as shown in figure 7.4 below. It can be deduced from sub figure 7.4b that lifetime extension is most impactful when the stock curve flattens. Since it directly reduces the outflow during the plateau, which is coupled with a decrease of annual inflow and consequent primary material inflow. When moving from 7 to 9 years, the 2045 inflow is reduced by roughly 50 kg/year compared to the baseline, with further extensions to 15 years resulting in diminishing reductions of roughly another 25 kg of yearly primary material inflow saved. In comparison, the reuse/recycling curves from figure 7.4c result in similar curves as the lifetime extension, with each shift upwards in recovery rate, slicing a higher fraction of the outflow back into the system.

Although annual primary material inflow of the two strategies show comparable results, its inherent effect on the cumulative primary material demand and waste outflows is different, further explored in paragraphs 7.2.3 and 7.2.4. Most noticeably, CRM reduction illustrated in sub figure 7.4a, demonstrates the highest converging curves beyond 2038 for each subsequent reduction step. Since, mathematically speaking, reduction is applied to every kilogram of inflow, with its effect compounding with the data driven demand increase which can be seen during the stock expanding periods in the model. These different patterns imply that strategies behave differently during the model sequences, indicating that a chosen strategy could more useful according to the period in time.



(a) CRM reductions

(b) Lifetime extensions



(c) Recycling/Reusing

Figure 7.4: Individual CE strategy results

7.2.3. Total CRMs saved

Comparison of total CRMs saved when implementing each CE strategy from 2024 until 2045 in absolute terms results in figure 7.5 below, with the percentage difference compared to the total primary CRMs used without interventions reported in the appendix. Figure 7.5 shows that reducing material intensity shows most potential from a primary material demand savings perspective, as both the medium and the high configuration savings are significantly higher compared to the lifetime and recycle/reuse counterparts at medium and high configuration. With each order of 10% added reduction resulting in the same total primary CRM reduction of 139.8 kg. Regarding the results of lifetime extensions, each higher order of lifetime extension shows diminishing savings of primary CRMs. As extension from 7 to 9 years, result in 144.5 kg saved, whereas an additional 2 years of extension amount to 91.1 kg saved and consequent 4 extra years only increases CRMs saved by 108 kg. Whereas reduction of material intensity with 30% has an aggregated reduction of more than 400 kg total material use, with recycling/reusing and lifetime extension measures showing similar results for increasing recycling/reusing to 40% and 60% when compared to increasing lifetime to 11 years and 15 years. However, implementation of recycling/reusing at 20% is considerably less than extending the lifetime to 9 years.

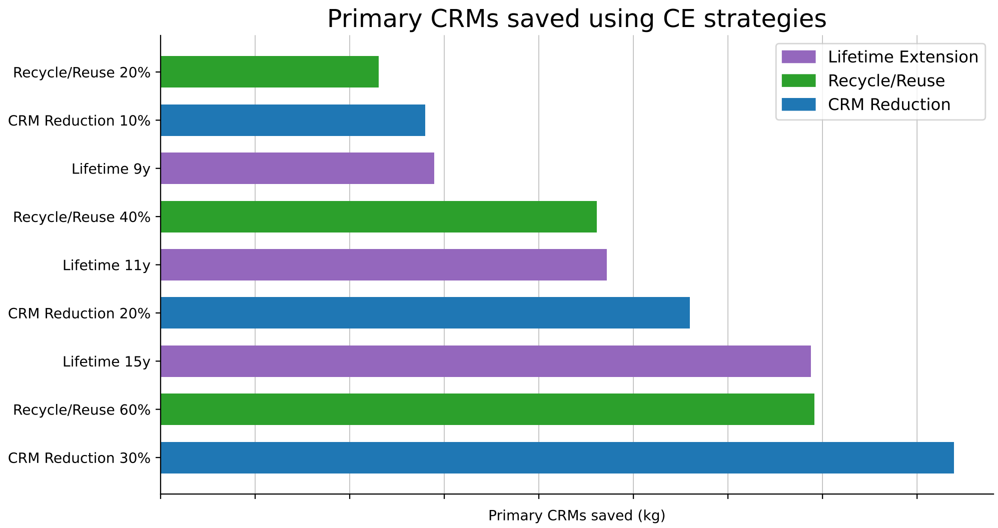


Figure 7.5: Cumulative primary CRMs saved

Although CRM reduction by 30% shows the most substantial savings in absolute terms, total primary CRM use in the baseline scenario without interventions results in a demand of 1398 kg. Evaluating the percentage difference in the appendix, it shows relative small overall effect as no individual strategy is capable of reducing primary CRM demand by more than 30.0%, 24.7% and 24.6% for a 30% CRM reduction, 60% recycling/reuse and lifetimes extension to to 15 years respectively.

7.2.4. Permanently lost CRMs

Besides CRM saved, the outflow pattern according to each strategy shows that the total outflow and the lost outflow, is exactly the same for each strategy except the recycling and reusing strategy as seen in figure 7.6 below. Since extending lifetime and reducing material intensity only affect the total inflow and total outflow patterns and not the share of outflow re-entering the system boundary. When comparing the permanently lost CRM outflow, recycling and reusing of 60% have the greatest effect on reducing waste stream out of the system. From the results below, it stands out that from a waste stream perspective, lifetime extension has relative substantial reduction of CRM outflow compared to the baseline and the other strategies. However, considering the structure of the model, reducing material intensity through CRM reduction drives down overall material need in the equipment, as was shown in figure 7.5, consequently having less outflow. Whereas recycling and reusing loops, accounting for the permanently lost CRM outflow out of the systems shows similar trends at 40% and 60%, compared to lifetime extension until 11 and 15 years.

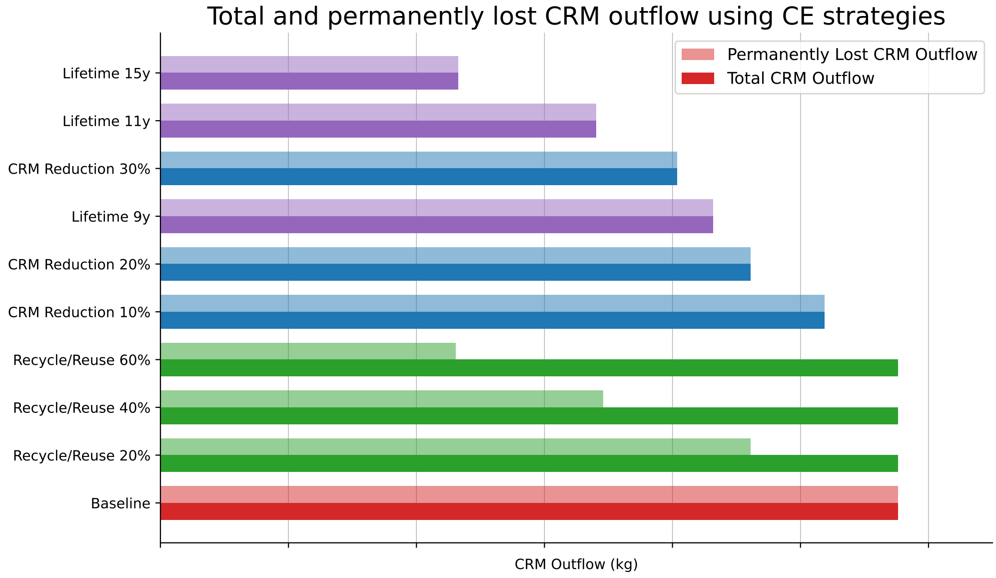


Figure 7.6: Lost CRM outflow compared to total CRM outflow

7.3. Compound effect of strategies

As demonstrated in the previous sections, primary CRM demand can be significantly reduced by implementation of individual CE strategies. Nevertheless, integration of individual strategies is not sufficient to significantly reduce the rising demand especially in the peak expansion period after 2038. Thus, combining multiple strategies, can yield advantages in its cumulative impact, which is also in line with the principles outlined in the EU's proposed CRM act (Hool et al., 2023). Figure 7.7 below shows the inherent expected and the actual primary CRMs saved using different configuration setups. In which the y-axis labels show abbreviations for 'Life x', describing the lifetime extensions to respectively 9, 11 and 15 years, 'R/R x' reflecting the recycle/reuse rate of 20, 40 and 60% and 'CRM x' describing the reduction of the material intensity by 10,20 and 30%.

The diagram illustrates that expected primary CRM savings are higher than the actual savings for each combination of strategies. As the anticipated savings comprise of the sum of the savings for each individual strategy. However, it appears that as configurations increase, the impact on primary demand savings is relatively less. The combined strategies appear to negatively effect the overall effect, although it is imperative to note how this gap is determined. The strategies are not independent in their effect on CRM demand and the synergized effect can be tracked back to the double counting that would arise when accumulating each strategy, as they draw from the same 'pool' of material flows. By extending the lifetime of a product, less outflow becomes available in the long term, reducing recycling/reusing throughput back into the system and resulting in overestimation when adding the savings from lifetime extension and recycling/reusing together. A reduction of the material intensity of a product will result in a reduction of both inflow and outflow in the system, with subsequent CRM outflow available for recycling/reusing also reducing. Therefore, the summation of the savings from the individual strategies does not amount to the actual effect of combining strategies.

If the percentage difference between the expected and actual savings is not considered, it can be deduced that from the combination of two strategies: CRM reduction combined with recycling/reusing has the most significant effect on reducing primary CRM demand when implementing. Whereas integrating all three strategies amount to the most substantial savings, outperforming the combination of two strategies in the same low, medium or high configuration of strategies. Moreover, an analysis of the various stages in the configuration ladder indicate that the material demand savings decrease with each subsequent step. The low configuration, comprising of lifetime extension from 7 to 9 years, combined with recycling/reusing of 20% and a material intensity reduction of 10% results in approximately 400 kilograms being saved. In comparison, an additional 200 kilograms is saved for the second tier and approximately 175 kilograms for the third and highest combination of all strategies.

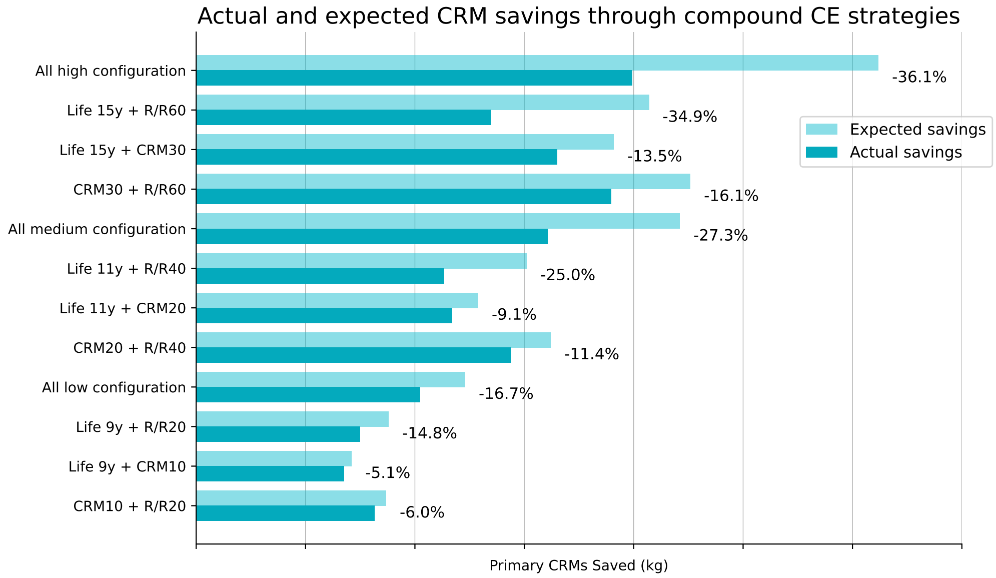


Figure 7.7: Actual and expected CRM savings by combined CE strategies

The relative savings of primary material demands are reported in the appendix for each combined strategy compared to the baseline primary material demand of 1398 kg. While the highest configuration of combined strategies is able to save 57.0% of total material demand, it is clear that all combinations of CE strategies in this model cannot compensate for more than 60% of the material need.

8

Implications of resilience strategies at organizational level

Besides quantifying the potential CRM savings, each strategy must be evaluated on its operational feasibility and the timing of its impact. Below, each measure is further analysed on what the current state and constraints are, supplemented with the implications from the timing and magnitude deduced from chapter 7 of the circular economy strategies and what the consequent organizational takeaways are for KPN.

8.1. Recycling

8.1.1. Current state and constraints of recycling

Currently recycling measures are hindered by a lack of strong economic drivers, especially for small volumes, and a cost competitive secondary material market (Karali & Shah, 2022). With primary material prices being lower than the recycled alternative and little incentive for third-party recyclers to reinject them into production (GSMA, 2022). Additionally, third party recyclers struggle with the lack of data on which material can be found in which part, component or sub-assembly (GSMA, 2022). From the perspective of the telecom operator, it is also a financial consideration of whether recycled or primary material is cheaper, whereas new equipment frequently is preferred (Sustainability advisor, 2025). However, increasing prices as a result of rising demand could drive the attractiveness of recycled material. For instance, neodymium and dysprosium prices had peaked in 2011 when platinum metal group demand demand increased significantly and China had reduced their quotas (Karali & Shah, 2022).

8.1.2. Temporal and magnitude aspect of recycling

Recycling is most effective during the 'plateau' from 2033 and 2038. As described in section 7.2, recycling at the highest configuration of 60% yields almost zero primary inflow during the stable phase, illustrated in figure 7.4c. This effect is due to the system producing a large cohort of outflow which is recaptured from 2033 onwards. However, returns are diminishing during rapid growth of the network, such as during the start when the installed equipment is least obsolete and during the post-growth starting around 2038, in which even 60% recycling of all material is less effective than reduction. Additionally, its effect is delayed and pushed back even further if combined with lifetime extension, decreasing its effectiveness at the start of the network expansion.

8.1.3. Organizational takeaways for recycling

OEM recycling

From a technical perspective, recycling currently is hindered for the end of life recycler through the lack of information about the concentration of CRMs used in the technology, making it harder for third party recyclers to recover elements efficiently and economically viable (Karali & Shah, 2022). Although a take-back system of the optical equipment at end-of-life with the OEM and subsequent internal recycling could provide possibilities since the manufacturer knows the material content and specific location within their products and this ensures the loop is closed with minimal loss (Sustainability advisor, 2025). However, from an economic perspective, it has been shown that recovery of valuable materials for low quantities causes losses in revenue, requiring large capacity recycling in order to reduce costs (D'Adamo et al., 2017). Thus, it could be challenging for a manufacturing firm to expand their operations for small amounts of CRMs in PCBs for instance.

Urban mining and recycling

Additionally, recycling of CRMs from existing urban mine sources could be incentivized, since Europe as a geographical region leads in generating waste electric and electronic equipment (WEEE), with each citizen generating 16.2 kg of WEEE on average in 2019 (Torrubia et al., 2023). Within the WEEE categories, waste PCBs from different applications as shown in the table in the appendix consists of overlapping CRMs. With antimony, bismuth, boron, magnesium, manganese, ruthenium, silicon, strontium, tantalum, tungsten and yttrium being present in waste PCBs. Whereas erbium, thulium, germanium, praseodymium have not been found in the reports from the table in the appendix. Besides recovery from the general pile of hibernating material stocks in Europe, it could be valuable for telecom companies to look into older generations of their own fleet of network infrastructure equipment which is transfixed across the Netherlands. Especially as locations of newly installed generation B of OTN is installed in parallel to older links on the net from generation A of the OTN, therefore exact information of the locations is known.

8.2. Reduction

8.2.1. Current state and constraints of reduction

In addition to recycling measures, the EU has proposed the Ecodesign Directive (Peiró et al., 2020). The principles consists of mandatory requirements on designing for disassembly, firmware availability, securing data deletion and disclosure of CRM content (Peiró et al., 2020). Although, ecodesign is hindered by a combination of technical and practical challenges. With technical challenges arising through conceptual ambiguity of what material efficiency is, with interchanging of design for disassembly versus design for dismantling, leading to confusion of what requirements should cover (Vanegas et al., 2018). While there also is a gap of standardized assessment to quantify material efficiency performance, limiting the transformation of policy goals into measurable requirements (Bundgaard et al., 2017). Lastly, historically, energy efficiency has been prioritized in the methodology for ecodesign of energy-related products, therefore, new CE metrics such as recycled content, poses difficult to prioritize (Mudgal et al., 2013).

From a practical perspective, implementation is limited through legal and proprietary knowledge barrier. As proprietary knowledge is protected by the manufacturer, obligations to publish instructions for disassembly or material content data could result in conflict with manufacturers' intellectual property (IP) (Ardente et al., 2015). Moreover, original equipment manufacturers may resist the additional durability or disassembly requirements that increases design and production costs, while recyclers and repair operators are the benefitting firms, with this misalignment reducing consensus (Dalhammar, 2016).

8.2.2. Temporal and magnitude aspect of reduction

Material reduction strategies are most effective during rapid moments of growth, especially seen in the post 2038 period. This is due to reduction acting as a multiplication across every kilogram of material in equipment, as a result, the biggest annual savings compile with surging inflow as seen in figure 7.4a. This leverage is therefore lower during the plateau periods, showing marginal results when reducing material intensity with 10% when compared to lifetime extension and recycling or reusing in figure 7.1.

8.2.3. Organizational takeaways for reduction

Collaboration for product design

To address these technical and practical challenges, multiple strategies can be used to maximize ecodesign principles for OEMs. Firstly, this can be integrated by maintaining a continuous and iterative consultation loop. In practice, this could be achieved by holding multiple stakeholders forums during the preparatory study and impact assessment stages, including OEMs, recyclers, repair and refurbishing specialists as well as market surveillance authorities to refine the requirements (Peiró et al., 2020). Furthermore, material efficiency experts should be brought in more frequently, with external expertise presenting technical evidence for data gaps on end-of-life flows and recycling economies (Hinchliffe & Akkerman, 2017).

Procurement

Besides extended collaboration on product design, telecom companies can strengthen their resilience through demanding certain criteria to be met during procurement. For instance, the EU's Green Public Procurement (GPP) framework can be implemented in the private sector. Whereas it currently is used in the public buying sector in the EU, promoting the life-cycle performance and urging purchasers to include criteria with a reduced environmental impact throughout the life cycle (Donatello et al., 2024). Using and tailoring the most relevant following criteria proposed in the GPP: technical specification of the equipment, describing the mandatory requirements every bidder should present, combined with 'award criteria' consisting of additional optional requirements making compliant products more competitive, from a material and environmental performance, with lastly 'contract performance conditions', in which rules are specified on how a contract is carried out with possible penalties if there is failure of compliance (Donatello et al., 2024).

Substitution

As described by Peck et al. (2015) and Goddin (2020), four types of substitution can be approached, substance-for-substance, service-for-product, process-for-process and new-technology-for-substance to reduce dependency of CRMs. Before going into the possibilities of substitution, it is important to note that substituting certain materials in terms of criticality could result in a critical substitute, as will be discussed below. And in terms of a circular standpoint, substitution could drive new forms of waste from the alternative process as well as waste from the original material if substituted immediately (Espinoza et al., 2020). From the identified CRMs, following substance-for-substance substitution, in which an element is directly substituted while maintaining fundamental properties (Goddin, 2020) are possible:

- Erbium found in amplifiers can be co-doped with ytterbium to reduce the pure erbium loading, while delivering equal gains (dB) in the C-band (Zakis et al., 2022). However, ytterbium can be found in the HREE group and is currently also considered critical.
- Praseodymium found in amplifiers can also be substituted directly, specifically by neodymium, as they both possess equal gains of signal in the 1.3 μm O-band wavelength range (Schimmel, 2006). However, neodymium is also a considered critical as it belongs in the LREE group.

- Within PCBs, bismuth functioning as a solder paste in the form of Bi-Sn can be replaced by SAC305, a compound consisting of 96.5 wt % tin, 3.0 wt % silver and 0.5 wt % copper, delivering mechanical reliability and respective validation of shear strength and aging compard to the Bi-Sn compound (Wu et al., 2023).

Regarding service-for-product, in which substitute ownership of a product with access to its function as service (Goddin, 2020), the following option could be prove useful:

- Leasing of optical equipment such as amplifiers and transponders from the OEM to outsource hardware and material risks since current use of equipment already consists of licensing costs (network architect, 2025). This could be realised by a bandwidth-on-demand service, in which there is real-time up- and downscaling of wavelengths according to client needs via automated interface by the lessor (Du-Pond et al., 2003). In turn, this reduces supplying risks, but shifts responsibility to the lessor to manage material management for the inventory in case of extra equipment for upscaling. Although, outsourcing this part of the network comes with dependency shifting from internal material management to service risk of reliable internet, furthermore, the OEM might still be vulnerable for supplying disruptions. If implemented correctly however, this method could result in lower capital costs for the leaser and returned products can be more easily leased multiple times to other users, increasing revenue for the lessor (Goddin, 2020).

Process-for-process substitution involves delivering the solution by different needs to overcome need for material in the first place, frequently accompanied by compromises in performance (Goddin, 2020). Multiple processes are possible:

- The current OTN, which is characterized as an active optical network, could be substituted with a passive optical network (PON), which uses passive splitters instead of amplifiers, excluding CRMs embedded in amplifiers, but having a trade-off in maximum distance through fiber attenuation and splitter loss as well as a reduction on the number of client channels (Lavery, 2013). Thus finding a balance of which metric for network performance is more important is key, through prioritization of material or reliability considerations.
- Regarding materials in PCBs found in transponders, a process-for-process substitution from a 6-layer to double sided boards, reduces total plating area and associated metal depletion up to 30% (Ochoa et al., 2019). In addition, reducing the amount of layers also has a positive compound effect on recycling as mechanical separation currently is becoming more difficult through the presence of multi-component and multi-layer constructions (Marques et al., 2013). However, less routing layers results in reduced density of interconnections, possibly compromising performance.

Lastly, new-technology-for-substance substitution describes using a new technology altogether in favour of the original substance (Goddin, 2020). This overhaul could be realised for amplifiers through:

- Substitution of new generations of fibre cables to reduce the need for in-line amplifiers. Currently, high-capacity telecom networks consist of silica based single-mode optical fibres (SMFs), while further attenuation reductions within SMF are expected to diminish (Komanec et al., 2020), resulting in increased dependence of amplifiers. Alternatively, Hollow-core fibres (HCFs), consisting of an air filled core, allows high levels of light confinement and consequent reductions in attenuation and amplifiers needs (Komanec et al., 2020). However as stated by Carrara et al. (2023), fibre cables consists of dopant materials which are also identified as critical raw materials, such as germanium, borate as well as a number of REEs (terbium, dysprosium, ytterbium, thulium, praseodymium and erbium). Moreover, the assembled component fibre cables shows even higher supply risks than PCBs according to (Carrara et al., 2023) due to dominance of China (43%), Japan

(23%) and US (16%).

- Another novel technology to substitute amplifiers at the ends of the OTN is through the use of semiconductor optical amplifiers (SOA). SOAs delivers signal gains approaching the currently deployed erbium doped fibre amplifiers, and is mainly used as integrable on-chip amplifier at the transmitting and receiving end, so in front of the transponders (Sobhanan et al., 2022). However, as with HCFs, substitution using this technology comes with constraints as the semiconductor layer is made up of gallium arsenide, indium phosphide or an alloy combing both compounds (Sobhanan et al., 2022). In which indium is the only element not considered critical according to the 2023 assessment of the EU (Grohol & Veeh, 2023).

8.3. Reusing

8.3.1. Current state and constraints of reusing

Current reusing practices are hindered by the lack of policies and regulations to encourage reusing and repurposing practices (Psarommatis et al., 2025). Additionally, the second-hand market is fragmented, small and it is estimated that 80% of collected products in telecom are dismantled and recycled due to low demands in second-hand use (GSMA, 2022).

8.3.2. Temporal and magnitude aspect of reusing

In terms of the dynamic impact of reusing, it mirrors recycling when set to the same yields. As both measures delay the inflow of CRMs identically, differentiating only in the corresponding feedback loops. Therefore, reuse also has the most significant impact during the plateau period between 2033 and 2038. Effectively, if equipment is reused beyond its conventional lifetime and expected Weibull outflow, it acts as a lifetime extension plus efforts, such as repairing and refurbishing required for the reuse. However, returns during the expansion in the early years is insignificant and also less effective in the end peak.

8.3.3. Organizational takeaways for reusing

Technological and supply chain management possibilities

However, technological advancements are currently being investigated to drive reusing and repurposing, these consist of predictive maintenance and AI analytics to forecast component longevity, combined with sensor technologies to monitor component degradation (Psarommatis et al., 2025). From a supply chain management perspective, a just-in-time supply network could have a positive effect on reusing and repurposing due to unpredictability or maintenance for the respective products, whereas just-in-time enables more interaction with the supplier of the transponder and amplifier cards (Anaba et al., 2024).

Inventory management

Besides using new technologies and supply chain methods, enhancing inventory management within KPN could be realised by mapping where the underutilised modules exist. So whether a link in the network, currently consisting of equipment with 400 Gbps capacity, can be redeployed with older compatible equipment. However, this would require further efforts in monitoring if generation A equipment is still viable as uptime is a valuable criterium for KPN and warranties could run out (GSMA, 2022).

8.4. Lifetime extension

8.4.1. Current state and constraints of lifetime extension

Lifetime extension measures are also correlated to the eco design principles. In which lifetimes can be extended through design for repairability. Increasing repairability can be achieved through faster and easier physical access to the components, while access to software support and firmware updates also contribute to increasing the repairability and consequent average in use lifetimes (Mudgal et al., 2013). However, as seen in a case study including key data storage and servers industry manufacturers, there is a concern of making the most recent firmware version public as proposed by (European Commission et al., 2016). The respective OEMs argue that they need to protect the intellectual property of the embedded software to 'sustain a competitive and innovative industry' (Digital Europe, 2016). Moreover, technical design of hardware and software alike has been made to limit lifespans of equipment, with consequently no incentive to manufacture hardware that covers a longer lifespan (GSMA, 2022). This is combined with a prioritization of higher energy efficiency and performance in new equipment compared to extending 'older' equipment (Sustainability advisor, 2025).

8.4.2. Temporal and magnitude aspect of lifetime extension

Since lifetime extension delays outflows and consequent necessary replacement flows along the modelling period, its effectiveness in this case would be useful from the initial start. In which replacements would be reduced into the plateau period in which the baseline lifetime of 7 years would frequently diminish. However, after 2038 replacements are not limited to obsolete equipment, but for rapid expansion, reducing the effectiveness of lifetime extension. Furthermore, the magnitude of the effects of lifetime diminishes with each additional year for the overall lifetime as previously shown in figure 7.5 , thus reducing overall incentive of extending for multiple extra years, especially if efforts rise non-linearly.

8.4.3. Organizational takeaways for lifetime extension

Firmware updates (with leasing)

Thus, from an organizational perspective, telecom operators should approach OEMs to work on service agreements which could guarantee access to firmware while protecting IP and consequently enable field upgrades. To also promote gains from the OEM, this strategy could be used in combination with the leasing proposition presented in the service-for-product to incentivize longer use through continuous payment and consequent revenue for the OEM.

8.5. Alternative (supplying) strategies

Besides circular economy strategies reducing material demands, and due to the presented constraints in the previous paragraphs in which none of the combinations brings primary material demand to less than 40% of the baseline, alternative strategies found in literature describe the possibility of implementing measures at the front side of the supply chain. Although, as will be elaborated in the following paragraphs, these proposed linear economy strategies are met with their own set of clear limitations.

Stockpiling

The first strategy is aimed at immediate strengthening of the supply of CRMs. This would be realised by accumulating strategic stock of a certain material to make telecom operators less vulnerable to disruptions on the market on the short term (Sprecher et al., 2015). Consequently, unexpected fluctuations in supply and price will have reduced effect on the supply chain. Although this strategy is often used by companies, there are also drawbacks of this strategy in the form of influencing price volatility (Sprecher et al., 2015) and the disconnection of KPN as service provider instead of OEM. With an instance of price volatility seen in 1970, in which an interruption of cobalt mining led to global shortage, whereas the US responded with strategic stockpiling, further decreasing availability of cobalt and spiking the global price with 380% (Patrahau et al., 2020). Regarding the disconnection, KPN does not manufacture their own equipment, thus stockpiling would not directly relieve pressure on equipment inflow. Lastly, material supplying problems are predicted to increase for decades, whereas stockpiling instead serves as temporary solution, even though the problem is structural and consequently prevents the continuation of 'traditional practice' as we know it (Peck, 2016).

Diversification of suppliers

Another method to reduce supply disruptions is through diversification of suppliers (Ezeafulukwe et al., 2024). As with diversifying suppliers on a geographical scale, dependency of a single source is reduced through spreading of risks while providing more flexibility of raw material sourcing (Ezeafulukwe et al., 2024). However, this method should be studied further as compatibility of certain optical (transponder & amplifier) cards is sometimes not possible when buying from different suppliers, as optical shelves could have different configurations according to standardization of the OEM (Network architect, 2025). Furthermore, supplier diversification is hindered by limited number of alternative suppliers (Frenzel et al., 2016), combined with the same supplying issues other OEMs run into for CRMs with a high supply risk indicator.

8.6. Compound strategy roadmap

To reduce dependency on primary CRM demand, KPN could adopt a coordinated, time-phased approach capitalizing on the temporal strengths of different CE strategies found in the previous paragraphs. The strategic roadmap is presented in table 8.1 below, and synthesizes both the quantitative outcomes from the material flow model and qualitative insights from internal desk research and literature. The roadmap is structured across three distinct temporal scopes, characterized by different model output behaviour, into the following periods: the short term (2025–2033), the medium term (2033–2038), and the long term (post-2038).

Within each time frame, the table first presents model based insights into which CE strategy demonstrates the highest effectiveness in terms of the dynamic results from section 7.2. These insights form the foundation for selecting appropriate strategies in each phase. Building on this, the right-hand columns of the table present, respectively, the key constraints that may limit implementation and the firm-specific resilience strategies that a telecommunications company like KPN can adopt.

Table 8.1: Roadmap of resilience strategy implementation in optical transport networks for a telecom provider organisation

Model-based strategic direction		Organisational implementation considerations	
Temporal Scope	Model findings of temporal aspect	Strategy constraints	Firm specific strategy
Short term (2025–2033) Characterized by initial optical transport network buildup	**Reduction** Effective in expanding phase, albeit relatively less than long term due to smaller scale of growth	**Reduction** • Prioritization of energy efficiency (Mudgal et al., 2013) • Protection of IP by OEMs limiting composition sharing (Ardente et al., 2015) • Increased costs for design for disassembly (Dalhammar, 2016)	**Reduction** • Increased collaboration through stakeholder forums during preparatory study and impact assessment stages (Peiró et al., 2020), including material efficiency experts (Hinchliffe & Akkerman, 2017) • Demanding better material performance through 'contract performance conditions' during procurement (Donatello et al., 2024) • Substitution through service-for-product leasing (Goddin, 2020)
	Lifetime extension Effective for delaying replacement inflows normally arriving in plateau period, although slowing down available reusing/recycling feedback flows	**Lifetime extension** • Public firmware releases constrained by OEM intellectual property (Digital Europe, 2016) • No incentive for OEMs to extend product lifetimes (GSMA, 2022) • Internal prioritization of newer, more efficient and better performing equipment (Network architect, 2025; Sustainability advisor, 2025)	**Lifetime extension** • Approaching OEMs to access firmware and enable field upgrades (combined with leasing to incentivize OEMs)
Medium term (2033–2038) Characterized by capacity transition from 400 to 800 Gbps phase	**Recycling** Shows most impact in the stable plateau period with increasing available outflows	**Recycling** • Low CRM volumes provide weak economic drivers (Karali & Shah, 2022) • Limited content transparency and data availability (GSMA, 2022)	**Recycling** • Take back system of optical equipment at the end of life with subsequent recycling process at OEM, leveraging upon composition knowledge of OEM (Sustainability advisor, 2025) • Urban mining and recycling from general waste PCBs (Torrubia et al., 2023), extended with recycling of hibernating parallel material stocks in OTN
	Reusing Loop shows similar impact during plateau period through increased available outflows	**Reusing** • Lack of policies to support reuse and repurposing (Psarommatis et al., 2025) • Low demand for second-hand telecom equipment (GSMA, 2022)	**Reusing** • Technological advancements in monitoring component degradation (Psarommatis et al., 2025) • Increased inventory management, possibly redeploying older OTN equipment if uptime and warranty requirements are met (GSMA, 2022)
Long term (Post 2038) Characterized by network expansion through exponential data traffic growth	**Reduction** Highest yield in rapid growth especially after 2038 surge, resulting from increased required inflow	**Reduction** • Replacement or substitution of new fibre optical technologies comes with introduction of GaAs or InP in photonic integrated chips (Sobhanan et al., 2022)	**Reduction** • Replacing OTN equipment if 1.6 Tbps capacity becomes available in the future (Pedro et al., 2020), to smooth down further expansion driven by data growth

9

Discussion

The following sections consist of a description of the relevance at societal/managerial level and the implications, after which the limitations of the conducted study are presented and the discussion concludes with recommendations for further research.

9.1. Societal/managerial relevance and implications

The main findings of the study makes several scientific contributions by extending dMFA to a firm level context within telecommunications via the optical transport network. While previous research has mainly focused on consumer electronics or national scale flow studies. Whereas this study tried to map future flow and stock accumulations for a fixed network infrastructure, specifically for amplifiers and transponder PCBs. By combining material data from internal desk research and extraction from case studies and supplier provided data, it enabled modelling of a stock driven model for telecom operators and consequent evaluation of the impact of implementing a variety of circular economy strategies. In turn, this study complements existing literature by providing a firm centered perspective to access CRM vulnerability. Although it must be noted that certain constraints arise when constructing a prospective dMFA model with available data, as will be discussed in detail in section 9.2. By bridging the techno-economic evaluation of material flows with social feasibility of the strategies, this study thus contributes to the dMFA field but also provides actionable strategies for reducing supplying risks.

Furthermore, the study introduces implications for both academic and practical implementation. Scientifically, the relatively modest savings from individual strategies highlights the limitations of the strategies in perspective with how stocks develop in time. Whereas combining strategies is coupled with limitations on feedback loops when combining lifetime extensions and recycling/reusing for instance. Furthermore, the study implicates that data growth on the optical transport network has considerable impact on primary material demand compared to other integrated parameters, which cannot be easily compensated as shown in the primary use rate plots. Practically, these insights suggest that telecom operators cannot only rely on established circular pathways to substantially reduce supply risks. Instead it must adopt multiple strategies integrating material reduction, lifetime extension, recycling and reusing improvements in close collaboration with its supplier. However, the insights also demonstrate that the strategies are constrained, by a number of factors such as trade-offs in performance and efficiency in favour of material reduction or extended (re-)use of equipment. Additionally, strategies are further limited by the high degree of dependency of geopolitical decision making for international trade, where telecommunication companies have relative small influence on.

9.2. limitations

The limitations of the study are divided by modelling limitations, consisting of main drivers, simplifications and sensitivity implications. With method limitations describing the constraints bound to (prospective) dynamic material flow analysis and the criticality assessment.

9.2.1. Model limitations

Data driven model output

The modelling of the complex knowledge gap is described with assumptions, resulting in limitations in terms of the feasibility of outcomes. The primary assumptions concern the equipment's data capacity, with the equipment being designed to carry 400 Gbps data packets and the same hardware being capable of being scaled up to carry 800 Gbps of data. However, the precise point at which this capacity is doubled remains undefined. For the model, this moment is set to be switched on from 2033 onwards in order to keep up with the data demand growth. The effect of shifting this moment on incoming and outgoing material flows is significant, as the capacity doubling transforms the equipment into a constant state in a relatively brief moment, while in reality, a telecom operator might anticipate the shift in a more smooth integration. In addition, the model in its core is driven by capacity as depending variable, while several studies, including (Welch, 2020) emphasize the role of energy efficiency through network simplification and 'immediate' cost savings as key drivers for technological innovation and adoption in optical networks.

In general, technological innovation cycles consists of multiple steps before adoption on a wide scale. Although exact time periods for future optical equipment innovation cycles are currently unknown, due to the relative new technology of currently installed transponders and amplifiers as described in earlier chapters, its cycle can be qualitatively analysed. Similar case studies from optical transport technologies describe subsequent early development, technology recombination, maturity and transition, breakthrough innovation, adoption and diffusion and lastly, continuous improvement. With early development characterized by imitation of existing technology through access to original equipment manufacturer (OEM) knowledge (Kao et al., 2007). Followed up by technology recombination, which includes novel combinations of existing components based on accumulated knowledge or internal R&D capabilities (lo Storto, 2008), and maturity cycles driven by market demand and technological limits of spatial multiplexing of optical signals (Benson et al., 2013). The maturity period can consist out of multiple consecutive and complementary cycles, possibly affecting total innovation time significantly. After maturity, breakthrough innovation is characterized by high cost savings and simplification, enabling industry transformation as mentioned before by Welch (2020). With the adoption and diffusion phase being characterized by extra initial costs followed by gains in efficiency, in particular for organizations with prior innovation experience (Garrone, 1995). The last innovation phase for optical data transmitting equipment consists of continuous improvement, which is described by monitoring performance and learning through data analytics to gradually enhance network capacity (Oda et al., 2018).

Model simplifications

Furthermore, network redundancy has been excluded, factoring out the effect of redefining the network links. Therefore, existing network infrastructure foundations are assumed to be reused with new equipment, parallel to existing nodes and links scattered within the geographical scope. As is the case with the implementation of equipment from generation A to B, described in the table in the appendix. However, performance efficiency developments could lead to operating while using less links to reduce costs and energy. This would change the total stock build-up of amplifiers for instance, as optical signals would then require less in-line amplifiers situated between the core routers. Moreover, network topology is also based on considerations surrounding minimizing bandwidth usage and minimizing latency (Kavian et al., 2009), limiting projections of required equipment further.

As with modelling recycling and reusing impact on primary demand, results from chapter 7 shows that primary demand on an annual basis is the same when used for the same recycling and reusing rates. Although this is a simplification of actual recycling rates which is different according to each critical raw material as presented in the table in the appendix, derived from current recycling practices. With consequent aggregated recycling flows of materials resulting in diminishing yields compared to reuse of all the components in the equipment.

Also, the recycling and reusing loop is modelled to treat the feedback flows instantly, in which material and equipment flowing out of the stock becomes available for reuse and recycling in the same year's inflow calculation. However, this characteristic neglects possible delays connected to refurbishing and extra steps for recycling, such as collection, dismantling, separation and chemical or mechanical extraction.

Sensitivity implications

As visualised in paragraph 6.5.2 surrounding the sensitivity analysis, the CAGR emerges as the most significant driver of total primary demand, while improvements of data efficiency and miniaturization of components demonstrate modest impacts with other parameters showing even less effect. This due to the CAGR being reapplied on an annual basis over a course of 20 years, resulting in a constant multiplication of the demand trajectory. In which small changes in input, correlates with exponential changes in output. On the other hand, other variables such as data efficiency development, functions as a constant reduction of the baseline data growth. WHereas miniaturization serves as a reduction of CRM mass per unit of equipment by a constant factor, resulting in smaller trend of material level growth compared to required equipment at each point in time.

Thus, data efficiency and miniaturization, as well as the other exogenous parameters integrated as multiplications are applied once per time step and do not have progressively higher values. As a consequence, when data efficiency is shifted from 0 to 20%, demand is cut by approximately 20%, whereas a miniaturization shift from 0 to 10% also reduces demand by roughly 10%. However, the savings are considerably smaller than the leverage of the CAGR on the demand development across all modelling years.

Besides the exogenous parameters integrated as a multiplication of the intermediate variable, the price elasticity of respectively PCBs and CRMs are implemented as exponents on the unit prices of PCBs and market prices of CRMs. This affects the effective recycling and reusing rates by a rate which is already close to 1, with the run configuration values used for price ratios or base of the exponent varying around 0.9 and 1.1. Also, their cumulative leverage remains small as with the parameters above, this refines the base recycling and reusing rate in the same way each year, rather than having progressively increased rates in each following year.

Therefore, the effect of price elasticity would be significantly more effective if the base of the exponent, so higher prices instead of factors (between 0 and 1) are used for PCBs and CRMs, reinforcing the equipment to be re-used and CRMs to be recycled more often. This however, requires extensive data on macro economic shifts from product and material level to substitute markets. Combined with research from (Radetzki & Warell, 2017), stating that material demand in a product is a derived demand from the whole end-product instead of individual materials, resulting in a low elasticity value for the cost increase or decrease of primary materials.

9.2.2. Method limitations

Dynamic material flow analysis

The objective of dynamic material flow analysis is to map long-term processes for product and consequent material flows and stock accumulation. However, the specific case study for this research shows technology characterised by fast innovative cycles and respective replacement of the network infrastructure, exceeding possible lifetime parameters.

Material content of PCBs have been taken from a certain snapshot in time for the OTN equipment based on results from the manufacturer as seen in the table in the appendix. Although as reflected by results from the table in the appendix, materials show varying dispersions for each case study period when comparing (Wagner et al., 2021) and (Xia et al., 2024). With material content of amplifying equipment derived from a study by Flik (2021), in which assumptions based on consultations with experts had to be made.

Regarding the determination of recycling values from end-of-life recycling, the input rates reported in the table in the appendix are subject to certain limitations. These limitations can be found in the calculated method for the 'ratio of recycling from old scrap to European supply of raw material' (Blengini, Nuss, et al., 2017). This methodology uses a system boundary for EoI-RIR focused on end-of-life returns into processing and manufacturing, without capturing potential urban-mining from upstream manufacturing scrap (Blengini, Nuss, et al., 2017). Furthermore, the EoI-RIR data from the Material systems analysis (MSA), initially drawn up by BIO (2015) for the European Commission, has most recently been updated in 2023 for most identified CRMs, although bismuth and tantalum were lastly updated in 2021 with manganese and nickel having their most recent update in 2020 (European Commission, 2024a). Additionally, recycling rates inherently possess uncertainties due to the presence of informal recycling adding up to 8% for ICT equipment (GSMA, 2022).

Moreover, recycled inflows in a dMFA model are strictly sourced from the outflow of previous cohorts within the equipment stock. Consequently, external recycling streams, such as material recovered from outside the system is not 'allowed' to contribute to the future inflows. As a result, the model could underestimate the potential availability of secondary CRMs in external regions where old cohorts of products with potential CRMs is currently processed and available, besides recycling of the internal pool of equipment.

Criticality assessment

The supply risk as defined by (Blengini, Blagoeva, et al., 2017), consists of a combination of the Herfindhal-Hirschmann Index, quantifying the contribution of global production and EU sourcing, with the Worldwide Governance Indicator reported by World Bank Group (2024), qualifying the level of governance of the countries. This methodology uses an average of sub-indicators such as political stability and control of corruption to match the last 5 years of production data (World Bank Group, 2024). For instance, in 2023, the assessed range was 2016-2020 (Espinoza, 2023). Consequently, governance indices could lag behind real-world shifts such as elections and sanctions, resulting in over- or underestimations of true supply risks. For example, HREEs and LREEs, which can be found in PCBs and amplifiers in tables in the appendix, are primarily processed by China (Grohol & Veeh, 2023). Which has seen some sub-indicators such as political stability and absence of violence/terrorism substantially reduce from 36 to 25 percentile rank between 2018 and 2023 (World Bank Group, 2024), resulting in dynamic index values for supply risk with different inclusions or exclusions of materials for each iteration, especially if the material is positioned near the supply or economic indicator threshold.

9.3. Recommendations for future research

Based on the scope and limitations of the study, the following recommendations for future research are presented and elaborated below.

Stakeholder analysis

As this study involves mostly quantitative methods to determine the effect of the different resilience strategies, a stakeholder analysis could extend the research rigour due to different factors. Since presenting an extensive list of the interests and objectives of the different stakeholders in the supply chain could show conflicts in consensus for the integration of CE strategies (Peiró et al., 2020). For instance, extending lifetimes of products could be desirable for the buying firm to reduce required novel material, however, consequently, the manufacturer would sell lower quantities of their technology. However, this is seen form a bilateral negotiation between the buying and selling party, whereas stakeholder engagement should be shifted from linear to a circular structure to drive sustainability (Fobbe & Hilletofth, 2023). In which linear stakeholder engagement involves the manufacturer, customer and government whereas a circular structure extends the engagement effort toward the users, waste companies and lower tier suppliers (Fobbe & Hilletofth, 2023). Helping to overcome the knowledge gap of product origin and better assess CE options for the specific product group (Guldmann & Huulgaard, 2020).

Telecom specific economic importance criteria

The identification of CRMs was based on the EU framework for this study. In this framework, the economic indicator is based on the share of end use in a material and the sector's value added defined by NACE sector (Blengini, Blagoeva, et al., 2017). With specific optical data transmission equipment most closely captured by key classes 26.30: 'Manufacture of communication equipment' and 27.31: 'Manufacture of fibre-optic cables' (Eurostat, 2008). Although these aggregated sectors are broad and with possibly only limited amounts of value added coming from the specific optical components studied in this report. Moreover, this classification uses historical data and fixed substitution indices (Blengini, Blagoeva, et al., 2017), resulting in economic importance changing for each iteration. Therefore, future research could be conducted to specify the economic value of optics in telecom on a longer term to address the changing nature of the Economic Importance indicator, as well as accounting for downstream end-users instead of the current macro-economic perspective.

Data efficiency development methods

As data efficiency development was determined to be one of the exogenous variables with a relative high reported R_2 of 0.038 besides miniaturization and most significantly the compound annual growth rate of data. Further research could be made on the effectiveness of different strategies a telecom company has on reducing data transmission across the optical transport network. With current strategies depending on considerations for costs of data transportation from a centralized location compared to costs of local caching of the same content destined for consumers from a decentralized location (Network architect, 2025).

Equipment scope expansion

As this study had a scope of optical equipment in the Netherlands, with an emphasis on transponders and amplifiers. It could be interesting to expand the research for optical data transmission infrastructures across Europe since printed circuit board assemblies have been reported by the supplier to be comparable for most fibre optics equipment within the fleet of the OEM (Supplier, 2025). As a result the overall impact of the fibre optic sector will be magnified and strategies from a European perspective could be formulated in the form of international regulations, or collaborations on new mining activities for instance.

10

Conclusion

As communication via the optical transport network is an integral part of data transmission in the fixed network and is prone to expansion in the future, this study was aimed at investigating how critical raw materials demand develops according to increasing equipment deployment. It was found that a variety of critical raw materials are embedded in amplifiers and PCBs in transponders respectively. Since critical raw materials are characterized by supplying risks based on a number of factors, it is important for telecommunication companies to become more resilient for the supplying risks in the future. Therefore, the following main research question was introduced:

What strategies can KPN implement in their operations to secure a resilient supply chain of critical raw materials embedded in optical transport network equipment?

In order to answer this research question, the research was divided to first define the static CRMs in relevant fibre optical equipment, followed up with mapping demand development in the future and lastly by evaluating the impact of resilience strategies on an firm level.

Static CRM composition of fibre optical equipment

In the first phase of the study, 16 different critical raw materials have been identified within amplifiers and in PCBs embedded in transponders. With silicon metal and bismuth present in both products. Whereas the CRMs only found in amplifiers include erbium, thulium, germanium, praseodymium, with CRMs in PCBs consisting of antimony, boron, magnesium, manganese, nickel, palladium, ruthenium, strontium, tantalum, titanium, tungsten and yttrium. While the concentration of CRMs in PCBs found in transponders each present a small fraction of the board mass, it collectively represents a variety of concentrated risks if supply is suddenly disrupted.

When CRM mass percentage is plotted against supply risk for both amplifiers and transponders, there seems to be no clear correlation, indicating that the mass percentage alone is insufficient for evaluating vulnerability to supply disruptions. Bulk elements such as silicon show low supply risks, whereas magnesium and yttrium cluster significantly higher in the supply-risk dimension despite their lower mass percentages. This lack of correlation underscores the necessity for KPN to adopt a tailored, CRM-specific approach to risk management rather than relying on mass based assumptions. Even minor disruptions in the availability of low volume CRMs could significantly impact amplifier and transponder production, consequently threatening both the expansion and necessary replacement of fibre optical equipment for KPN.

Primary CRM demand development

Regarding the next phase and corresponding sub-research question, the prospective dMFA model quantifies how equipment rollout drives CRM demand. While, from 2025 to 2045, total amplifier and transponder equipment stock is projected to substantially increase in the latter years from 2033 onwards, causing primary CRM inflows to rise in the same order of growth. Depending on the scenario, the least growth, for sustainable and circular economy scenario still requires a factor 9 increase of primary material demand compared to a factor 14 seen for the AI driven scenario. This is also illustrated by the primary use rate in each point in time, in which even high recycling yields cannot fully account for the rapid initial and especially post 2038 network growth and the absence of corresponding 'older' cohorts.

Although the absolute mass of CRMs, particularly found in transponder PCBs, is modest during the model window, competing sectors could negatively affect pricing and availability of CRMs. Primarily nickel, praseodymium and manganese shows considerable growth between 2030 and 2050 through its usage for the transition to e-mobility and wind turbines, possibly increasing supplying risk as a consequence. These findings highlight a growing operational risk, since demand for fibre optical communication is scaled with data growth, as demonstrated in the sensitivity analysis. Consequently restraining KPN to meet the compound annual growth of data transmission if equipment inflow is stalled.

Firm level resilience strategies

Finally, the third phase described the evaluation of the quantified impact of strategies combined with managerial implications from the perspective of a telecommunication company. With results showing that individual circular economy strategies can reduce primary CRM demand by up to 25 and 30% for a lifetime extension to 15 years, a recycling or reusing yield of 60% and material intensity reduction of 30% respectively. Indicating that integration of individual strategies is insufficient to reduce material independency significantly. Although compound strategies show more potential than individual strategies by reducing primary CRM demand up to roughly 57% when integrating an all round high configuration, its actual savings compared to expected savings is limited by the dampening effect of combining strategies. In which the biggest gap is created by combining lifetime extension with recycling/reusing due to the delay of available outflow for the feedback loops. From a temporal perspective, it could be seen that strategies are preferable at different points in time for the OTN equipment, with a distinction of short (2025 - 2032), medium (2033 - 2038) and long term (post 2038) periods characterized by respective smaller initial growth, stable maintenance and high growth. In which reduction yields most savings during the expansion phase at the beginning and especially in the post 2038 peak. While lifetime extension is also effective in the short term, it hinders recycling/reusing which shows most potential during the plateau period between 2033 and 2038.

In addition to quantitative results, specific resilience strategies from an organizational perspective shows the constraints for a telecommunication company from economic and transparency limitations of recycling small amounts of CRMs for instance and subsequent issues with substitution of CRMs including other CRMs when shifting to other elements or even technologies for semiconductors and fibre cables. Whereas reusing and lifetime extensions show similar limitations on access to software and knowledge of the composition of hardware, combined with a lack of policy and incentive to extend lifetimes. To address some of the constraints for this type of equipment, organisation specific strategies are proposed which require early intervention and close collaboration with OEMs, regarding equipment take-back and firmware updates for instance. However, this dependency on supplier eco-design choices and constraints with alternative supply strategies underlines the need of internal circular strategies, but also shows the limited control KPN has without upstream influence.

Future research

Regarding future research and the identified methodological and modelling limitations of the current conducted study, there are some topics which could be addressed. First of all, a more thorough stakeholder analysis could be integrated to get a better understanding of what the powers and interests of the relevant stakeholders are, and whether a circular structure instead of the current linear engagement proves effective. In addition, telecom specific economic importance should be addressed for a longer period in time and data efficiency methods should be investigated on the considerations made for centralized data transmission or local caching of content. Lastly, as this study only included two products in the infrastructure of KPN, expansion of the scope of the study could magnify the impact on a higher level.

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11

Final remarks

The appendix has been excluded from the repository report version due to confidentiality of the data for KPN.