Optimizing the Copper Recycling Network in Europe under the Critical Raw Materials Act (CRMA)

Assessing the Impact of the CRMA on Copper Supply Chains

by

V.C. van Citters

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Student number: 5871026

Thesis committee:

Committee chair, first supervisor:	Dr. P.S.A. Stokkink
Second supervisor:	Dr.ir. A. van Binsbergen
Supervisors KPMG:	Drs. L. van Mens, Drs. P.M.L. Clercx

Abstract

The European Union's (EU's) Critical Raw Materials Act (CRMA) aims to strengthen the EU's resource resilience by increasing the autonomy of Critical Raw Material (CRM) supply through EU-based extraction, processing, and recycling, thereby reducing external dependencies and promoting a circular economy. The CRMA mandates, among others, that at least 25% of CRMs come from EU-based recycling. Copper, a key CRM, faces growing demand, and with mining alone, future supply will not fulfill demand. This research analyzed the copper supply chain before and after the CRMA. It was found that recycling is the most promising solution for adherence to the CRMA and a sustainable and resilient future. The study develops a Mixed Integer Linear Programming (MILP) model to optimize the European copper recycling network under the CRMA recycling requirement. The model minimizes total costs while determining the optimal number, locations, and capacities of recycling facilities. The model is tested through a case study of a natural resource company and is usable to similar firms. Results identify four optimal facility locations: Stuttgart, Geithain, Bologna, and Barcelona, which were selected based on, among others, geographic centrality and supply and demand quantities. Sensitivity and scenario analyses reveal the network is vulnerable to facility outages, supply shortages, and significant demand increases. Decentralizing the network by adding a fifth facility improves resilience with limited additional cost.

Preface

Dear reader,

This thesis marks the final step of my Master in Transport, Infrastructure, and Logistics at the TU Delft, with a specialization in Transport Networks. The research was conducted for KPMG, where I was part of the Supply Chain & Procurement team.

Writing this thesis has been an enriching journey, one filled with many phases of exploration, challenge, and growth. From the start, I aimed not only to meet academic requirements but also to create something meaningful, both for KPMG and for myself. As someone who is passionate about sustainability, I wanted my work to contribute to a more sustainable future in a way that aligns with my values.

Throughout this process, I was fortunate to receive great support from my academic supervisors, Patrick Stokkink and Arjan van Binsbergen. Their insights, critical perspectives, and reassuring talks, especially in the early stages when I felt stuck, helped me move forward. I want to thank them for their guidance and valuable feedback.

I am also grateful for the opportunity to conduct this research at KPMG. I would like to extend my thanks to my company supervisors, Philippe Clercx and Liselotte van Mens, for their continuous support, and insightful feedback. Additionally, I want to thank all the colleagues from the team for their mental and positive support and for ensuring I had a great time.

Lastly, I want to express my gratitude to my friends and family. Their belief in me, along with the encouragement, countless motivational conversations, and the occasional needed distraction provided me with the support I needed.

Diving into the landscape of EU regulations, Critical Raw Materials, the Critical Raw Materials Act, copper supply chains, and recycle network optimization has provided me with valuable knowledge and insights that I will carry forward in my career. Beyond the research itself, the experience of writing this thesis has been an incredible learning process, shaping both my professional and personal growth. Looking back, I am grateful to conclude my Master on such a positive note. I hope this thesis contributes to broader discussions in this field and serves as a valuable resource for KPMG in the future.

Veerle van Citters
Amsterdam, March 2025

Contents

List of Abbreviations

CRMA	Critical Raw Materials Act
CRM	Critical Raw Materials
EC	European Commission
EU	European Union
SCM	Supply Chain Management
SDGs	Sustainable Development Goals
ESG	Environmental, Social, and Governance
EoL	End of Life
MILP	Mixed-Integer Linear Programming
CoG	Center of Gravity
GTC	Generalized Transport Costs
WF	Wiggle Factor
NUTS	Nomenclature of Territorial Units for Statistics

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1 Introduction

Modern supply chains face numerous challenges, including increasing supply disruptions and the growing importance of sustainability. In particular, the supply of Critical Raw Materials (CRMs) will face a significant risk. While demand for CRMs is expected to rise, Europe relies heavily on imports, often from third countries. To ensure economic resilience, the European Union (EU) must address the risks associated with these strategic dependencies, especially after recent developments such as the COVID-19 pandemic and geopolitical conflicts. As a result, the EU should prioritize strategic autonomy and secure access to CRMs, which are essential for achieving the climate ambitions (Commission, 2023a).

Moreover, as sustainability has become a crucial concept, the United Nations' 2030 Agenda, along with its 17 Sustainable Development Goals (SDGs) introduced in 2015, has set new expectations for businesses to align their strategies and operations with these global goals (Wu et al., 2024). Furthermore, during the COP 28 UN Climate Change Conference in Dubai in 2023, it became clear that progress after the Paris Agreement was slow. The participating countries agreed on measures to accelerate action in these areas by 2030, urging governments to prioritize transitioning from fossil fuels to renewable energy sources (Nations, 2024). As a result, many organizations are striving to integrate sustainability into their operations and supply chain management (Wu et al., 2024). This results in an increased demand for CRMs, as these materials are essential for products used in the energy transition, such as batteries, solar panels, and wind turbines.

In response to these challenges, the EU has introduced regulatory frameworks such as the Critical Raw Materials Act (CRMA), which came into force in May 2024. The CRMA aims to strengthen the EU's resource resilience by increasing the autonomy of CRM supply through EU-based extraction, processing, and recycling, thereby reducing external dependencies and promoting a circular economy (Hool et al., 2023). The CRMA mandates, among others, that at least 25% of CRMs come from EU-based recycling.

This thesis first investigates the effects of the CRMA on a copper supply chain network. Copper, a CRM classified as a Strategic Raw Material (SRM), plays an essential role in modern industries, particularly in electrification and clean energy technologies. Therefore, copper has become indispensable to the energy transition, increasing demand (Commission, 2023c). The study will specifically focus on natural resource companies, as they will be directly affected by the CRMA. After evaluating the copper supply chain of these companies, it is concluded that the most relevant and effective area for improvement within the supply chains of these companies lies in the recycling phase (including collection of waste, recycling, and distribution of recycled copper to customers). Unlike mining and processing operations, which are more challenging to adapt and are not sustainable in the long term, the recycling component offers an opportunity for change and enhancement. By improving recycling practices, these companies can align their operations with the CRMA's sustainability goals and achieve long-term supply chain resilience.

Secondly, this research focuses on optimizing the copper recycling network within Europe for natural resource companies. The research identifies the optimal number, locations, and capacities for copper recycling facilities using Mixed Integer Linear Programming (MILP) while adhering to the CRMA's recycling requirement. Using publicly available data, a case study on a leading natural resource company is conducted. Additionally, multiple scenarios, such as supply and demand fluctuations and disruptions, are analyzed to assess the network's performance under varying conditions.

1.1 Relevance

Global warming and the climate crisis have underscored the need for a transition toward cleaner and more sustainable energy systems (including energy generation, storage, and transport). This energy transition is critical in reducing greenhouse gas emissions and reducing the impacts of climate change. As nations and industries aim to decarbonize and adopt renewable energy technologies, the demand for materials like copper has increased. However, this growth in demand also highlights vulnerabilities in global supply chains, as they become increasingly exposed to risks related to environmental disruptions, geopolitical tensions, and resource scarcity. These issues are deeply interconnected (as can be seen in Figure 15.1 in Appendix 15.1), where the effects of global warming worsen supply chain risks and vice versa (Forum, 2023).

As mentioned before, the EU has introduced the CRMA, which aims to enhance the EU's capacity to secure CRMs, such as copper, and reduce dependence on external sources. The CRMA requires that at least 25% of CRMs used in the EU come from recycling efforts. This regulation directly impacts natural resource companies as their customers will respond to the CRMA by buying more recycled-based materials.

Focusing on copper recycling is particularly relevant, as mining and processing alone will not be sufficient to meet future demand. The timeline to develop new mines is substantial, often taking 10 to 20 years. As highlighted by experts at the TU Delft, the pressing issue is not the depletion of critical metals, but rather the inability to secure them in time for the urgent needs of industries, especially as the EU pushes for a green transition. Mining cannot meet demand in the required time frame, and new mining projects will likely fail to meet environmental goals (Peck and Sprecher, 2023).

On the other hand, recycling copper presents a promising solution. Copper is one of the few materials that can be recycled indefinitely without losing quality. The quality of recycled copper is identical to that of mined copper, making it a sufficient substitute. Focusing on improving copper recycling can contribute significantly to reducing the environmental impact and dependency on mined sources.

2 Literature review

In this section, the literature review and methodology for finding the literature will be presented. Background information on the subject will be provided, as will methods for supply chain optimization. First, an exploration of sustainable supply chain management and resilient supply chains will be addressed. An introduction to the CRMA will follow this. Lastly, various quantitative models for supply chain optimization will be explained.

2.1 Methodology

Search engines Google Scholar and Scopus were used to find suitable articles. All articles were published in an academic journal or are European Commission (EC) documents. The concept groups, keywords and truncations used are summarized in table 2.1. Apart from the combinations shown in this table, other keywords were also used to find the most suitable articles for this literature review.

Table 2.1: Conceptual and methodological framework for literature review

Concept groups	Supply chain management, CRMA, resilience, sustainability, optimization techniques
Key words	Supply chain management: supply chain (optimization), network design CRMA: CRMA, metals, EU policies/ regulations Sustainability: sustainability, circularity, closed-loop, remanufacturing Resilience: resilience, disruptions optimization techniques: linear/ robust programming
Truncation	(Supply chain management) AND (network design) (Supply chain management) AND (EU regulations) (AND (sustainability)/ (resilience)) (Supply chain management) AND (metals) AND (CRMA) (Supply chain optimization) AND (linear/ robust programming)

After the searching process, in which only the most suitable articles were selected, a final literature list was found encompassing 28 sources: (Hool et al., 2023), (Longo and Cardillo, 2024), (EU, 2023b), (Commission, 2023c), (EU, 2023a), (Nations, 2015), (Wu et al., 2024), (Waltho et al., 2019), (Turken et al., 2017), (Turken et al., 2020), (Wang et al., 2019), (Konstantaras et al., 2021), (Wang and Wu, 2021), (Luo et al., 2022), (Lotfi et al., 2022), (Lotfi et al., 2024), (Ivanov, 2022), (Paul et al., 2015), (Hishamuddin et al., 2013), (Manupati et al., 2024), (Cia and Cunha, 2024), (Arabi et al., 2024), (Khalili-Fard et al., 2024). (Lotfi et al., 2020), (Dulia and Shihab, 2024), (Baghalian et al., 2013), (Saeedi et al., 2024), and (Ala et al., 2024).

2.2 Sustainable Supply Chain Management

Sustainability has become an increasingly important concept due to the rise of socio-environmental issues like climate change, air pollution, and health problems related to pollution. The United Nations' 2030 Agenda and the 17 Sustainable Development Goals (SDGs) present new challenges for businesses to align their operations and strategies with these goals (Nations, 2015). Consequently, many organizations are working to integrate sustainability into their operations and supply chain management. The field of sustainable and green operations and supply chains has seen significant growth in literature. Numerous studies have reviewed various aspects of sustainability within supply chains, such as carbon emissions, waste management and reverse logistics. However, these studies often overlook the influence of government policies, which include new regulations to encourage environmental responsibility among companies (Wu et al., 2024).

Therefore, Wu et al. (2024) studied how various environmental guidelines affect sustainable and green operations and supply chain management. The study outlined specific operations management decisions and evaluated three areas of sustainable performance: economic performance (ECP), environmental performance (ENP), and social welfare (SW), as highlighted in the existing literature. Three environmental policy instruments are identified: command and control regulations (CCRs), market-based instruments (MBIs), and information-based instruments (IBIs). Additionally, different parts of operations and supply chain management processes were categorized: pricing, production planning, inventory management, technology management, cooperation and competition, recycling, transportation decisions, and supply chain network design.

Wu et al. (2024) found that some research has been executed on the impact on supply chain network design of four MBI policies: carbon cap, carbon offset, cap-and-trade and carbon tax (Waltho et al., 2019). Waltho et al. (2019) reviewed 105 articles focusing on green, environmentally friendly, and sustainable supply chain network design, analyzing the trade-offs between environmental impact and cost. The review is organized around the carbon policies and measurable emission sources within the supply chain network design. Examples of studies that focus on supply chain network design under the four MBI carbon policies are Turken et al. (2017) and Turken et al. (2020), in which the effects of carbon tax and command-and-control legislation are studied on supply chain network design focusing on ECP and ENP. Moreover, Wang et al. (2019) and Konstantaras et al. (2021) study the effects of the MBIs carbon cap-and-trade and carbon tax on inventory management and Wang and Wu (2021) and Luo et al. (2022) researched the effects of the MBIs carbon tax and carbon cap and trade on recycling/remanufacturing focusing on ECP and ENP.

However, apart from several studies on these MBI carbon policies, no literature can be found on the impact on supply chains of recently implemented EU regulations such as the CRMA, CBAM, or BATT2, which is also suggested as an area for further research in some of the literature.

2.3 Resilient supply chains

Next to studies related to sustainability and supply chains, much research has been conducted on viable supply chains. The Viable Supply Chain (VSC) is an emerging concept in supply chain management that emphasizes sustainability, agility, and resilience. After the COVID-19 pandemic, managers have increasingly focused on the resilience and flexibility of supply chains. A resilient supply chain is the ability to recover quickly from disruptions. Additionally, as mentioned before, there exists a growing concern from governments and consumers for sustainability. Moreover, the key aspect of agility is the capacity to deliver products and services promptly, minimizing delays and effectively meeting demand (Lotfi et al., 2022). Lotfi et al. (2022) shows in their research a viable supply chain with a vendor-managed inventory approach by considering blockchain, risk and robustness.

Among others, Lotfi et al. (2022), Lotfi et al. (2024) and Ivanov (2022) discussed models on viable supply chains in different areas. First of all, Lotfi et al. (2022) researched a viable supply chain with a vendor-managed inventory approach considering blockchain, risk and robustness, in which a supply chain is optimized in terms of costs considering resilience, agility and sustainability, having multiple vendors, multiple retailers and using MILP robust and stochastic optimization. Following up on this, Lotfi et al. (2024) executed similar research but with the addition of one single variable and lastly Ivanov (2022) studied the concept of the VSC and proposed a VSC framework that enables decision-makers to design supply chains capable of responding to both positive changes and harmful disruptions. Such a model ensures long-term viability and effective recovery from crises such as the COVID-19 pandemic.

Lastly, disruption recovery has also been researched tremendously. For example, Paul et al. (2015) developed a disruption recovery model for an imperfect single-stage production-inventory system and Hishamuddin et al. (2013) obtained a recovery model for a two-stage production and inventory system with the possibility of transportation disruption.

Like the literature on sustainable supply chain (optimization), the literature on VSC has never included recently implemented EU regulations.

2.4 Critical Raw Materials Act and EU regulations

In May 2024, the Critical Raw Materials Act came into force. The European Commission formally proposed CRMA as part of its broader strategy to strengthen the EU's resource resilience (Hool et al., 2023). Moreover, CRMA is part of the Green Deal Industrial Plan, next to the European Green Deal, a transformative initiative in response to the Sustainable Development Goals (SDGs), introduced by the United Nations in 2015. The Green Deal focuses on achieving climate neutrality, promoting a circular economy, and reducing emissions. At the same time, the Industrial Plan enhances the competitiveness of zero-emission industries and supports net-zero technologies (Longo and Cardillo, 2024). Critical raw materials (CRMs) are of great economic importance to Europe and are highly susceptible to supply disruptions due to growing global demand, particularly as economies transit towards decarbonization (EU, 2023b). Products produced from CRMs include engines and turbines, batteries, LED lights, wind turbines and navigation equipment. These companies will feel the impact of this newly entered regulation in their supply chains (Commission, 2023c).

Therefore, the Critical Raw Materials Act aims to enhance the EU's capacity for CRMs, reduce dependency on external sources, boost preparedness, and promote circularity and sustainability within the supply chain (EU, 2023a). Key guidelines for 2030 set by the Act include:

1. At least 10% of the EU's annual consumption must come from extraction;
2. At least 40% should be processed within the EU;
3. At least 25% must be recycled;
4. No more than 65% of annual consumption can originate from a single third country.

This legislation targets explicitly reducing the EU's reliance on other countries for crucial metals, including rare earths, promoting diversification of supply sources. It also aims to reduce administrative burdens by simplifying the approval processes for CRM projects while maintaining strong social and environmental standards. Additionally, selected strategic projects will benefit from financial support and reduced permitting timelines (Commission, 2023c). Furthermore, EU member states must enhance the collection and recycling of CRM-rich waste and investigate the recovery of these materials from extractive waste. The Act empowers the Commission to establish environmental footprint regulations for CRMs. This will help to increase the circularity and sustainability of CRMs placed on the EU market, fostering informed customer choices about products containing CRMs (EU, 2023b).

In addition to the Critical Raw Materials Act (CRMA), the EU has introduced several other necessary regulations, including the Corporate Sustainability Reporting Directive (CSRD), the Corporate Supply Chain Due Diligence Act (CSCDDA), the Ecodesign for Sustainable Products Regulation (ESPR), the Carbon Border Adjustment Mechanism (CBAM), the EU Battery Regulation (BATT2), and the Regulation on Deforestation-Free Products (EUDR). In Table 2.2 an overview of these regulation is provided.

Table 2.2: Other important regulations introduced by the EU

CSRD	Requires large and publicly listed companies to report on the social and environmental risks they encounter regularly, as well as the impacts of their activities on people and the environment (Commission, 2024e).
CSCDDA	Promotes sustainable and responsible corporate behavior to facilitate a fair transition towards a sustainable economy (Commission, 2024d).
ESPR	Aims to make sustainable products within the EU norm (Commission, 2024f).
CBAM	Serves as the EU's tool to assign a fair price to the carbon emissions associated with the production of carbon-intensive goods entering the EU, thereby encouraging cleaner industrial practices in non-EU countries (Commission, 2024b).
BATT2	Ensures that batteries sold in the EU market are sustainable and circular throughout their entire lifecycle (Commission, 2024a).

2.5 Quantitative models

In terms of (sustainable and resilient) supply chain optimization, many different models can be used. Depending on factors such as open or closed loop, uncertainty due to disruptions, and single or multi-objective, the model is defined.

First, the linear programming optimization technique is the most used model. For example, Manupati et al. (2024) developed a mixed-integer linear programming (MILP) model aimed at minimizing the total costs associated with the proposed remanufacturing supply chain network for EOL tires (single-objective). With this model, the recovery and remanufacturing operations of the EOL tires were managed effectively, while minimizing costs. On the other hand, Cia and Cunha (2024) used a multi-objective linear optimization approach for designing a sustainable logistics system that identifies the optimal flow of ultrafine mineral residue, known as tailings, to various destinations using an efficient multimodal system. The model is designed to maximize total profit while minimizing negative socio-environmental impacts. MILP can also be combined with bi-level programming in which the model is divided into two levels (leader and follower). For example, Arabi et al. (2024) proposed a mixed-integer linear bi-level programming model that accounts for operational and disruption risks to design a robust and resilient mining supply chain network. The government was considered the leader, and the iron ore supply chain was considered the follower.

Nevertheless, nonlinear programming techniques are also used. Such as Turken et al. (2017) who examined the impact of environmental regulations, specifically a carbon tax and command-and-control legislation, on a firm's plant capacity and location decisions. In this context, command-and-control referred to a cap on total emissions with penalties for any polluters exceeding this limit, while a carbon tax introduced a variable cost for emissions. An exact algorithm was developed to tackle the resulting discontinuous nonlinear integer problem. Besides, Konstantaras et al. (2021) focused on a supply chain system that integrates manufacturing, remanufacturing, and repair activities (closed-loop manufacturing) to address time-varying demand within the regulatory framework of a carbon tax. The total cost of the system was presented, followed by the formulation of a mixed-integer nonlinear programming problem aimed at determining the optimal policy for manufacturing, remanufacturing, and repair cycles.

In addition, robust, stochastic, or fuzzy programming can add an uncertainty factor to the model, for instance, to reflect disruptions. First of all, the concept of robust optimization involves defining an uncertainty set for unpredictable parameters and optimizing based on the worst-case scenarios within that set. Lotfi et al. (2020) and Khalili-Fard et al. (2024) made use of such model. Lotfi et al. (2020), introduced a closed-loop supply chain framework that integrates sustainability, resilience, robustness, and risk aversion. To address this problem, a two-stage mixed-integer linear programming model was developed, supplemented by a robust counterpart model to manage uncertainties effectively. Moreover, Khalili-Fard et al. (2024) presented a bi-objective data-driven optimization model to design a sustainable forward-reverse steel supply chain network. The model utilizes a data-driven robust optimization method that leverages historical data to create a dynamic uncertainty set.

Secondly, in stochastic programming, an uncertainty factor is added through a probability function for each uncertainty parameter (Dulia and Shihab, 2024). This method is widely used for robust programming. For example, Dulia and Shihab (2024) proposed a stochastic optimization model for the integrated supply chain planning of aircraft manufacturing, aimed at maximizing their operating profits. The enlightened uncertainties are supplier pricing and capacities, manufacturing costs and demand. Furthermore, Baghalian et al. (2013) developed a stochastic mathematical formulation for designing a multi-product supply chain network that includes various capacitated production facilities, distribution centers, and retailers in uncertain markets. This model simultaneously addresses both demand-side and supply-side uncertainties. Last, Saeedi et al. (2024) presented a two-stage stochastic programming model designed to create a sustainable closed-loop supply chain for electric vehicle batteries. The model considers economic, environmental, and social criteria, such as costs, energy consumption, carbon emissions, and job creation.

Thirdly, fuzzy programming can be used for uncertainty factors. This method is usually used when data is imprecise or vague. Instead of deterministic (robust) and probabilistic (stochastic), variables are treated as fuzzy sets. As many parameters are considered imprecise, Ala et al. (2024) used a fuzzy optimization approach to enhance the healthcare supply chain network. The study presents a novel optimization model aimed at achieving multiple objectives, including minimizing total costs and environmental impacts while simultaneously maximizing social benefits, such as job creation.

Finally, heuristic and genetic algorithms can be used as optimization techniques. Heuristic algorithms are simple, rule-based approaches that help find reasonable solutions quickly, while genetic algorithms imitate natural selection to evolve better solutions over time. These models can be helpful when a model is very complex and time-consuming. Among others, Saeedi et al. (2024) and Manupati et al. (2024) used these techniques to obtain their solutions.

2.6 Conclusion

This section included background information on sustainable supply chain management, resilient supply chains, the CRMA, and quantitative models used for supply chain optimization.

First, the literature on sustainable supply chain management highlights the importance of integrating sustainability into operations due to increasing regulatory pressures and socio-environmental concerns. While extensive research exists on sustainable supply chains, particularly regarding carbon policies, studies on the impact of newly implemented EU regulations, such as the CRMA, remain limited. This gap highlights the need to examine how the CRMA affects supply chain network design.

Similarly, research on resilient supply chains and the Viable Supply Chain (VSC) framework emphasizes the need for supply chains to be adaptable and robust. However, no existing research considers the impact of the CRMA or similar EU policies on resilience.

Reviewing quantitative models provides a foundation for selecting an appropriate methodology for optimizing a recycling network. Linear and nonlinear optimization approaches, including MILP, bi-level programming, stochastic, robust, and fuzzy optimization, have been widely used for supply chain design under uncertainty and sustainability constraints.

2.7 Research gap and contribution

As mentioned in the previous section, much research has been conducted on sustainable and resilient supply chain optimization. Moreover, many different variations of supply chain management have been addressed and optimized using a variety of models, including linear, robust, stochastic, fuzzy, and heuristic techniques. These models have been applied to various industries and challenges, such as waste management, remanufacturing, and integrating environmental policies like carbon taxes and emissions regulations.

However, no research has been done on the impact of recently implemented EU regulations, such as the Critical Raw Materials Act (CRMA), on open and closed loop supply chains involving critical raw materials (CRMs). This thesis introduces a study that aims to fill this gap in the literature regarding the impact of CRMA on supply chain networks or recycling network optimization involving CRMs. This study provides valuable insights for natural resource companies. It supports optimizing their recycling network while ensuring compliance with the CRMA recycling requirement. Additionally, the research enhances companies' understanding of the regulation's impact on supply chains.

The research is executed for the consulting company KPMG N.V. The CRMA regulation is currently a central topic within KPMG, making this research valuable for the firm. The study will provide KPMG with essential insights into the complexities of sustainable supply chain management in the context of new regulations. Moreover, this knowledge will enhance the development of sustainable supply chain thought leadership through the network design solution. With sustainable supply chains being one of KPMG's core value propositions, this research directly reinforces their knowledge.

3 Research questions

3.1 Research objective

The objective of this research is to determine how the CRMA impacts the copper supply chain, and how to optimize the copper recycling network of natural resource companies in Europe. Additionally, the study will fill the research gap that no literature exists on supply chain or recycling network optimization considering the CRMA. The objective will be to minimize costs. Moreover, the model's output will be an optimized recycle network for natural resource companies (with the ambition to expand in copper recycling operations), including the number, locations and capacities.

3.2 Research questions

The main research question that is constructed based on the research gap is defined below:

How does the CRMA impact the copper supply chain, and how can the copper recycling network of a natural resource company be optimized to comply with the regulation while minimizing costs?

Sub-questions are formed to break down the main question into manageable parts. Together, these sub-questions will help answer the main research question. In the first two sub-questions, background research is performed, after which a conceptual model is created. Afterwards, during sub-question 3, a mathematical model is constructed, which will be implemented and tested in sub-questions 4 and 5.

1. What are the key requirements of the CRMA, and how do they translate into constraints and opportunities for a supply chain network?
2. What are the processes and structure of a general copper supply chain of natural resource companies, and which parts are most impacted by the CRMA?
3. How can the copper recycling network of natural resource companies be optimized while adhering to the CRMA?
4. What is the optimal design of the copper recycling network under CRMA requirements?
5. How does the optimized copper recycling network perform under scenarios such as supply- and demand fluctuations, and disruptions?

3.3 Thesis outline

In this section, the thesis outline will be presented. First of all, Chapter 4 will describe the research approach used for the study. Afterwards, in Chapter 5, the theoretical background will be introduced, including research on the CRMA, and copper supply chains generally, as well as specifically for natural resource companies. During this chapter, the scope will be determined.

Moreover, Chapter 6 will present the conceptual model, including all the aspects influencing the main goal of the research. Also, the specific optimization will be presented as well as all parameters and aspects influencing this. Fifthly, the mathematical model will be presented in Chapter 7, including the Mixed Integer Linear Programming (MILP) model.

After this, the case study will be presented in Chapter 8 and the data collection process is explained in Chapter 9. An explanation of the derivation of all parameters is discussed.

Furthermore, in Chapter 10 the results of the optimization model will be elaborated on, explaining the structure of the optimal network. These results are verified in Chapter 11, where multiple sensitivity analyses are performed to test the behavior of the model.

Following, in Chapter 12, the robustness of the network is tested using different scenarios, including supply- and demand fluctuations, and disruptions. Finally, a conclusion is drawn in Chapter 13 and the limitations and suggestions for future research are discussed in Chapter 14.

4 Research Approach

This section presents the research approach for this study. In Figure 4.1, the framework is depicted. The framework provides the steps required for answering the research question. The research begins with a definition of the problem, followed by an extensive background investigation. During the background research, the specifications of the problem become clearer. This results in an iteration back to the problem definition and research objective. Subsequently, after analyzing the background and context of the problem, the scope can be defined. Moreover, all the aspects impacting the objective can be mapped, due to which the conceptual model can be developed. The conceptual model serves as a representation of all aspects influencing the objective. Following up, a mathematical model is created to solve the optimization. Given the limited availability of real-world data, a dummy dataset will be constructed using data accessible online, after which the data can be implemented in AIMMS, the software used. Finally, the designed model or framework will undergo a validation process to ensure its reliability and applicability.

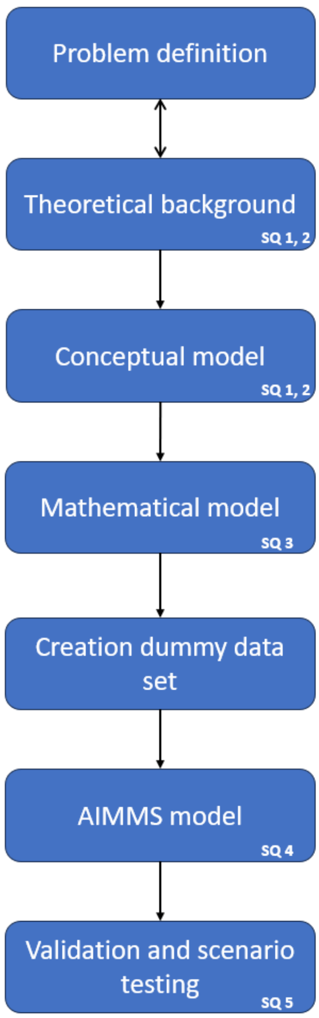


Figure 4.1: Research framework

4.1 Theoretical background and definition of the problem through literature research

Defining the research problem is a crucial first step, as it sets the foundation for the study by ensuring a focus on the right research questions (Verschuren and Doorewaard, 2010). In this research, the problem definition is developed alongside background research to provide context and refine the scope iteratively.

For the first and second sub-questions, literature research will be conducted through desk research, which involves analyzing existing literature and materials collected by others (Verschuren and Doorewaard, 2010). The outcome of the desk research can be read in the theoretical background in Chapter 5. In addressing the first sub-question, the focus will be on identifying the key requirements of the CRMA. This will involve reviewing documents, reports, and academic studies, such as those found on the European Commission's website.

For the second sub-question, studies of supply chain network models from companies using copper will be reviewed to identify the typical structure of such supply chains. Through the research, it will be possible to identify key areas that require adaptation once the CRMA is introduced.

Lastly, literature is reviewed to explore existing mathematical models and optimization techniques, such as linear programming, robust optimization, and stochastic programming. After this, the most suitable optimization method is selected. An extensive overview of potential methods is already available in the literature review in Chapter 2.

4.2 Conceptualizing: relation between CRMA, copper network, and optimization

A conceptual model is a tool used to explain the causal relationships between the core concepts of a research project. It helps to define the research boundaries, identify important variables, and explain their interactions within the study's framework. By mapping the relationships, researchers can organize their understanding of how various elements interact with each other and connect to existing theories (Verschuren and Doorewaard, 2010). The conceptual model, presented in Chapter 6, will serve as a representation of the current situation and the scope of the research.

4.3 Mixed Integer Linear Programming

For the third subquestion, Mixed Integer Linear Programming (MILP) will be used as the optimization technique. MILP is widely utilized in supply chain optimization models due to its simplicity, flexibility, and extensive coverage in academic literature.

Additionally, MILP is well supported in AIMMS, the platform used by KPMG. AIMMS is a powerful optimization platform that provides an interface for modeling and solving, among others, MILP problems (AIMMS, 2023b). In this research, the SC Navigator will be used, which is the supply chain network design software enabling advanced scenario modeling and supply chain analytics (AIMMS, 2024).

The optimization method is structured as depicted in Figure 4.2. First, the mathematical model is created using MILP. In Chapter 7, the mathematical model is described. Afterwards, the necessary data can be collected. This also includes selecting recycle candidate locations using the CoG tool within SC Navigator (described in more detail in the next section). With the data input, the optimal locations are found by running the model in SC Navigator.

A more detailed explanation of MILP and the tools used in AIMMS is provided in Chapter 7.

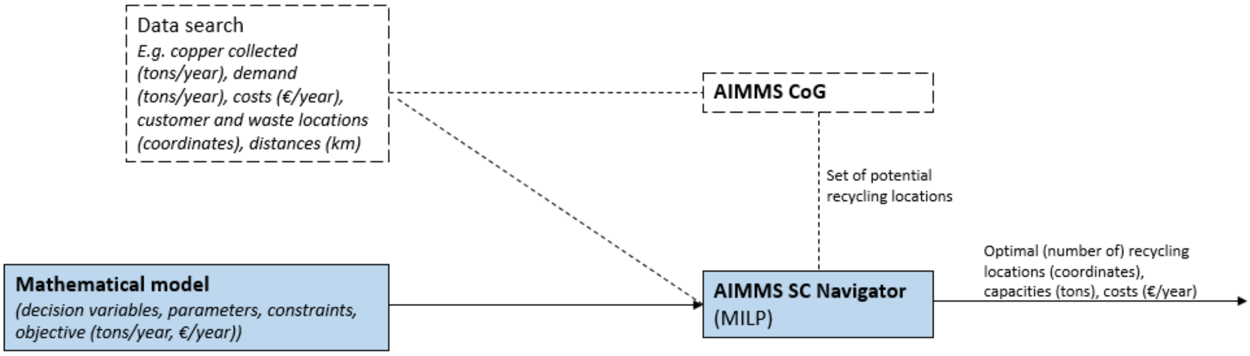


Figure 4.2: Optimization method

4.4 Data search

The data is crucial to test the created model and to run it in AIMMS. As limited data is available, a dummy dataset will be created. Chapter 9 outlines the data used and the necessary assumptions made. The starting point of the study is the demand data published on the website of the use case, namely the natural resource company Glencore. Moreover, public databases are used, such as Eurostat and Statista. Also, existing literature is consulted for data points such as transport costs and recycling capacities.

Furthermore, the Center of Gravity (CoG) tool within AIMMS is used to find a set of candidate recycling facilities (AIMMS, 2023a). The waste and customer data serve as an input after with which the recycling locations can be found. In Section 9.3, a more detailed explanation of the tool is given.

4.5 Testing and validating the model

For the fifth sub-question, which focuses on evaluating how the model performs under different supply chain scenarios (such as supply- and demand fluctuations, disruptions or regulatory changes), scenario-based testing is an ideal tool. In Chapter 12, the scenarios are presented.

Scenario-based testing is useful because it provides insights into how the optimized recycle network reacts to unexpected events or shifts in external conditions. By simulating different scenarios, potential vulnerabilities in the network are identified. The SC Navigator is a perfectly suitable tool as variables, such as demand and supply, can be adapted easily.

5 Theoretical background

This chapter will give an overview on Critical Raw Materials (CRMs) and the Critical Raw Materials Act (CRMA). This knowledge will serve as the base for this research. Thus, in this chapter, the following research question will be answered: *What are the key requirements of the CRMA, and how do they translate into constraints and opportunities for a supply chain network?*

In addition, the chapter will focus on the CRM copper, providing background knowledge on what copper is, what it is used for, what a general supply chain of copper looks like, and what effects the CRMA will have on the copper supply chain. Also, the type of company focused on will be elaborated on and how the CRMA influenced such companies. Therefore, the chapter will also answer the following research question: *What are the processes and structure of a general copper supply chain of natural resource companies, and which parts are most influenced by the CRMA?*

5.1 Critical Raw Materials

The EU defines Critical Raw Materials (CRMs) as materials of great economic importance to Europe and are highly susceptible to supply chain risks due to growing global demand, particularly as economies transition towards decarbonization. This accounts for specifically metals and minerals that cannot be substituted with more common alternatives and have a risk of supply disruption. If the supply of these materials is disrupted, it can lead to economic consequences (EU, 2023a). Materials like lithium and rare earths are vital for key products crucial to Europe's green and digital future, including solar panels, batteries, wind turbines, electric vehicles, and computer chips (Commission, 2023c).

Raw materials provide an industrial foundation for various goods and applications utilized in daily life and advanced technologies. However, access to certain raw materials is becoming an increasing concern both within the EU and globally. Also, the supply chain for critical materials is vulnerable and in many cases highly concentrated. In response to this challenge, the European Commission has established a list of CRMs for the EU, which is checked and updated every three years (Mathieux et al., 2018).

The updated list of critical raw materials 2023 includes those outlined in figure 5.1. Nickel and copper are noted with an asterisk, as they are classified as Strategic Raw Materials (SRMs) but not as CRMs. A specific list of SRMs has been created for those expected to experience exponential growth in supply. These materials have complex production requirements and, as a result, face a greater risk of supply disruptions (Commission, 2023c).

aluminium/bauxite	coking coal	lithium	phosphorus
antimony	feldspar	LREE	scandium
arsenic	fluorspar	magnesium	silicon metal
baryte	gallium	manganese	strontium
beryllium	germanium	natural graphite	tantalum
bismuth	hafnium	niobium	titanium metal
boron/borate	helium	PGM	tungsten
cobalt	HREE	phosphate rock	vanadium
copper*	nickel*		

Figure 5.1: EU list of critical raw materials (EU, 2023a)

An extensive overview of the significant EU suppliers as well as the major EU CRM producers can be found in Appendix 15.2.

The reasons why CRMs are important are listed in the overview of Critical Raw Materials by the European Commission (EU, 2023a):

1. **Link to Industry**: Non-energy raw materials play a vital role in various industries throughout all stages of the supply chain;
2. **Modern Technology**: Technological advancements and improvements in quality of life depend on access to an increasing variety of critical raw materials. For instance, a smartphone can contain up to 50 different types of metals, each contributing to its compact size, lightweight design, and functionality;
3. **Environment**: Raw materials are essential for clean technologies, as they are irreplaceable components in solar panels, wind turbines, electric vehicles, and energy-efficient lighting solutions.

5.1.1 Methodology to define CRMs

Economic importance and supply risk are the two primary parameters used to assess the criticality of raw materials for the EU. "Economic importance" examines how raw materials are allocated to end-uses based on their industrial applications. "Supply risk" considers factors such as the collection of global production of primary raw materials in specific countries, the governance of supplier nations, the role of recycling, substitution potential, EU reliance on imports, and trade restrictions in third countries (EU, 2023a).

5.1.2 Energy transition

Critical raw materials (CRMs) are essential for the energy transition, as they are important in developing technologies such as electric vehicles, renewable energy innovations, and energy-efficient infrastructure. However, the challenges lie not in the depletion of these materials but in their timely availability and the EU's dependency on a single third country for their supply.

Given that opening new mines is a slow process, with new mines taking 10 to 20 years to establish, alternative solutions such as reducing demand, reusing, repairing, remanufacturing, recycling, and recovering metals are critical to meeting future needs. Innovation, particularly in designing more efficient products and improving the recycling of existing materials, will play a crucial role in addressing the growing demand for CRMs (Peck and Sprecher, 2023).

Moreover, the development of new mines could create irreparable environmental damage, which impacts the quality of life of local people. This could result in protests as has happened in Serbia last year when tens of thousands of Serbians protested all summer in 50 cities because the EU wants to start lithium mining (NOS, 2024b).

Therefore, the EU's push for increased mining must be balanced with sustainable practices, such as responsible mining and efficient use of mine waste, to ensure a cleaner and more circular approach to CRM supply. Ultimately, mining, efficient product design, and innovative recycling methods will be necessary to secure the raw materials required for Europe's energy transition (Peck and Sprecher, 2023).

5.2 The Critical Raw Materials Act

As mentioned, CRMs are essential to Europe's economy but are also very vulnerable to supply disruptions. The demand for these materials is rising; for instance, the EU's demand for rare earth metals is projected to increase sixfold by 2030 and sevenfold by 2050. Similarly, lithium demand is forecasted to rise twelvefold by 2030 and twenty-onefold by 2050 (Commission, 2023d). Europe heavily depends on imports, often from a single third country, and recent crises have highlighted the EU's strategic dependencies, putting its climate and digital objectives at risk (EU, 2023a).

The Critical Raw Materials Act (CRMA), which came into force in May 2024 (Hool et al., 2023), responds to these challenges. The Act aims to ensure that the EU can establish strong, resilient, and sustainable value chains for CRMs. The Act will reinforce all stages of the European critical raw materials value chain, diversify the EU's imports to diminish strategic dependencies, enhance the EU's capacity to monitor and mitigate supply risks, and improve circularity and sustainability (EU, 2023b).

5.2.1 Background of the legislation

To address the concern regarding the secure supply of valuable raw materials for the EU economy, the European Commission launched the European Raw Materials Initiative in 2008. This integrated strategy aims to implement targeted measures to secure and improve access to raw materials within the EU. One of the initiative's key actions was to create a list of Critical Raw Materials (CRMs) at the EU level. The Commission established the first list in 2011 and committed to update it at least every three years to reflect market, production and technological developments (Mathieux et al., 2018).

President von der Leyen announced the CRMA during her 2022 State of the Union speech. The CRMA is part of its broader Green Deal Industrial Plan, next to the European Green Deal, a transformative initiative in response to the Sustainable Development Goals (SDGs), introduced by the United Nations in 2015 (Longo and Cardillo, 2024). Moreover, the Act is in conjunction with a Net-Zero Industry Act (NZIA) (Hool et al., 2023).

5.2.2 Consequences of the CRMA on companies

Various stakeholders will be impacted by the CRMA, experiencing both consequences and opportunities due to the new regulation. The different stakeholders affected by the CRMA are: the natural resource industry, the manufacturing industry, the recycling industry, local communities, consumers, national governments, non-EU actors, and investors (Hool et al., 2023).

The CRMA introduces requirements for companies operating within the European Union (EU) and engaged in the sourcing, production, processing, or recycling of CRMs. The CRMA primarily targets large companies and strategic projects within the EU. A 'large company' means a company with more than 500 employees on average and a net worldwide turnover of more than EUR 150 million in the most recent financial year for which annual financial statements have been prepared. Furthermore, the EU also identifies companies based on the dependency on CRMs, and relevance to strategic sectors, such as electronics, renewable energy, and automotive industries (Commission, 2023d). The different consequences the CRMA has for the targeted companies are listed below:

1. Requirements for selected companies

The Act establishes guidelines along the value chain focused on sourcing, processing, and recycling. The benchmarks set by 2030 are the following (EU, 2023a):

1. At least 10% of the EU's annual consumption must come from extraction;
2. At least 40% should be processed within the EU;
3. **At least 25% must be recycled** (focus area of the research, as explained in Section 5.4.4);
4. No more than 65% of annual consumption can originate from a single third country.

2. Conduct regular risk assessments
Companies using SRMs must conduct risk assessments every three years. These assessments involve mapping raw material sources, analyzing potential supply vulnerabilities, and identifying disruption risks. The need for frequent risk evaluations pushes companies to maintain proactive risk management practices (Commission, 2023d).

3. Implement mitigation strategies
Once vulnerabilities are identified, companies are required to implement mitigation strategies. This could involve diversifying supply sources, substituting materials, or other actions to reduce dependency on high-risk suppliers, especially those outside the EU (Commission, 2023d).

4. Maintaining transparency
Companies must maintain transparency in CRM sourcing, processing, and recycling, including public disclosure of an environmental footprint declaration detailing the sustainability of their CRMs. Moreover, companies selling CRMs must publish an environmental footprint declaration for customers, which details the environmental impact of their materials (Commission, 2023d).

5. Compliance and Surveillance
Before placing products containing CRMs on the EU market, companies must conduct conformity assessments to ensure compliance with CRMA standards. Surveillance authorities are empowered to monitor compliance, adding regulatory oversight that pressures companies to maintain accurate records and continuous adherence to the CRMA. Commission (2023d) does not outline exact penalties; nevertheless, in standard EU regulatory practices, non-compliance may result in fines or market restrictions.

5.2.3 Opportunities for companies

While the CRMA imposes strict requirements on companies using CRMs, it also presents opportunities. By encouraging sustainable practices, the CRMA positions companies to enhance their competitiveness in a market increasingly driven by environmental responsibility.

1. Market Differentiation and Competitive Advantage
Complying with the CRMA provides companies a competitive advantage by aligning with the EU's sustainability goals. As customer demand for environmentally friendly products grows, companies demonstrating CRMA compliance can appeal to a broader customer group. By aligning with EU policies, companies can foster consumer trust and enhance their brand reputation, improving their market positioning (Hool et al., 2023) (Commission, 2023d).

2. Financial and Technical Support for Strategic Projects
The CRMA appoints specific CRM-related projects as "Strategic Projects," making them eligible for regulatory support. A project can become a "Strategic Project" when it is mutually beneficial to the Union and the country concerned and adds value to that country. Companies involved in these projects benefit from streamlined permitting procedures, shorter approval timelines, and access to coordinated financing options through EU funds, such as the European Regional Development Fund and the Just Transition Fund. By easing administrative burdens and facilitating financial access, the CRMA encourages companies to invest in sustainable CRM supply chains. For example, the establishment of strategic stocks could be executed with funds (Tröster et al., 2024) (Hool et al., 2023) (Commission, 2023d).

3. Joint Purchasing Agreements
To mitigate price volatility and enhance supply security, the CRMA introduces a joint purchasing mechanism for CRMs. The Commission will establish and manage a system to track the demand of interested companies within the Union that consume CRMs and SRMs and to source offers from suppliers to meet this combined demand. This allows companies to negotiate favorable terms with CRM suppliers collectively, stabilizing prices and reducing costs (Hool et al., 2023) (Commission, 2023d).

4. Building Strategic Stocks for Resilience
The CRMA encourages companies to establish strategic CRM stocks, meaning that companies keep reserves of CRMs. Strategic stocks or stockpiling enable companies to maintain continuity during shortages. The EU actively supports this approach by coordinating stockpiling efforts across Member States, ensuring that strategic

stocks are effectively managed and accessible when needed. As mentioned before, the CRMA promotes stockpiling by providing regulatory support and incentives, such as streamlined permitting and financial assistance for companies investing in stockpile facilities (Hool et al., 2023) (Commission, 2023d).

5. Advancing Circular Economy Practices
The CRMA promotes circularity by motivating companies to adopt recycling technologies and circular economy practices. By integrating recycling into operations, companies can reduce reliance on primary CRM sources and achieve cost savings through secondary raw materials. This shift aligns with EU environmental goals. As the CRMA encourages recycling and waste management, companies can create additional revenue while enhancing resilience in their supply chains (Tröster et al., 2024) (Hool et al., 2023) (Commission, 2023d).

5.3 Conclusion

This section answered the question: *What are the key requirements of the CRMA, and how do they translate into constraints and opportunities for a supply chain network?*

The Critical Raw Materials Act (CRMA) directly addresses the EU's growing concerns regarding the security and sustainability of Critical Raw Materials (CRMs). CRMs are essential for the energy transition, yet their supply chains are highly vulnerable due to global demand and reliance on a few key suppliers. The CRMA introduces requirements to mitigate these risks by increasing domestic extraction, processing, and recycling while reducing dependency on a single third country.

In conclusion, the specific requirements and consequences derived from the CRMA are summarized below.

1. At least 10% of the CRMs used in the EU must be sourced from EU-based extraction sites;
2. A minimum of 40% of CRMs should be processed within the EU;
3. **At least 25% of CRMs must come from EU-based recycling efforts** (focus area of the research, as explained in Section 5.4.4);
4. No more than 65% of any CRM should be imported from a single third country;
5. Companies must perform risk assessments on CRM supply sources every three years, and as a result of this, mitigation strategies must be implemented;
6. Companies must maintain transparency, including public disclosure and environmental footprint reporting;
7. Before placing CRMs on the EU market, companies must conduct a conformity assessment to ensure compliance with CRMA standards;
8. Companies may be required to manage CRM waste responsibly, with possible financial obligations.

In addition, the opportunities are summarized below:

1. Complying with the CRMA provides companies with a competitive advantage;
2. Certain CRM-related projects are classified as "Strategic Projects" under the CRMA, making them eligible for EU financial and technical support;
3. The CRMA introduces a joint purchasing mechanism, allowing companies to negotiate favorable terms with CRM suppliers collectively;
4. The CRMA encourages the creation of strategic stocks or stockpiling which EU funds and regulatory incentives support;
5. The CRMA promotes adopting circular economy practices, motivating companies to enhance their recycling technologies.

Consequently, these consequences and opportunities will necessitate a shift towards more regional and sustainable practices. Thus, the model should prioritize optimal locations for extraction, processing, and recycling facilities within the EU.

Due to the long timeline required to establish new mines (10–20 years) and the impact mining has on the environment, alternative solutions such as recycling, remanufacturing, and efficient product design are essential to meet future CRM demand. Innovation in recycling technologies and product efficiency will play a key role, while the EU must balance increased mining efforts with sustainable and responsible practices. Ultimately, mining, efficient product design, and innovative recycling methods will be necessary to secure the raw materials required for Europe's energy transition.

5.4 Copper supply chain

The CRM focused on in this thesis is Copper. This chapter presents background knowledge on what copper is, what it is used for, what a general supply chain of copper looks like, and what effects the CRMA will have on the copper supply chain. Moreover, this chapter will answer the following research question: *What are the processes and structure of a general copper supply chain of natural resource companies, and which parts are most impacted by the CRMA?*

5.4.1 What is copper

Copper is a malleable and ductile metallic element known for its sufficient conductivity of heat and electricity, as well as its corrosion resistance and antimicrobial properties. It naturally occurs in the Earth's crust in various forms, including sulphide deposits, carbonate deposits, silicate deposits, and as pure "native" copper. Copper is also present in humans, animals, and plants, as organic life has evolved in an environment containing copper. As an essential nutrient, copper is crucial in maintaining health (ICSG, 2024).

Copper is not only a CRM with high supply risk and economic importance, but also a SRM, which is expected to see exponential growth in supply. Copper is a crucial metallic element with a wide range of applications, playing a significant role in many aspects of human life (Fonseca, 2024). Moreover, copper is crucial for electrical transmission (Glencore, 2024e). It is used in among others, li-ion batteries, fuel cells, electrolysers, wind turbines, traction motors, solar panels, heat pump,s data transmission networks, data storage and servers, smartphones, tablets, laptops, robotics, satellites and drones (Carrara et al., 2023).

Copper is one of the most recyclable metals, making it an environmentally sustainable resource. The ability to recycle copper repeatedly makes it a preferred material. Recycled or secondary copper is indistinguishable from primary copper (ICSG, 2024).

5.4.2 Supply chain of copper

A general overview of the copper supply chain is depicted in Figure 5.2.

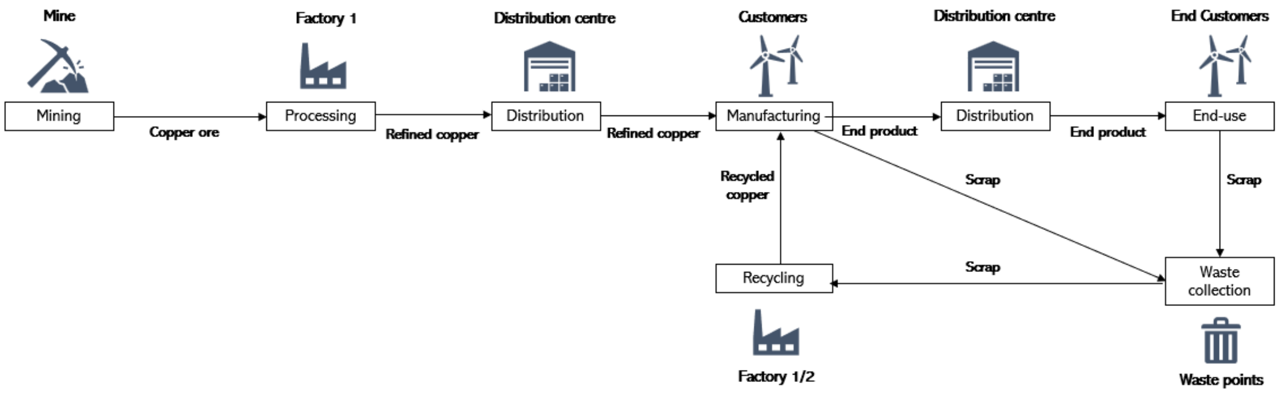


Figure 5.2: Schematic diagram illustrating the general copper supply chain (Author)

At first, the copper ore is mined at a **mine**. The market leaders in copper are based on geology. Although copper is a global industry, certain countries are clear leaders in its processing and refinement (Wincewicz-Bosy et al., 2021). Figure 15.4 in Appendix 15.3 illustrates a map with the global copper supply (including two types of deposits originating from different types of sources).

Copper-containing ores generally contain only a small percentage of copper, with the rest being uneconomic. There are two main types of copper ores: copper oxide ores and copper sulfide ores. Sulfide ores possess higher concentrations of copper but are less abundant and costlier to process, whereas Oxide ores are more abundant, and found near the surface, but tend to have low grades of copper (Capitalist, 2024).

There exist several copper grades throughout its life cycle, including, among others, copper ore, copper concentrate, blister copper, and copper tube. These grades change throughout the different stages in the supply chain and result in different trade commodities for companies (Li et al., 2021).

Secondly, copper is processed, typically at a **processing factory** in the exact location where it is mined. There are two primary processing methods for copper. The first is pyrometallurgy, used for copper sulfide ores, where the ore is smelted and then refined. The second is hydrometallurgy, used for copper oxide ores, which involves leaching followed by electro-winning (Flores et al., 2020) (Fonseca, 2024).

Once processed, the refined copper is distributed to **distribution** centers and sent to customers. These **customers** manufacture the copper into end products and span various industries worldwide. These are, for example, industrial, construction, electronic or automotive manufacturers. These industries use 5-35% of copper in their products (5% in consumer goods to 35% in wires or pipes). Table 15.1 in Appendix 15.3 provides an overview of the major importers and exporters of copper.

After manufacturing into end products, the copper products are distributed to **end customers** for end-use. These customers, consisting of businesses or individuals, use the products made from copper. For example, electric vehicles or construction materials.

The copper scrap is collected at **waste points**, where waste is collected from manufacturers (customers) and end customers. There are also specific cases where the recycling center already has contracts to collect waste directly at the manufacturing site (Aurubis, 2024). Nevertheless, in this study, the waste collection is focused on just the waste points. Waste copper is primarily generated from construction and demolition waste, electronics waste (e-waste) and automotive waste (electric vehicles) (Commission, 2020) (Christofyllidis, 2023) (Commission, 2023b).

Lastly, the copper is recycled. Copper is a highly recyclable material. However, according to (Henckens and Worrell, 2020), about half of copper ends up in landfills, and globally, copper recycling is 45%. Therefore, there is significant potential for improvement. The **recycling factory** could be the same factory as the processing factory. However, copper is often used in other geographical locations (e.g., other continents) and, therefore, recycled in different factories. Therefore, the factory is indicated as either factory 1 (when it is the processing factory) or 2.

5.4.3 Natural resource companies

To determine how the CRMA will influence a copper supply chain, the research has to be scoped down into a specific company. Therefore, this research investigates how CRMA influences natural resource companies.

Natural resource companies are selling their commodities to customers all over the world. These companies mostly focus on the mining, processing, distributing and recycling of materials. As such, companies have the expertise to smelt and refine materials, they often also focus on recycling activities.

This type of company's typical customers are manufacturers in electronics, automotive, and renewable energy (Glencore, 2024b). These customers rely heavily on a steady and sustainable supply of raw materials like copper, which are critical for producing products ranging from electric vehicles to solar panels and wind turbines. Moreover, the customers will have to deal with the CRMA benchmarks for 2030.

The CRMA results in significant challenges for natural resource companies. As mentioned before, customers will have to comply with the CRMA benchmarks of 2030, meaning that 10% of CRMs have to be sourced from EU-based extraction sites, 40% of CRMs should be processed within the EU, 25% of CRMs should come from EU-based recycling efforts, and not more than 65% of any CRM should be imported from a single third country. Furthermore, the benchmarks will result in customers being likely to reduce their imports from non-EU based extraction sites, and increase their sourcing from EU based extraction and recycling efforts. Therefore, these companies must expand their EU mining and recycling operations.

5.4.4 Why should the focus be on recycling copper

As is depicted in Figure 5.3, the copper demand will exceed the copper supply around 2026, which will result in a supply gap. Moreover, the timeline to build new mines and expand raw material extraction in the EU is not viable, as developing a new mine typically takes 10 to 20 years (Peck and Sprecher, 2023). Thus, there should be a **focus on recycling**, reducing, reusing and repairing as the lengthy process of opening new mines makes it impossible to meet future demand and the CRMA's targets.

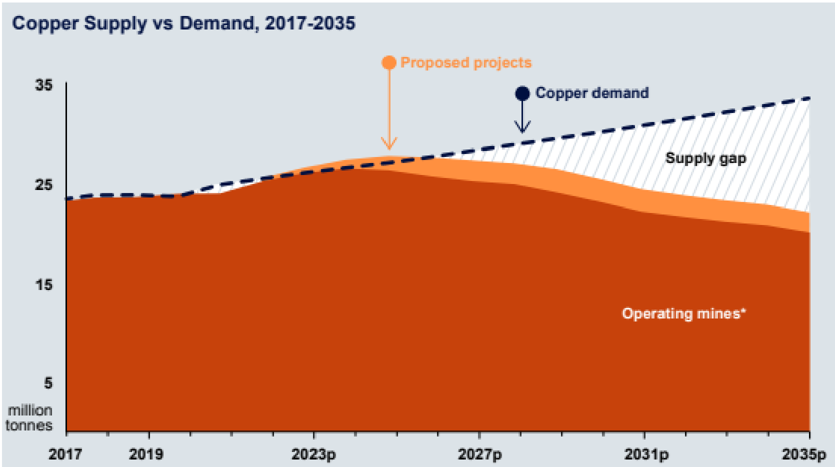


Figure 5.3: Copper Supply vs Demand, 2017-2035 (Mackenzie, 2024)

As reducing, reusing, and repairing are the responsibility and in the power of the customers and end customers of natural resource companies[1], the focus of this study is recycling, which is in the power of natural resource companies. By increasing the amount of copper recycled, ensuring that at least 25% is recycled within the EU, the benchmark can be met, while also providing a competitive advantage. The demand for recycled copper is expected to rise, presenting an opportunity for market expansion. When anticipated timely on the CRMA by optimizing the recycling network in Europe, natural resource companies can enhance their market position.

Focusing on recycling will have the following advantages:

- The recycling expansion would not only comply with the CRMA but also position companies advantageously in the European market;
- By increasing the supply of recycled copper, companies can mitigate the challenges associated with developing new mines within the EU, which will not be feasible in the short term;
- Recycling copper consumes less energy and reduces emissions than primary extraction. Additionally, because the recycling occurs within Europe, transportation emissions will be reduced. When reporting on its environmental performance, this will be beneficial to demonstrate compliance with the CRMA and build trust with stakeholders. The reduction in emissions would be beneficial for its scope 1 and 3 emissions[2].

Nevertheless, it is crucial to note that recycling also faces several challenges. One major difficulty lies in the collection and processing of copper scrap. Modern devices are designed for efficiency and durability rather than recyclability, making disassembly complex and often unprofitable. Additionally, mixed-material components can make copper recycling difficult, as separation is difficult. Without proper pre-separation techniques, valuable raw materials may be lost or underutilized (S. Steeneken, personal interview, 2025).

[1] Customers (industrial and manufacturing companies) are responsible for ensuring their products are repairable or reusable and end customers are responsible for reducing their buying behavior and repairing instead of buying.

[2]
- Scope 1: Direct emissions from owned or controlled sources, for instance, natural resource or recycling operations;
- Scope 2: Indirect emissions from the generation of purchased energy;
- Scope 3: All other indirect emissions occurring in the value chain, including both upstream and downstream activities, for example, transportation costs (Teske et al., 2022).

Furthermore, to optimize the recycling network, all European copper scrap streams must be identified and evaluated for economic feasibility. Currently, significant portions of European scrap are exported to countries such as Cambodia and Vietnam due to lower processing costs (S. Steeneken, personal interview, 2025). Thus, the recycling industry must be strengthened by ensuring higher economic feasibility of recycling within Europe (which will potentially be the result of the CRMA).

Also, companies should shift towards material-focused recycling instead of focusing only on reusing scrap within specific product groups. Rather than rebuilding an identical product from recycled components, businesses should prioritize extracting materials like copper and reintegrating them into the broader supply chain (S. Steeneken, personal interview, 2025).

5.5 Conclusion

After the research in this chapter and the definition of what impact the CRMA has on the copper supply chain, the sub-question *What are the processes and structure of a general copper supply chain of natural resource companies, and which parts are most impacted by the CRMA?* can be answered. This section concludes the second part of this chapter.

CRM copper was chosen for this research. The copper supply chain consists of multiple stages: mining, processing, distribution, manufacturing, waste collection, and recycling. Copper is a highly recyclable material with extensive industrial applications, particularly in electronics, renewable energy, and transportation. However, despite its recyclability, a significant portion of copper still ends up in landfills, indicating room for improvement in circularity.

Natural resource companies primarily focus on extracting, processing, distributing, and recycling copper. Their customers rely on a stable and sustainable copper supply. With the introduction of the CRMA, these customers must comply with new regulatory benchmarks, including sourcing 25% of CRMs from EU-based recycling efforts. This shift directly impacts natural resource companies, as demand for recycled copper will increase, while primary copper sourcing may decrease due to supply chain restrictions.

A major challenge is that copper demand is expected to exceed supply around 2026, creating a supply gap. Expanding mining activities in the EU is not a viable short-term solution, as opening new mines takes 10 to 20 years, meaning that recycling operations should be increased anyway. Therefore, the most feasible (time-wise), effective and sustainable approach (when comparing changing a company's mining, processing and recycling operations) to meeting CRMA requirements is to enhance recycling operations in Europe. By strategically optimizing the copper recycling network, natural resource companies can strengthen their market position, reduce scope 1 and 3 emissions and ensure compliance with the CRMA while contributing to a more sustainable and resilient supply chain.

Nevertheless, recycling also has its challenges. Modern devices are not designed for recycling, making disassembly difficult and often unprofitable. Additionally, separating copper from mixed materials is complex. Currently, a major problem is that significant amounts of European copper scrap are exported to countries like Cambodia and Vietnam due to lower processing costs. To strengthen the recycling industry, recycling must become more economically feasible. Companies should also adopt a material-focused recycling approach, prioritizing copper recovery for reintegration into the general copper supply chain instead of the supply chain of a product group.

5.6 The copper supply chain before and after the CRMA

At this point, the first section of the research question "*How does the CRMA impact the copper supply chain?*" can be answered. Table 5.1 summarizes the copper supply chain **before and after the implementation of the Critical Raw Materials Act (CRMA)** (both general and for natural resource companies), based on this chapter. All relevant stages and aspects are represented in the table, clarifying the before-and-after situation.

Table 5.1: Copper supply chain before and after the CRMA

	Before CRMA	**After CRMA**
Sourcing and processing (*Section 5.4.2*)	Mining and processing mostly outside EU (Wincewicz-Bosy et al., 2021; Flores et al., 2020).	10% of copper must be sourced from EU-based extraction; 40% processed in EU. (EU, 2023a)
Recycling share and location (*Section 5.4.2*)	Only 45% of copper globally recycled; significant EU scrap exported to low-cost countries (Henckens and Worrell, 2020).	At least 25% of copper must be recycled within the EU; focus on recycling scrap locally (Henckens and Worrell, 2020; Hool et al., 2023).
Strategic focus (*Sections 5.1, 5.4.2*)	Supply chain optimized for cost efficiency and global competitiveness (Glencore, 2024b).	Focus on EU autonomy, circularity, emission reduction, and CRM compliance benchmarks (EU, 2023a; Hool et al., 2023; Tröster et al., 2024).
Design and disassembly (*Section 5.4.4*)	Devices designed for durability and efficiency, not for recyclability; complex disassembly.	Shift towards recyclability of products to meet CRMA goals.
Emissions and transport (*Section 5.4.2*)	High emissions from long-distance transport and global recycling (Teske et al., 2022).	Reduced emissions due to local, short-distance EU-based recycling (Teske et al., 2022).
Permitting and implementation (*Section 5.2*)	Long permitting timelines, fragmented national processes, low EU coordination (Hool et al., 2023).	Strategic projects enjoy shortened permitting; streamlined coordination (Tröster et al., 2024).
Market opportunities (*Section 5.2.2*)	Limited regulatory incentives for recycling.	CRMA offers a competitive advantage through compliance, EU funds, strategic stockpiling, and joint purchasing (Commission, 2023d).
Stakeholder involvement (*Section 5.2.2*)	Limited involvement of companies in raw material governance (Hool et al., 2023).	Increased transparency obligations, environmental footprint declarations, and CRM conformity assessments required (Hool et al., 2023).
Recycling costs (*Section 5.4.4*)	Priority for cost-efficiency by exporting copper scrap to lower cost countries.	Potentially higher costs due to domestic recycling (Tröster et al., 2024).

6 Conceptual model

After answering the first two sub-questions, the conceptual model can be formed. The representation of the current situation will be presented, as well as how to optimize the situation. Thus, this chapter will answer the question: *How can the copper recycling network of natural resource companies be optimized while adhering to the CRMA?*

It can be concluded that the recycling part (particularly the recycling location) of the supply chain is the most significantly impacted by the CRMA and plays the most crucial role in ensuring compliance and long-term sustainability. Therefore, as mentioned before, this study will focus on optimizing the copper recycle network of a natural resource company, focusing on the recycling part as depicted in green and thick arrows in Figure 6.1.

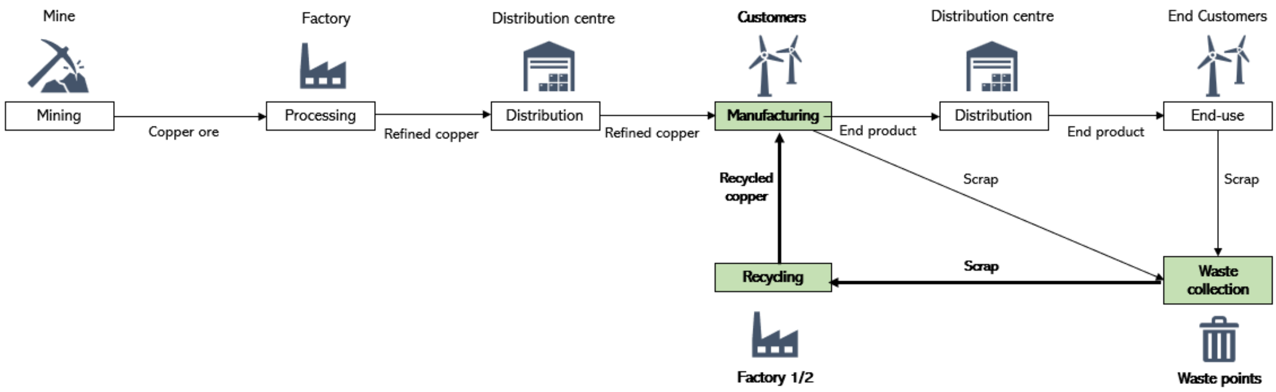


Figure 6.1: Focus area of this research (Author)

This research, focusing on network optimization, includes the:

1. Optimal number of facilities;
2. Optimal facility locations;
3. Required capacities of the facilities to fulfill the customer demand.

The conceptual model is shown in Figure 6.2. Most importantly, the objective is to find the optimal number, locations, and capacities of new recycling facilities within Europe while minimizing costs. The expansion of already existing facilities is left out of scope. Furthermore, the goal of the model is to reach this objective under the CRMA recycling constraint, which includes that 25% of the customers' demand should be based on EU-recycled materials.

The parameters influencing the optimization are also indicated in the figure, namely transport costs, in-transit costs, unit costs, fixed costs, subsidies and risks. Moreover, the waste points, customer locations and capacities also affect the optimization. The waste points represent the waste collection locations, where the waste of the (end) customers is collected. Furthermore, the customers represent the manufacturing companies, as explained in Section 5.4.2.

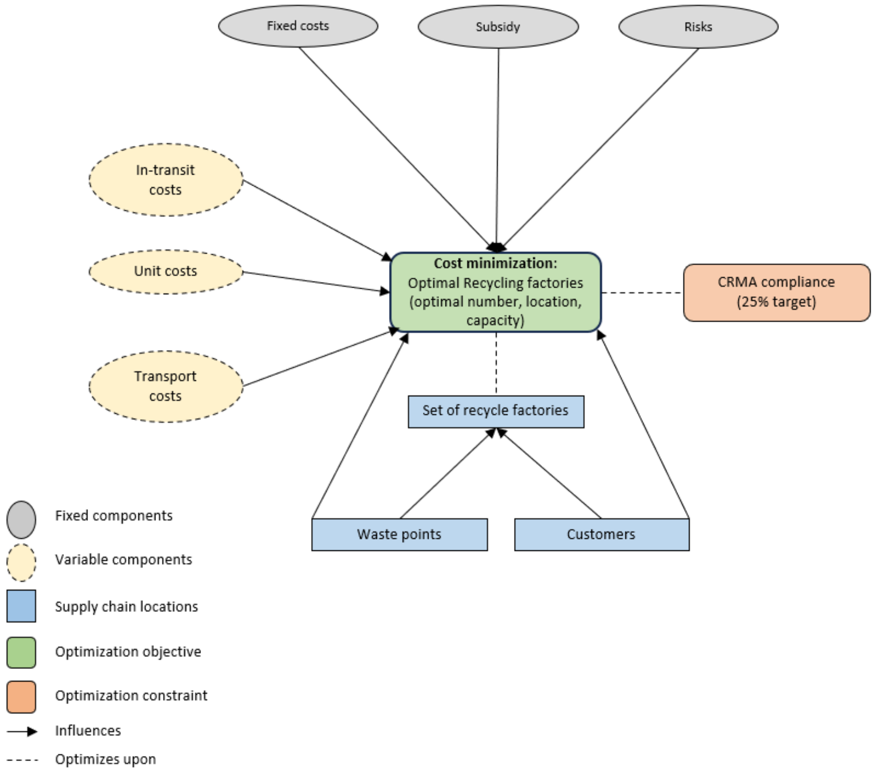


Figure 6.2: Conceptual model (Author)

The specific meaning of the interrelations and colors is summarized in the next section. First, the green node indicates the optimization objective, and the red node represents the optimization constraint. Moreover, the blue nodes represent the different locations, including the customers, the waste points and the recycling facilities. As the specific model focuses on opening new recycling facilities, the set of potential optimal facilities also depends on waste and customer locations. A detailed explanation on how this set is obtained can be found in Section 9.3.

Moreover, the yellow dashed nodes represent the variable components in the system. For example, the in-transit costs, the unit costs and the transport costs. Additionally, the gray nodes represent the fixed components, including the fixed costs, potential subsidies and risk costs. A more detailed overview of all specific parameters can be found in Chapter 7.

The black arrows indicate that a parameter or waste- or customer location influences the outcome of the cost minimization, or that the waste- or customer locations influence the selection of potential recycling facilities, as explained in Section 9.3. For example, the selection of the optimal recycling facility is influenced by transportation costs.

Lastly, the dashed arrows mean that the cost minimization is optimized based on the set of potential recycling facilities and the CRMA constraint. The model chooses from the potential facilities while adhering to the CRMA constraint.

6.1 Detailed overview of the optimization

Figure 6.3 represents a more detailed structure of how the optimization will look. The figure represents two (of the 30) potential optimal facilities (i). Their optimality depends on the waste points (j) and customers (k).

The figure includes two active recycling facilities, while in reality, a different number may be chosen. Additionally, please note that the arrows have a different meaning in this image compared to the previous model. In this model, the arrows represent the flow of scrap or recycled copper to and from the recycling facilities.

The waste or copper scrap quantities flow from the waste points to the facilities. Waste copper quantities, the waste point locations, and the different flows should be determined in Europe. As mentioned in EU (2023b), EU countries will take measures to enhance the collection of critical raw material-rich waste. Therefore, mining companies should be in contact with waste points, such as governmental institutions, and have contracts to gain waste copper.

Afterwards, the recycled copper is transported to the customers. The optimal location(s) and capacities depend on the waste points, quantities, customer locations, and demand. It is important to notice that multiple facilities can serve one waste point or customer.

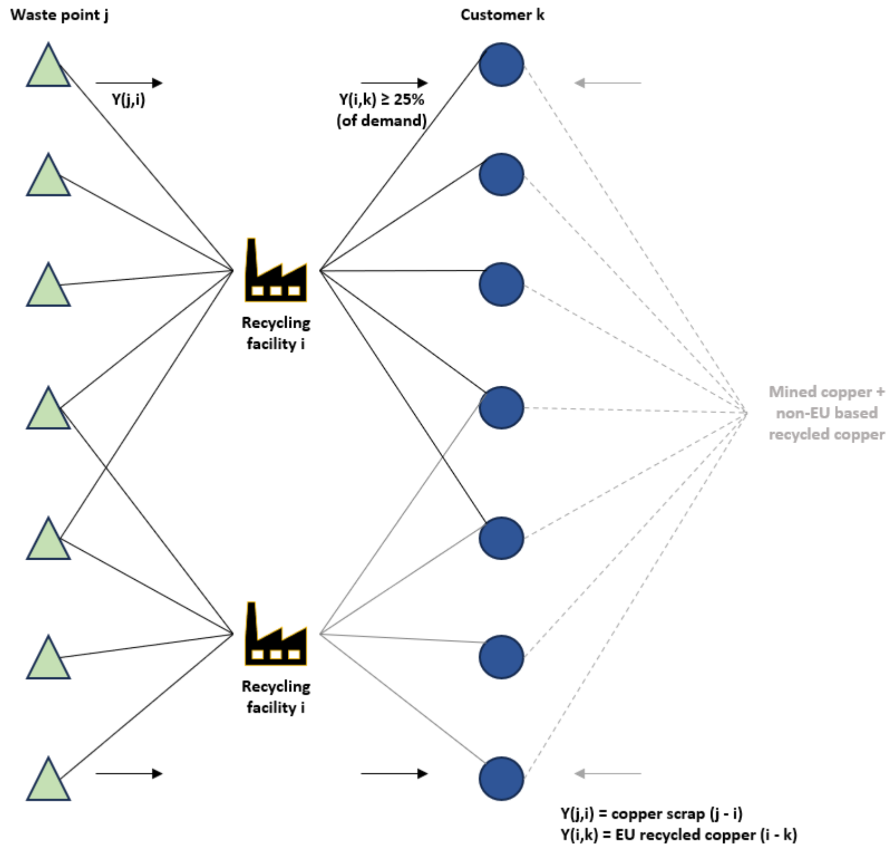


Figure 6.3: Overview of recycling facility i serving waste points j and customers k (Author)

Copper supplied to customers can originate from three different sources:

1. **EU-based recycled copper** (focus of the model);
2. Non-EU-based recycled copper;
3. Mined copper (from both EU and non-EU sources).

It is important to note that natural resource companies often operate globally, with mines and processing facilities inside and outside the EU. Therefore, the total supply of copper for these companies consists of mined copper (from within and outside the EU) and recycled copper (from within the EU and from non-EU sources). This thesis focuses on the EU-based recycled copper supply of natural resource companies.

The optimization model ensures that 25% of the demand of all customers[3] of a natural resource company can be fulfilled with EU-based recycled copper, ensuring that the CRMA benchmark is met. Therefore, the optimization will include the EU-based recycled copper flow, but exclude mined copper and non-EU-based recycled copper (indicated in light gray in Figure 6.3).

This model only focuses on one company's supply. Nevertheless, it is essential to note that customers do not solely rely on one supplier. They also receive copper from other companies. Therefore, customers could shift to competitors due to changing circumstances, such as lower prices or better service. This uncertainty factor should be kept in mind.

6.2 Conclusion

This Chapter answered the question *How can the copper recycling network of natural resource companies be optimized while adhering to the CRMA?*

The recycling network is the most impacted part of the copper supply chain under the CRMA. This study focuses on optimizing the network for copper recycling facilities of a natural resource company, ensuring that at least 25% of EU customer demand comes from EU-based recycling efforts by 2030.

Three key decisions define the optimization problem:

1. Optimal number of facilities;
2. Optimal facility locations;
3. Required capacities of the facilities to fulfill the customer demand.

The conceptual model highlights the cost-minimization objective, including transport costs, in-transit costs, unit and fixed costs, subsidies, and risks. Moreover, the model also considers the dependencies of the optimal recycling locations on waste points and customers (locations, supply and demand). Multiple facilities can serve the waste points and customers.

Copper supplied to customers can originate from three different sources:

1. **EU-based recycled copper;**
2. Non-EU-based recycled copper;
3. Mined copper (from both EU and non-EU sources).

The optimization focuses on EU-based recycled copper and ensures that 25% of the demand of all natural resource company customers can be fulfilled with EU-based recycled copper. Nevertheless, it is important to note that customers do not solely rely on one supplier, meaning that market shifts due to pricing or service differences should be considered an uncertainty factor.

[3]taken the demand separately for all customers so 25% of every customer's demand, not the demand as a whole.

7 Mathematical model

In the following section, the methodology for the optimization will be introduced, including MILP, as well as the software that will be used. Additionally, the mathematical model for the optimization will be presented. Moreover, this chapter will continue answering the research question: *How can the copper recycling network of natural resource companies be optimized while adhering to the CRMA?*

7.1 Mixed-Integer Linear Programming

Mathematical models are formed to reformulate a problem so that it is convenient for analysis. The mathematical model of a problem is the system of equations and related mathematical expressions that describe the essence of the problem. A mathematical model typically includes different necessary components: indices, parameters, decision variables, objective function, and constraints.

To determine what optimization technique is suitable, the literature is consulted. As mentioned in Chapter 2, several techniques are considered, each with its strengths and limitations. Four optimization techniques were reviewed:

1. **Nonlinear Programming (NLP)**: allows for complex relationships between variables and is suitable for problems with nonlinear constraints or objective functions. For example, Turken et al. (2017) developed an NLP model to assess the impact of environmental regulations on plant location and capacity decisions. Since the problem considered in this research does not have nonlinear relationships, NLP is not used;

2. **Stochastic optimization (SP)**: incorporates probabilistic distributions for uncertain parameters, making it a powerful tool for supply chain optimization under uncertainty, as seen in (Dulia and Shihab, 2024) and (Saeedi et al., 2024). However, SP requires extensive historical data to define probability distributions, which may not always be available. Since the primary goal of this research is to develop a deterministic base model before considering uncertainties, SP was not considered as the most appropriate approach at this stage;

3. **Heuristic algorithms**: These methods are beneficial when dealing with large-scale, highly complex problems where exact optimization techniques become impractical. Manupati et al. (2024) and Saeedi et al. (2024) employed heuristic approaches to solve complex supply chain problems. However, these methods do not guarantee optimality. Given that this research aims to derive an optimal solution, a heuristic algorithm is not used;

4. **Robust Optimization (RO)**: is handy when dealing with uncertainty in supply chain parameters. Lotfi et al. (2020) introduced a robust optimization model for a closed-loop supply chain that integrates resilience and risk aversion, ensuring the solution remains feasible under worst-case scenarios. Since this research focuses on an initial deterministic optimization before integrating potential uncertainty factors, RO was not selected as the primary optimization technique. However, this technique could be used when expanding the model to make it more resilient.

The mathematical model presented in this research consists of linear and integer variables, making Mixed Integer Linear Programming (MILP) the most suitable optimization technique. Furthermore, in (Francisco Saldanha-da Gama, 2024), several facility location models are presented. The Facility Location inspires this research with the Direct Allocation model (FLDA) and the Capacitated Facility Location Problem (CFLP). The FLDA model assumes facilities have infinite or unspecified capacities, which is unrealistic in recycling networks. Conversely, the CFLP assumes that capacities are fixed inputs, which does not align with determining optimal capacities.

Therefore, the Facility Location with Capacity Design model is the most realistic and suitable approach, making MILP the ideal optimization technique to address this problem effectively.

In this research, the AIMMS SC Navigator software is used. SC Navigator is designed to handle complex supply chain models using MILP, which is used in this study. The software can address both location and capacity decisions.

One of the key advantages of SC Navigator is its user-friendly interface, allowing for the customization of objective functions and constraints to model specific case requirements. Users can modify the objective function and parameters such as transportation costs, fixed costs, and facility capacities, creating specific scenarios.

Additionally, the software supports advanced scenario modeling, allowing for evaluating various situations. It includes, for example, a tool for easily increasing or declining demand. Furthermore, constraints, such as the use of facilities, can be relaxed or enforced, ensuring the possibility of testing different facilities under different conditions.

7.2 Mathematical model

This section presents the mathematical model. As mentioned before, the model's objective is to minimize costs while finding the optimal number of facilities, locations, and capacities. Below is an explanation of the parameters and indices influencing the objective function.

Waste points (j), (W_j): These refer to the waste locations and quantities throughout Europe. The locations and quantities depend on the users in different locations.

Customers (k), (D_k): These refer to the customer locations and recycled copper demand throughout Europe. Customers can be manufacturers or industries that require recycled copper for production. Demand varies geographically and must be matched with available supply from recycling facilities.

Transport costs (t_{mn}): Transport costs are a major factor in determining the optimal location of new recycling facilities (Xie et al., 2024). These represent the costs of moving copper from waste points to recycling facilities and from facilities to customers. Transport costs are route-specific and depend on:

- Distance traveled;
- Volume transported;
- Fuel costs;
- Personnel wages (driver salaries, maintenance staff);
- Road tolls, and other transportation fees.

In-transit costs ($\frac{\textbf{VoT}}{\textbf{Speed}}$): These refer to the time-related costs incurred while in transit. In-transit costs reflect the cost of capital tied up during transportation. These costs may include:

- The cost of delayed revenue;
- Additional storage or handling costs if transportation takes longer than expected.

The in-transit costs are determined by the Value of Time (VoT) divided by the speed, resulting in the costs per ton per hour.

Distance ($Distance_{mn}$) and Wiggle Factor (WF): The total transport costs are calculated by multiplying the transport cost per unit distance by the distances. AIMMS calculates the distances using straight lines. However, in reality, transport routes do not follow straight lines. To account for this, the distances are adjusted using the Wiggle Factor (WF), which introduces a correction factor that more accurately represents real-world transport paths (Domínguez-Caamaño et al., 2016).

Unit costs (c_i): The expenses incurred to operate the recycling facility. These costs are expressed per installed capacity unit rather than per production unit. Thus, the model focuses on attributing the costs to capacity rather than fluctuating production.

Fixed costs (f_i): These represent one-time investment costs when a new facility is opened. Fixed costs are facility-specific and include:

- Land acquisition or lease costs;
- Facility construction and infrastructure setup costs;
- Initial equipment and installation costs.

Since these costs are not paid all at once, a depreciation factor (DEPR) is included to distribute the investment over time. The depreciation period is set to 30 years (Tadaros et al., 2022).

Subsidies (S_i): These are financial amounts provided by governments to encourage recycling activities. Subsidies are location-specific and can significantly reduce facility setup costs. Companies receive the subsidy at the beginning of the investment.

Risk costs (R_i): Additional costs are incurred due to uncertainties at facility locations. These risks can arise from, for example, natural risks and governmental risks (Commission, 2024g). Risk costs act as a financial penalty for operating in a specific location.

Internal rate (IR): This represents the cost of capital associated with the facility investment (Tadaros et al., 2022). The internal rate is applied as a percentage of the initial investment cost to account for:

- The opportunity cost of using company funds for facility construction instead of alternative investments;
- The facility financing cost, such as interest rates on loans.

Unlike depreciation, which spreads costs over time, the internal rate is applied as a one-time percentage of the total investment cost.

The mathematical notation for the problem is described below.

Table 7.1: Mathematical model

Sets and indices		
i	Index for recycling facilities	$i \in I$
j	Index for waste points	$j \in J$
k	Index for customer locations	$k \in K$
m	Origin locations (waste points j, facilities i)	$m \in J \cup I$
n	Destination locations (facilities i, customers k)	$n \in I \cup K$
Parameters		
W_j	Waste at j	[ton]
D_k	Demand at k	[ton]
f_i	Fixed cost of facility i	[€]
DEPR	Depreciation years	[years]
t_{mn}	Transport costs $m \to n$	[€/ton/km]
c_i	Unit costs at i	[€/ton]
Speed	Average transport speed	[km/hour]
λ	CRMA coefficient	[fraction, $0 < \lambda \leq 1$]
η	Recycling efficiency	[fraction, $0 < \eta \leq 1$]
VoT	Value of time	[€/ton/hour]
Distance_{mn}	Distance $m \to n$	[km]
WF	Wiggle factor	[fraction, $0 < WF \leq 1$]
$Subsidy_i$	Regional subsidy for i	[€]
$Risk_i$	Regional risk costs for i	[€]
IR_i	Internal rate at i	[fraction, $0 < IR \leq 1$]
$C_{\max}$	Facility max capacity	[ton]
Decision variables		
x_i	Facility i open (1) or closed (0)	[binary]
y_{mn}	Copper transported $m \to n$	[ton]
z_i	Linearized capacity at i	[ton]
C_i	Total installed capacity at i	[ton]

$$\min \quad \sum_{i \in I} \Big((\frac{f_i}{\text{DEPR}} - \text{Subsidy}_i + Risk_i + f_i \cdot IR) x_i + c_i \cdot C_i \Big) + \sum_{m \in J \cup I} \sum_{n \in I \cup K} \left(\left(t_{mn} + \frac{\text{VoT}}{\text{Speed}} \right) \cdot \text{Distance}_{mn} \cdot (1 + WF) \cdot y_{mn} \right) \quad (7.1)$$

Subject to:

$$\sum_{i \in I} y_{ji} \leq W_j \qquad \forall j \in J, \quad (7.2)$$

$$\sum_{i \in I} y_{ik} \geq \lambda D_k \qquad \forall k \in K, \quad (7.3)$$

$$\sum_{j \in J} y_{ji} \cdot \eta = \sum_{k \in K} y_{ik} \qquad \forall i \in I, \quad (7.4)$$

$$z_i \leq C_{\max} x_i \qquad \forall i \in I, \quad (7.5)$$

$$z_i \leq C_i \qquad \forall i \in I, \quad (7.6)$$

$$z_i \geq C_i - C_{\max}(1 - x_i) \qquad \forall i \in I, \quad (7.7)$$

$$\sum_{j \in J} y_{ji} \leq z_i \qquad \forall i \in I, \quad (7.8)$$

$$x_i \in \{0, 1\} \qquad \forall i \in I, \quad (7.9)$$

$$y_{ji}, y_{ik}, z_i, C_i \geq 0 \qquad \forall i \in I, j \in J, k \in K. \quad (7.10)$$

The objective function is subdivided into the following components:

1. Represents the fixed cost for opening a facility at location i divided over the depreciation period, and including a potential subsidy, regional risks, and an internal rate:
$$\sum_{i\in I}\Big((\frac{f_i}{\text{DEPR}}-\text{Subsidy}_i+Risk_i+f_i\cdot IR)x_i\Big)$$
2. Represents the capacity installation cost:
$$\sum_{i\in I} c_i C_i$$
3. Represents the transportation costs from origin m to destination n, including in-transit holding costs (value of time divided by average speed) multiplied by the distance times the wiggle factor (which is a correction factor described as the ratio between the real distance traveled by road and the straight line between the two points (Domínguez-Caamaño et al., 2016)):
$$\sum_{m\in J\cup I}\sum_{n\in I\cup K}\Bigg((t_{ji}+\frac{\text{VoT}}{\text{Speed}})\cdot\text{Distance}_{mn}\cdot(1+WF)\cdot y_{mn}\Bigg)$$

Furthermore, the constraints can be explained by the following:

1. **Waste allocation:** Constraint 7.2, ensures that the total amount of waste transported to one or more facilities must not exceed the total amount generated at point j.
2. **Demand allocation:** Constraint 7.3 makes sure that at least $\lambda = 25\%$ of the demand of customer k must be fulfilled by one or more facilities (to comply with CRMA recycling requirements).
3. **Waste transported to customers:** Constraint 7.4 ensures that the total recycled copper sent to customers is equal to the inflow of waste at a facility multiplied by the recycling efficiency rate (η). The recycling efficiency accounts for not all waste processed at the facility is successfully converted into recycled copper.
4. **Capacity constraints:** Constraints 7.5-7.8 are introduced to linearize the non-linear capacity constraint involving the binary variable x_i and the continuous variable C_i:
$$\sum_{j\in J} y_{ji}\le C_i\cdot x_i$$
A new continuous variable (z_i) in introduced to replace the non-linear product $C_i x_i$. If $x_i = 0$ (facility i is not opened), then $z_i = 0$ and no capacity is installed. If $x_i = 1$ (facility i is opened), then $z_i = C_i$, allowing the capacity to be used (see below for verification):

   Case 1: Facility is closed ($x_i = 0$)

   - From (7.5): $z_i \le 0 \Rightarrow z_i = 0$.
   - From (7.6): Since $z_i = 0$, it follows that $C_i = 0$ (no capacity is installed).
   - From (7.7): $z_i \ge C_i - C_{\max}(1-0) = C_i - C_{\max}$, which forces $C_i = 0$.
   - Conclusion: If $x_i = 0$, then $C_i = 0$ and $z_i = 0$, meaning no capacity is allocated, as required.

   Case 2: Facility is open ($x_i = 1$)

   - From (7.5): $z_i \le C_{\max}$.
   - From (7.6): $z_i \le C_i$.
   - From (7.7): $z_i \ge C_i - C_{\max}(1-1) = C_i$.
   - Since $z_i \le C_i$ and $z_i \ge C_i$, it can be concluded that $z_i = C_i$.
   - Conclusion: If $x_i = 1$, then $z_i = C_i$, meaning the facility operates at its full installed capacity.
5. **Non-negativity and binary constraints:** Equation 7.9 and 7.10 ensure that waste flows and capacities are non-negative, and facility opening decisions are binary.

7.3 Conclusion

This chapter answered the question *How can the copper recycling network of natural resource companies be optimized while adhering to the CRMA?*

This chapter presented the Mixed-Integer Linear Programming (MILP) model, which was developed to optimize the copper recycling network for natural resource companies while ensuring compliance with the recycling constraint of the CRMA. The model determines the optimal number, locations, and capacities of recycling facilities in Europe, to minimize total costs while meeting the requirement that at least 25% of customer demand is supplied from EU-based recycled copper by 2030.

The model accounts for key cost components: transportation, in-transit, unit, and fixed costs (divided by the depreciation factor), the internal rate, risk costs, and subsidies. Distances are corrected with a Wiggle Factor to represent real-world transport lanes. Moreover, the model ensures that waste flows efficiently from waste points to recycling facilities and customers, considering distances, facility capacities, and costs.

AIMMS SC Navigator is used to solve the MILP model. It provides a user-friendly interface for optimizing and testing multiple scenarios.

8 Case study: Glencore

To test the model, data have to be collected. And therefore, a specific case study has to be chosen. This chapter will present the case study selected for this research.

A case study is performed on Glencore, a natural resource company. Glencore is recognized as one of the world's leading globally diversified natural resource companies. Glencore's portfolio includes the production and marketing of over 60 different commodities that play a pivotal role in everyday life.

Furthermore, at Glencore, the core mission is to responsibly source the raw materials that drive progress in daily life. The company is committed to fostering sustainable growth and creating opportunities for all stakeholders, including customers, shareholders, employees, and the local communities and nations Glencore is active in (Glencore, 2024b).

What's more, in the 2024-2026 Climate Action Transition Plan Glencore mentions it will be investing in areas such as recycling and carbon solutions, that can support the global energy transition (Glencore, 2024a). Moreover, the company is committed to recycling to address the escalating demand for metals, particularly in light of the expanding electric vehicle market and the increasing necessity to recycle and re-purpose battery manufacturing scrap. Glencore also sees the potential due to its significantly lower energy consumption and emissions than mining and smelting primary metal, offering a more sustainable approach.

As the CRMA focuses on EU consumption of CRMs, it will impact the consumption behavior of Glencore's customers. As the regulation mandates that at least 25% of CRMs must come from recycled sources, customers will prioritize recycled materials over newly mined ones. This shift may lead to an increased demand for Glencore's recycling products. Also, the CRMA's focus on sustainability necessitates that Glencore and its customers adhere to stricter environmental standards. Thus, commitment to responsible sourcing and processing will be crucial for maintaining and expanding market presence within the EU (EU, 2023b).

8.1 Copper supply chain of Glencore

Globally, Glencore is an important figure in the production and distribution of copper. The copper extraction and processing operations are in South America, the Democratic Republic of Congo, and Australia. While in North America, the focus is on recycling copper scrap. Moreover, the company engages in the smelting and refining of copper, selling to diverse clients in the automotive, electronics, and construction industries (Glencore, 2024c).

The copper commodities Glencore sells are copper concentrate and copper anode as intermediate products and copper semis (wire, rod and tubes) as first-use products (Glencore, 2024d). Moreover, as mentioned before, the copper assets range from mines to smelters, refineries and recycling plants (Glencore, 2024c). Glencore has copper mines in, among others, Congo, Chile, Peru, and Argentina (Glencore, 2023). After mining, the raw materials are produced. The main copper production comes from the four biggest mines. The production process will take place at the same location, after which the copper is shipped throughout the whole world. The exact mining and production quantities, as well as the overall costs and expenses, can be found in the publications online.

After it has been shipped to customers all over the world, the copper has the potential to be recycled. There exists a smelting and refining location in North America, where the copper is recycled. Scrap is already the origin for about a third of the approximately 30 million tons of annual total global copper supply (Glencore, 2024a). Nevertheless, as far as public documents tell, these processes occur in North America.

Thus, there is significant potential for expanding Glencore's recycling operations within Europe. By enhancing its recycling efforts within the EU, Glencore can anticipate changing customer demand and align the sustainability requirements of the CRMA.

Several annual, financial, and sustainability publications are available on Glencore's website. These documents, among other things, list the amount of (recycled) copper produced yearly and provide mining and processing information. The yearly customer demand is also registered, which can be used as a baseline for this study.

8.2 Conclusion

Glencore, a major global natural resource company, plays a key role in the copper supply chain, with operations spanning mining, processing, smelting, refining, and recycling. As the company currently performs copper recycling only in North America, the CRMA presents an opportunity for expanding recycling activities within the EU.

Furthermore, Glencore's mission is to source raw materials responsibly while fostering sustainable growth for all stakeholders. As part of its 2024-2026 Climate Action Transition Plan, the company is investing in recycling and carbon solutions. Moreover, the company is committed to recycling to address the escalating demand for metals.

With the CRMA mandating that at least 25% of critical raw materials must come from recycled sources, customer demand for recycled copper in Europe is expected to increase. By enhancing its recycling efforts within the EU, Glencore can anticipate changing customer demand, align the sustainability requirements of the CRMA, and take action considering its Climate Action Transition Plan.

Glencore's publicly available reports and financial documents provide data on customer demand, which serve as a basis for this research. This information will be used to test and validate the optimization model.

9 Data collection

As the exact data points are unavailable online, a dummy dataset is created to test the model and run the results. This chapter will present the creation and collection of the dummy dataset. Firstly, the data that serves as the CoG tool's input must be collected, including all waste points and the customer data. Afterwards, all other data points, including transport and fixed costs, must be collected. An overview of how the data is collected is depicted in Figure 9.1.

Figure 9.1: Overview of how the data is collected

9.1 Set of waste points (j) and quantities W_j

As mentioned before, the input for the center of gravity stage has to be determined, including the index for the waste points (j) and the customer locations (k), as well as the waste generated and the demand. The copper (waste) data within the EU was not available online. Therefore, the copper waste locations and quantities were determined based on the highest copper-consuming countries and the industrial zones within Europe.

The countries with the highest copper consumption in 2020 are defined by (Statista, 2023) with copper consumption in thousand metric tons. For this research, the 15 largest copper-consuming countries are chosen. The largest copper-consuming country is Germany, followed by Italy, Spain, Poland, Belgium, France, Sweden, Greece, Bulgaria, The Netherlands, Finland, Sweden, and Serbia. In addition, Germany, Spain, Poland and Belgium are also involved in copper processing activities (Commission, 2023c). Therefore, selecting these countries is a solid starting point.

As consumption is spread over countries, it has to be determined where it takes place. The major amount of copper consumption most likely takes place in industrial zones. Therefore, it is defined where the largest industrial zones in Europe are. For this, the dataset Employment (thousand persons) by NUTS 3[4] region is used, which is available in the Eurostat database (Union, 2024b). The dataset is filtered for the category [B-E] Industry and the NUTS 2 regions. This was the most suitable region for this study as the NUTS 3 regions lacked specific cities linked to the regions. Moreover, the NUTS 1 regions were too large.

The year 2021 was chosen because more recent years had missing values. Only the largest copper-consuming countries mentioned before are selected. Thus, the dataset entails the number of employees in the industry in the high copper-consuming countries. Furthermore, empty rows and columns are deleted, and all regions not in the specified countries are deleted, leading to a dataset of 257 datapoints. Lastly, the data is reduced to the regions with more than 100.000 employees, leading to a dataset of 105 datapoints. To determine the coordinates (j), the regions are linked to the most

[4] To reference countries' regions for statistical reasons, the EU has introduced a classification known as NUTS (Nomenclature of territorial units for statistics). NUTS divides each EU country into 3 levels (Union, 2024a):

1. NUTS 1: major socio-economic regions;
2. NUTS 2: basic regions (for regional policies);
3. NUTS 3: small regions (for specific diagnoses).

important nearby cities, after which the longitudes and latitudes are determined.

Additionally, to specify the copper consumption for each city, the proportion of employees in the city relative to the total workforce of the entire country is calculated. Secondly, the copper consumption per country in the sector industry is defined (approximately 30% of copper consumption is allocated to industrial equipment and manufacturing (GROUP, 2024)) (and based on the previously mentioned Statista database (Statista, 2023)). Furthermore, these industry consumption numbers are multiplied with the proportion of employees per city to determine the copper use per city.

Lastly, the waste generated (W_j) has to be determined. As stated by (Association, 2022), approximately 56% of global copper waste is collected at the end of its life cycle. Therefore, the copper consumption per city is multiplied with this factor, indicating the amount of waste per city.

In table 9.1, an example of one data point can be found.

Table 9.1: Datapoint of waste point in Antwerp, Belgium

NUTT 2	**Country**	**Employees**	**City**	**long**	**lat**	**% / all Employees**	**Consumption (kT)**	W_j
Prov. Antwerpen	Belgie	114,40	Antwerp	4,4028	51,2194	20%	14,17	7936,6

9.2 Set of customer locations (k) and demand (D_k)

For the customer locations, it is realistic that a natural resource company has some customers spread out over Europe. These customers will likely be electronics, automotive, renewable energy, construction, power generation, and transmission companies. These industries are, just as the waste points, located in the specified cities.

The company most likely has a few large customers for the recycled copper. To indicate the highest copper-consuming zones, the cities with a copper consumption of more than 12kT/year are chosen. This results in 18 locations: namely Antwerp, Stuttgart, Karlsruhe, Freiburg im Breisgau, Munich, Düsseldorf, Cologne, Dortmund, Barcelona, Valencia, Paris, Nantes, Lyon, Turin, Milan, Venice, Bologna, and Katowice. It is therefore assumed that the company will have customers (k) located in these cities.

The demand (D_k) is determined as follows. Glencore's total marketing volumes sold in 2023 were 3.3 mT (Glencore, 2024d). According to (International Copper Association, 2023), approximately 15% of the total share of copper demand goes to Europe. So, 15% of 3.3 mT is 495.000 tons of copper transported to Europe yearly. As the demand for copper will increase in the coming years, circa 23% by 2030 (Klose and Pauliuk, 2023), the amount of copper flowing to Europe will increase, resulting in a total of 608.850 tons.

The percentage of copper allocated to each customer city is based on the proportion of total consumption that the city represents. For instance, Stuttgart accounts for 11.87% of the total consumption among these cities, so 11.87% of the demand is directed to Stuttgart. In Appendix 15.5 in table 15.2, the table of the customer data can be found.

9.3 Set of potential recycling facilities (i)

As there is no existing set of recycling facilities, the data for this research is obtained through the Center of Gravity (CoG) tool of AIMMS. This tool calculates the candidate locations for recycling facilities by balancing the distance between waste points (j & W_j) and customer locations (k & D_k). The total cost depends on the transportation costs, which are proportional to the distances between the waste points, customer locations, and candidate CoG locations. The center of gravity tool calculates the points considering distances and volumes.

In AIMMS, the CoG tool can be determined using the "number of CoGs Scenario". In this scenario, the user chooses a fixed number of CoGs, and the algorithm calculates the locations to minimize the total travel distance to all demand/supply locations. The CoG algorithm calculates the location of each CoG, assigning demand/supply points to the closest CoG and adjusting the CoGs based on new CoGs until an optimal balance is found. This process minimizes the total travel distance of the load (AIMMS, 2024).

To obtain the optimal facility locations, the number of CoGs is set at 30. During the CoG, all the waste and customer locations are selected. For the transport costs, the average generalized transport costs value is investigated by (Persyn et al., 2022). This research is explained in more detail in the next section. The transport costs are given in Table 9.2. Moreover, the function of selecting the nearest city to the CoG location is selected, resulting in a geographically feasible location. This results in a set of 30 optimal recycling facility locations (k), including their longitudes and latitudes. This set serves as an input for the full optimization. The locations set is given in Appendix 15.5 in table 15.3.

9.4 Input MILP

This section will present the methods for obtaining the remaining parameter data, including the fixed costs (f_i), the transport costs (t_{mn}), the unit costs (c_i), the VoT (VoT), the distances ($Distance_{mn}$), the Wiggle Factor (WF), the subsidies ($Subsidy_i$), the risk costs ($Risk_i$), and the internal rate (IR).

According to (Tadaros et al., 2022), the fixed costs for opening a new recycling facility in Sweden are 218 million euros. This amount is the base cost for opening a recycling facility in Sweden. To estimate the different costs for the other cities, proportions for the cities are taken based on (Arcadis, 2023). In this study, construction costs across cities are determined by material costs, labor expenses, equipment costs, inflation rates, and energy costs. By incorporating these diverse cost elements, the analysis sufficiently reflects the cost variations across different locations. This method was chosen as the specific calculation of the fixed costs per city was based on too many assumptions, making this more realistic. The total fixed costs (f_i) data can be found in Appendix 15.5 in Table 15.6.

Secondly, for the transport costs parameter (t_{mn}), the study of (Persyn et al., 2022) is used. The study develops a methodology to estimate generalized transport costs (GTC) in European freight transport for a 40-ton truck, with a carrying load of approximately 25 tons. These costs are determined by various distance, time and infrastructure factors. Distance-related factors include fuel expenses, toll and vignette costs, and maintenance and tire expenses. Moreover, the time-related costs include driver wages based on national wage levels and regulatory limits on driving hours. The transport costs are also affected by speed limits, congestion, and terrain complexity, which influence total travel time. Besides these costs, annual vehicle taxes and ferry charges are incorporated in the transport costs, with ferry costs dependent on waiting times and trip distance. To estimate the transport costs, the study uses OpenStreetMap (OSM) data to construct a European road network and applies Dijkstra's algorithm to find cost-optimal routes. The transport costs for the different cities are depicted in Appendix 15.5, Table 15.4.

Third, in this research, the unit costs (c_i) include labor costs, which will depend on the country in which the facility is located. The labor costs of different EU countries can be based on (Eurostat, 2024). The most recent labor costs are chosen (2023). Moreover, according to (Today, 2024), around 40 to 45 tons a day of copper can be produced. Therefore, assuming a continuous 24-hour operation, this translates to processing approximately 1.77 tons of copper per hour. With this information, the labour costs per ton can be calculated. The data is depicted in Appendix 15.5 in Table 15.5.

Fourthly, for the VoT parameter (VoT), the report by (Kouwenhoven et al., 2023) is consulted. This report specifies values for the Value of Travel Time for Freight (VTTF) in logistics, breaking it down into the transport services component (e.g., fuel costs, staff wages, vehicle costs), and a cargo component (e.g., opportunity costs of delayed cargo). As the transport costs already cover the transport services component, for the VoT (or in transit costs), the cargo component. The cargo component relates to the value of the shipment, its depreciation, its tendency to degrade, or its risk of being stolen. Moreover, it depends on the importance of the shipments or the commodity (varying from 10-20% of total transport costs). Thus, for this study, an average of 14.5% is taken, resulting in 0,789 €/ton/hour[5].

[5]This comes from a cargo component cost of 6,3 €/hour, which is calculated for a load of 8 ton. Thus, the cost per ton is 6,3/8=0,789 €/ton/hour

Fifthly, the distances ($Distance_{mn}$) are calculated by AIMMS with its LocationIQ API, which is a geocoding and location data API that provides the service to obtain coordinates and distances or travel times between locations (AIMMS, 2024). Furthermore, AIMMS calculates the distances of the coordinates using straight lines. Therefore, a wiggle factor (WF) is used to correct the terms. The wiggle factor is based on the study by (Domínguez-Caamaño et al., 2016) who performed a statistical analysis with more than 10.000 Spanish routes, including both road infrastructure in rural, more hilly- and mountain areas (WF=0.36) and high-capacity roads, which are typically motorways and flat areas (WF=0.29). As the arcs represented in this research flow through both flat, hilly and mountain areas, the average is taken (WF=0,33 or 33%).

For the subsidies ($Subsidy_i$), the European Union or member countries have several initiatives for the financing of projects that enhance the circular economy in Europe (Bank, 2024) (Davis, 2024) (Commission, 2024c) (voor Ondernemend Nederland, 2025). Additionally, as mentioned before, companies can apply as a 'Strategic Project' and receive EU funds. Nevertheless, the amount of these funds is project dependent (Commission, 2024h). Subsidies are small and difficult to obtain (S. Steeneken, personal interview, 2025). Therefore, in this research, 10% of the fixed costs are taken. Refer to (Appendix 15.5, Table 15.6) for the subsidy data.

The risk costs ($Risk_i$) are based on the informed risk factor. INFORM is a collaboration of the Inter-Agency Standing Committee Reference Group on Risk, Early Warning and Preparedness and the European Commission. Moreover, it is a generalized risk factor including hazard & exposure (natural disasters), vulnerability (socio-economic), and lack of coping capacity (institutional, government, infrastructure, communication) (Commission, 2024g). The risk parameters are calculated by normalizing the INFORM Risk Index scores for each location on a scale of 0 to 1, based on the dataset's minimum and maximum risk scores. The normalized score interpolates a percentage between the range 1–2%. These percentages are multiplied by the fixed costs. The risk costs are given in Appendix 15.5 in Table 15.7.

For the internal rate, an average is taken from (Tadaros et al., 2022) and (Sunaryo et al., 2020). (Tadaros et al., 2022) used 5% to establish lithium-ion battery recycling facilities. Furthermore, (Sunaryo et al., 2020), who focused on ship recycling, estimated 12-17%. A 9% internal rate is a sufficient estimate as it balances between these two studies in which similar facilities are considered. Appendix 15.5, Table 15.6 depicts the data.

In Table 9.2, an overview of all the data points, including the sources for the depreciation, average speed of the truck, the maximum capacity, the recycling rate, and the internal rate, is given.

Table 9.2: Overview datapoints parameters

Parameter	**Datapoint**
DEPR	30 years (Tadaros et al., 2022)
Average tc	0,082[6] €/ton/km (Persyn et al., 2022)
Speed	90 km/hour (Persyn et al., 2022)
η	0,56 (Association, 2022)
λ	0,25 (EU, 2023a)
IR	0,09 (Tadaros et al., 2022) (Sunaryo et al., 2020)
VoT	0,789 €/ton/hour (Kouwenhoven et al., 2023)
WF	0,33 (Domínguez-Caamaño et al., 2016)
$C_{\max}$	50.000 tons/year (Tadaros et al., 2022) (S. Steeneken, 2025)

[6]Derived from 2,039 €/km, which are the costs for a 40-ton truck with a carrying load of 25 tons. Therefore, the cost per ton per km is 2,039/25 = 0,082€/ton/km.

10 Results

This section presents an in-depth analysis of the optimization results, focusing on facility utilization, cost distribution, transport flows, and deviations in expected capacity usage. Moreover, in this chapter, the research question: *What is the optimal design of the copper recycling network under CRMA requirements?* is answered.

10.1 Optimal network structure

In Figure 10.1, the optimization results are displayed. Also, in Figures 15.7 and 15.8 in Appendix 15.6, the results are shown through a different representation (with 15.7 showing all nodes, including the in-active ones, and 15.8 showing high and low demand areas).

The green triangles are depicted as the waste points, the blue circles are the customers, and the orange facilities are the recycling facilities. Furthermore, the blue arcs are the copper waste flows (y_{ij} or collection) from the waste points to the facilities and the black arcs represent the recycled copper flows (y_{ik} or distribution) from the facilities to the customers.

As shown in Figure 10.1 and Table 10.1, the optimal recycling facilities are located in Barcelona, Bologna, Geithain and Stuttgart. These locations were selected based on the lowest costs. Furthermore, in the figure, it is visible from which waste points are collected. As can be seen, not all waste supplied is necessary to fulfill demand. Therefore, the nearest waste points are chosen.

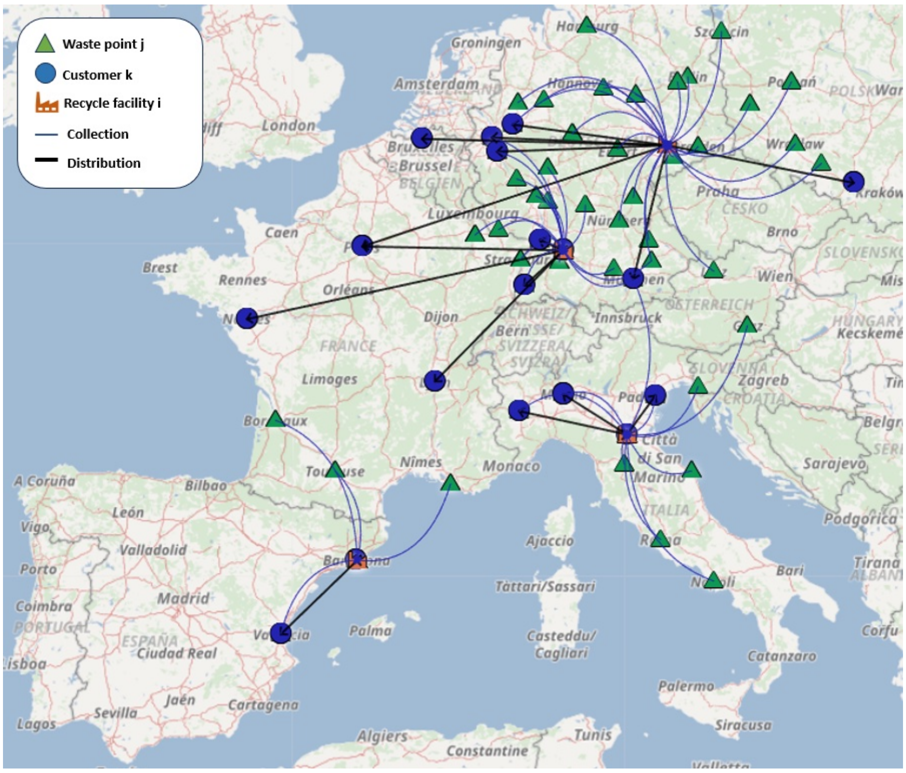


Figure 10.1: Optimal recycling network, active nodes

Table 10.1 depicts the rounded optimal capacities and belonging costs. For the unrounded numbers, refer to Appendix 15.6, Table 15.8. The total processing capacity used across these facilities is 152.210 tons, equal to the demand. The total processing capacity used across these facilities is therefore 152.210 tons. The total cost is €33,6M, which is divided as follows. The fixed costs are the dominating costs with 60%, indicating as the most important factor for the network's performance. The variable costs are low with 9,3%, suggesting that the labour costs are relatively inexpensive. Last, the transport costs make up 30,7%, showing that the logistics efficiency is an important factor in the network performance.

Moreover, transport costs are split between collection (y_{ij}) and distribution (y_{ik}). These numbers are specified in Tables 10.2 and 10.3. These are the rounded numbers; the unrounded numbers can be found in Appendix 15.6, Table 15.9 and 15.10. Additionally, in Appendix 15.6, Table 15.11, the specific output of y_{ij} and y_{ik} are listed, including the costs of all the arcs. The collection costs are higher than the distribution costs, indicating that collecting waste is more costly than distributing the recycled copper to its customers. This is logical as the waste has to be collected from more locations than it has to be sent to customers.

Table 10.1: Costs (€) per facility i (rounded)

Facility i	C_i	**Fixed**	**Variable**	**Collection**	**Distribution**	**Total**
Barcelona_REC	16.600	4.843.300	230.300	862.500	294.600	6.230.700
Bologna_REC	39.200	5.133.900	660.700	1.681.200	736.200	8.212.000
Geithain_REC	46.400	3.876.700	1.082.700	2.043.600	2.099.100	9.102.100
Stuttgart_REC	50.000	6.300.000	1.166.500	1.131.400	1.491.000	10.088.900
Total	152.200	20.153.900	3.140.200	5.718.600	4.621.000	33.633.700

Table 10.2: Collection costs (€) per location (rounded)

Facility i	y_{ji}	$Distance_{ji}$ **(km)**	t_{ji}	**In-Transit Costs**	**Total Transport Costs**
Barcelona_REC	29.700	1.700	801.800	60.600	862.500
Bologna_REC	70.200	3.600	1.518.800	162.400	1.681.200
Geithain_REC	83.100	7.100	1.816.100	227.500	2.043.600
Stuttgart_REC	89.500	3.500	994.900	136.400	1.131.400
Total	272.500	15.900	5.131.700	586.900	5.718.600

Table 10.3: Distribution costs (€) per location (rounded)

Facility i	y_{ik}	$Distance_{ik}$ **(km)**	t_{ik}	**In-Transit Costs**	**Total Transport Costs**
Barcelona_REC	16.600	100	273.900	20.700	294.600
Bologna_REC	39.200	200	665.100	71.100	736.200
Geithain_REC	46.400	600	1.865.400	233.700	2.099.100
Stuttgart_REC	50.000	400	1.311.300	179.700	1.491.000
Total	152.200	1.300	4.115.700	505.300	4.621.000

A striking observation is that Stuttgart operates at full capacity (50.000 tons), whereas Barcelona, Bologna, and Geithain do not reach their maximum processing limits (16.570, 39.230, and 46.410 tons, respectively). This variation in facility utilization suggests a combination of waste availability, transport cost minimization, and customer proximity influencing the model's decisions.

Stuttgart is the only facility operating at full capacity. This is primarily due to its central location within the network, allowing it to collect and distribute copper efficiently. The waste points assigned to Stuttgart are all within short to medium distances, keeping collection costs relatively low, as seen in Table 10.1 and 10.2.

Additionally, Stuttgart serves as a major distribution hub for recycled copper, supplying cities such as Lyon, Nantes, and Paris and local cities such as Freiburg. Also, these costs are low compared to the other facilities, as seen in Table 10.3. Therefore, despite having the highest fixed costs, Stuttgart can function under relatively low total costs, as transport costs are kept low because of its central location.

Geithain is the second largest operator. This is logical considering its central location. Nevertheless, the distance from waste points to Geithain is generally higher than that of other facilities, making it more expensive to transport additional waste. Furthermore, Geithain serves long-distance customer locations such as Katowice, Cologne, and Dortmund, leading to higher distribution costs. As can be seen in Tables 10.1, 10.2 and 10.3, the total transport costs for Geithain are among the highest in the network, indicating that while it is an important recycling facility, further increasing its utilization would lead to reduced cost efficiency.

Bologna is the third largest recycling facility. Its collection and distribution are mainly from northern Italian locations, reinforcing its role as a key recycling center in Italy. Despite its importance, Bologna does not reach full capacity because it primarily serves regional customers, reducing the need for higher processing volumes. This is convenient as collection costs are already higher than Stuttgart despite its lower volume, as seen in Table 10.2. Furthermore, Bologna distributes recycled copper efficiently to customers in Milan, Venice, and Turin, minimizing distribution costs, as can be seen in Table 10.3.

Lastly, Barcelona operates at the lowest capacity in the network. This is primarily due to the limited waste supply from nearby sources. The main waste points serving Barcelona are all located within a relatively short distance. Moreover, as Barcelona serves only local demand, it does not require more processing capacity. Its primary customer locations are Valencia and Barcelona itself. As a result, transport costs for Barcelona are the lowest in the network. The model does not assign additional supply to Barcelona because it would require long-distance transport, increasing costs.

10.2 Conclusion

This chapter answered the sub-question *What is the optimal design of the copper recycling network under CRMA requirements?*

The optimal recycling network under CRMA requirements consists of four facilities in Stuttgart, Geithain, Bologna and Barcelona with a total processing capacity of 152.210 tons, meeting demand. The model prioritizes cost minimization, with fixed costs accounting for 60% of total costs, followed by transport costs (30.7%) and variable costs (9.3%). Considering transport costs, waste collection is more expensive than distribution, as facilities must source from multiple waste points, whereas customer distribution is more concentrated.

Stuttgart operates at full capacity (50.000 tons) due to its central location, which minimizes transport costs for both collection and distribution. Geithain, the second-largest operator, has higher transport costs due to long-distance shipments but remains crucial for serving key European customers. Furthermore, Bologna does not reach full capacity as it primarily serves localized demand. Lastly, Barcelona operates at the lowest capacity due to limited nearby waste supply and local customer demand, resulting in the lowest transport costs in the network.

Therefore, the results highlight the importance of waste availability and regional demand in determining optimal facility locations and capacities.

11 Sensitivity analyses

This section presents the findings of the sensitivity analyses conducted on three key parameters: maximum facility capacity, transport costs, and fixed costs, as well as on demand and supply fluctuations. The sensitivity analyses test how sensitive certain parameters are and how variations in these parameters impact the network. This will give insights into the sensitivity for uncertainties in data points and the cost structure of the model.

11.1 Maximum capacity

First of all, the impact of changing the maximum facility capacity on the costs and number of facilities. The maximum capacity analyzed is 200.000 as this exceeds the customer demand (of 152.000). As can be seen in Table 11.1, the number of facilities decreases with higher facility capacity. Also, as is depicted in Figure 11.1, the total costs decrease significantly when capacity is increased.

Table 11.1: Impact of changing capacity on the number of facilities

Capacity	Number of facilities	Facility locations
20.000	8	Barcelona, Bologna, Dortmund, Freiburg, Geithain, Katowice, Poznan, Stuttgart
Base case (50.000)	4	Barcelona, Bologna, Geithain, Stuttgart
70.000	3	Bologna, Geithain, Stuttgart
100.000	2	Bologna, Darmstadt
200.000 / no limit	1	Stuttgart

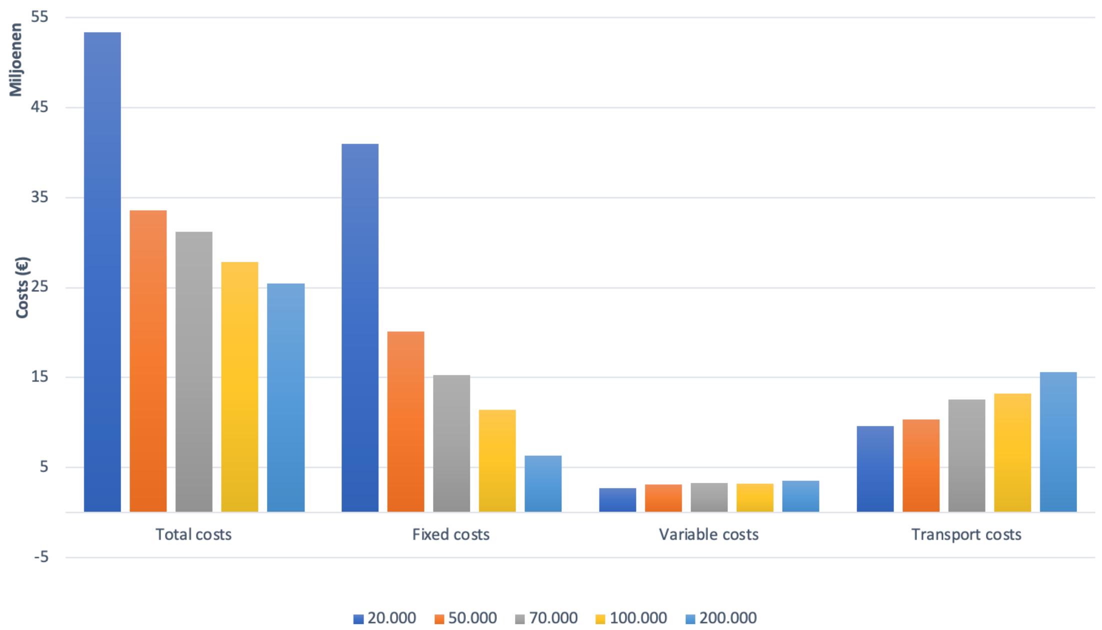


Figure 11.1: Sensitivity analysis maximum capacity

Facility capacity is crucial in determining the number and locations of active recycling centers. With a low facility capacity of 20.000 tons, the model requires eight facilities, including locations such as Barcelona, Dortmund, Freiburg, Geithain, and Katowice. This decentralized structure reduces transport distances but increases fixed costs. As capacity increases, the number of facilities decreases, with the network transitioning into four locations at 50.000 tons (base case), three at 70.000 tons, and ultimately a single facility at 200.000 tons (Stuttgart).

The changing facility locations suggest that certain locations are more cost-effective than others, remaining in the network across multiple scenarios. Bologna and Stuttgart consistently appear in nearly all scenarios. In contrast, other locations such as Poznan, Dortmund, and Freiburg only appear in the low-capacity scenario, suggesting that they are only necessary when more decentralized processing is required. Notably, Geithain remains active up to a capacity of 70.000 but is removed when capacity reaches 100.000 tons, when it is replaced by a more centrally located facility, reducing transport costs.

Furthermore, total costs decrease consistently as facility capacity increases. At the lowest tested capacity of 20.000 tons per facility, total costs reach €53M, significantly higher than the base case (€33M). This cost difference is primarily due to the need for additional facilities and thus higher fixed costs. At higher capacities, the cost reductions continue, with total costs decreasing to €25M when facilities can process 200.000 tons each. This reduction is driven by a decline in fixed costs, which drop to €6M in the highest capacity scenario. The results indicate that fixed costs are the most dominant cost driver in the network.

In addition, variable costs remain relatively stable across all scenarios. Thus, increasing or decreasing facility capacity has only a minor impact on the variable costs, indicating that the variable costs are not a prominent cost driver. Even with other labor costs in the different locations, this does not make a great difference. However, transport costs increase as facility capacity increases. This is because fewer facilities lead to longer distances to collect and distribute copper, leading to higher transport costs. At the lowest capacity scenario, transport costs are around €9M, rising to €15M when only one facility is active. Nevertheless, the higher fixed costs of an additional facility still outweigh the transport costs.

11.1.1 Conclusion

Facility capacity significantly impacts the number and locations of recycling centers, total costs, and transport efficiency. With a low capacity (20.000 tons per facility), the model requires eight facilities, increasing fixed costs but reducing transport distances. As capacity increases, the number of facilities decreases, reaching one facility in Stuttgart at 200.000 tons.

Total costs decline consistently with increasing capacity, dropping from €53M (8 facilities) to €25M (1 facility). This is driven by lower fixed costs, which dominate total expenses. Variable costs remain stable, while transport costs increase as fewer facilities lead to longer collection and distribution routes. Despite higher transport costs at larger facilities, the savings in fixed costs outweigh transport expenses, making high-capacity facilities the most cost-effective option.

However, operational feasibility, network resilience, and long-term flexibility must be considered. While a single large facility minimizes costs, it increases risk in case of disruptions. A balanced approach, maintaining some differentiation in facility locations, may provide a more robust and sustainable solution for long-term network stability. In addition, a recycling facility producing 200.000 tons of copper annually may not be as realistic.

11.2 Transport costs

Secondly, the sensitivity of an even increase in transport costs is analyzed. An increase of 10 to 600% is evaluated. As seen in Table 11.2, the number of facilities does not change when transport costs increase. Only when the transport costs are increased by 600%, the number of facilities increase. This is because fixed costs dominate the cost structure, making it more cost-effective to absorb higher transport costs rather than open new facilities.

Table 11.2: Impact of increasing transport costs on the number of facilities

Transport costs	Number of facilities	Facility locations
Base case	4	Barcelona, Bologna, Geithain, Stuttgart
10% increase	4	Barcelona, Bologna, Dortmund, Stuttgart
40% increase	4	Barcelona, Bologna, Dortmund, Stuttgart
70% increase	4	Barcelona, Bologna, Dortmund, Stuttgart
300 % increase	4	Barcelona, Bologna, Dortmund, Stuttgart
400% increase	4	Barcelona, Bologna, Dortmund, Stuttgart
500% increase	4	Barcelona, Bologna, Dortmund, Stuttgart
600% increase	5	Barcelona, Bologna, Dortmund, Katowice, Stuttgart

Unlike capacity changes, transport cost increases do not significantly change the number of facilities in the network until the extreme 600% increase. Throughout the scenarios, up to a 600% increase, the network remains stable at four facilities (Barcelona, Bologna, Dortmund, and Stuttgart). Even with large cost increases, the model does not react by opening additional locations.

Notably, there occurs a switch from Geithain to Dortmund when increasing costs by 10%. As can be seen in Table 15.6 in Appendix 15.5, Geithain has lower fixed costs compared to Dortmund. Nevertheless, when transport costs increase, it is more beneficial to switch to a more centrally located facility.

As mentioned before, only when transport costs increase by 600%, the model introduces Katowice (located in Poland) as a new facility, expanding the network to five locations. Therefore, at very extreme transport costs, it becomes more beneficial to open an additional facility rather than incurring higher transport distances, particularly in Eastern Europe. Most likely due to the customer located in Katowice.

Logically, as shown in Figure 11.2, total costs increase as transport costs rise. Moreover, fixed and variable costs remain constant as the same facilities are active. Only in the base case, when Geithain is included instead of Dortmund, and during the 600%, when the fifth facility, Katowice, is opened, the fixed costs are different. The variable costs also show a negligible change (slightly lower for the 600% increase case as labor costs are lower in Katowice).

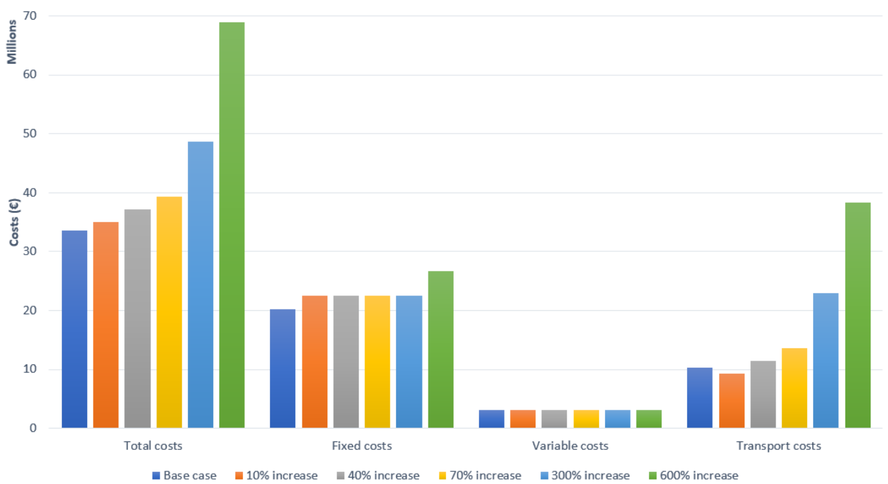


Figure 11.2: Sensitivity analysis transport costs

As seen in Figure 11.3, all distances, except for the base case and the 600% increase case, are equal and transport costs rise linearly. For the base case, the distance is higher due to the facility located in Geithain (which has lower fixed costs and is therefore chosen). For the 600% increase case, the distance is lower due to the newly introduced facility in Katowice, resulting in lower distances to waste points and customers and therefore lower transport costs.

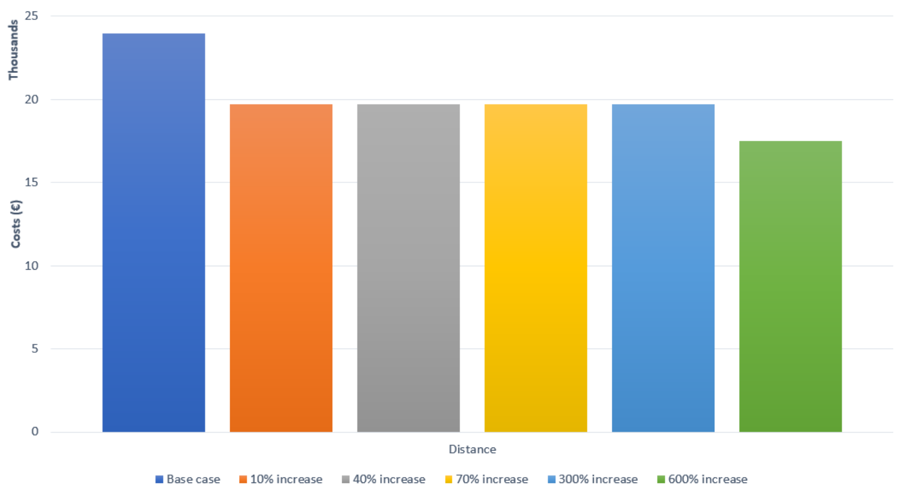


Figure 11.3: Changing distance during transport costs increases

The reason that the model opens an extra facility during the 600% case is that opening the facility in Katowice (which has a fixed cost of 4.1M euros) is ultimately less expensive than continuing to absorb the increased transport costs without it. In the 600% increase scenario, the total costs are €68.9M, of which €39.1M is attributed to transport. When forcing the model only to use the original four facilities (Barcelona, Bologna, Dortmund, and Stuttgart) and excluding Katowice, the total costs increase significantly to 79.8M euros, of which 56.4M are transport-related. This results in a transport cost difference of 17.3M euros.

Therefore, by allowing the activation of Katowice, the model reduces transport costs substantially by more than four times the additional fixed cost of the new facility (17.3M vs. 4.1M). This confirms that, under extreme transport costs, the trade-off favors increasing the number of facilities to minimize long-distance transport, especially those in Eastern Europe.

11.2.1 Conclusion

The sensitivity analysis on transport costs shows that network structure remains unchanged until an extreme 600% cost increase. Up to 600% increase, the model retains four facilities (Barcelona, Bologna, Dortmund, and Stuttgart), indicating that fixed costs dominate location decisions and it is more cost-effective to absorb higher transport costs rather than open new facilities.

A key switch occurs at 10% increase, where Dortmund replaces Geithain due to its more central location, reducing transport costs despite higher fixed costs. At 600% increase, a fifth facility (Katowice) is added, lowering transport distances, particularly for Eastern European customers. At this point, the transport costs would decrease significantly. This trade-off becomes favorable because the 4.1M euro cost of opening Katowice is outweighed by a 17.3M euro reduction in transport costs.

Total costs increase linearly as transport costs rise, except in the base case (higher distances due to Geithain) and the 600% case (lower distances due to Katowice's inclusion). These results highlight that location shifts and facility activations are only necessary at extreme transport cost increases, confirming that fixed costs are the primary cost in the network.

11.3 Fixed costs

Thirdly, the fixed costs are evaluated, which are decreased evenly. For the results, refer to Table 11.3 and Figure 11.4. The fixed costs are the largest cost component in the model, making them a crucial factor in facility selection. Just as the transport costs, the number of facilities does not change with a small decrease in fixed costs. Only when fixed costs are decreased by 80%, the number of facilities increases to 5. Furthermore, with a 90%, the facilities increase to 8.

Compared to the transport cost increase scenario, the network reacts more quickly to fixed cost reductions because fixed costs comprise the largest share of the total cost structure. When these costs are lowered, it becomes financially feasible to open more facilities. This explains why facility expansion begins at an 80% reduction in fixed costs but occurs at a 600% increase in transport costs.

Table 11.3: Impact of decreasing fixed costs on the number of facilities

Fixed costs	Number of facilities	Facility locations
Base case	4	Barcelona, Bologna, Geithain, Stuttgart
10% decrease	4	Barcelona, Bologna, Dortmund, Stuttgart
40% decrease	4	Barcelona, Bologna, Dortmund, Stuttgart
70% decrease	4	Barcelona, Bologna, Dortmund, Stuttgart
80% decrease	5	Barcelona, Bologna, Dortmund, Katowice, Stuttgart
90% decrease	8	Barcelona, Bologna, Dortmund, Katowice, Milan, Nantes, Stuttgart, Valencia

From a 10% reduction on, Geithain is replaced by Dortmund. As mentioned before, Dortmund has higher fixed costs than Geithain. Nevertheless, when fixed costs decrease, Dortmund, is more a cost-effective alternative. This suggests that Geithain was only chosen due to its low fixed costs and not because of its location efficiency.

However, at a 80% reduction, a fifth facility (Katowice) is introduced. This suggests that with low fixed costs, decentralization becomes more cost-effective, reducing the need for long-distance collection and distribution.

Also, at a 90% reduction, the network expands significantly to eight facilities, adding Milan, Nantes, and Valencia. Thus, at extremely low fixed costs, the model prioritizes local facilities, reducing transport distances and costs.

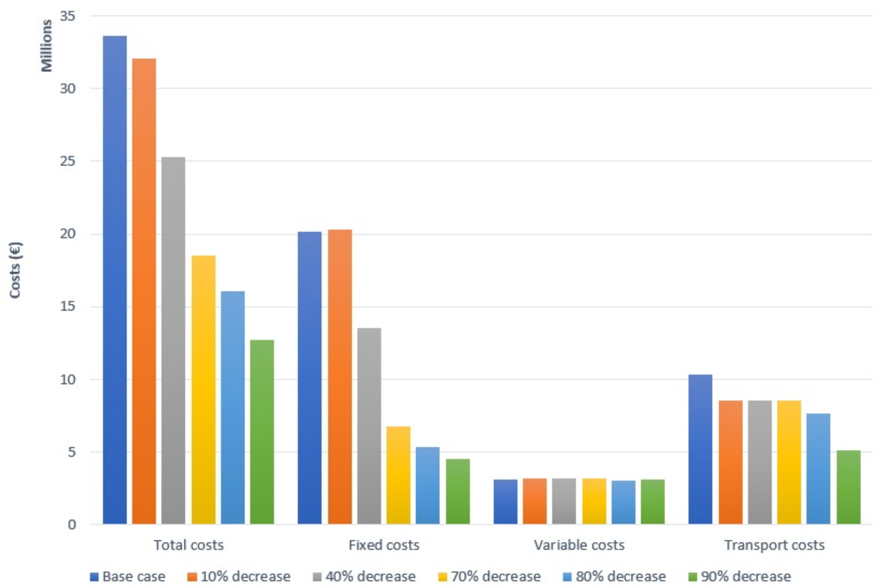


Figure 11.4: Sensitivity analysis fixed costs

As depicted in Figure 11.4, the total costs decrease significantly as fixed costs decline, showing that these costs are the primary cost driver. Logically, transport costs stay the same when the same facilities are open, as well as variable costs. Only when Dortmund replaces Geithain, the transport costs decrease. As well as during the 80% and 90% decrease. The transport costs decline as distances become smaller. Thus, from a 80% decrease on, decentralization offsets transport costs.

11.3.1 Conclusion

The sensitivity analysis on fixed costs shows that lowering costs significantly impacts facility selection and network structure. At a 10% reduction, Dortmund replaces Geithain, suggesting that Geithain was only preferred due to its lower fixed costs, not its location efficiency.

At 80% reduction, a fifth facility (Katowice) is added, and at 90% reduction, the network expands to eight facilities (adding Milan, Nantes, and Valencia), reducing collection and distribution costs.

As shown in Figure 11.4, total costs decline sharply as fixed costs decrease, proving that fixed costs are the primary cost driver. Transport costs remain constant until 80% reductions, where they decrease due to shorter distances. Thus, when fixed costs are reduced, decentralized networks become more beneficial, offsetting high transport costs.

11.4 Demand fluctuations

The next section presents the sensitivity analysis performed on evenly decreasing and increasing demand. As seen in Table 11.4, with lower demand levels, only three facilities are open, as the decrease in demand makes a fourth facility unnecessary. Therefore, reducing total demand allows the model to consolidate operations into fewer, higher-utilization facilities, eliminating the need for additional facilities. Furthermore, when demand increases by 10%, Stuttgart is replaced with Dortmund, which can be explained by the fact that a large amount of waste points and customers are located near this location (see Figure 15.6 in Appendix 15.5). This indicates that Dortmund has become more cost-effective with increased volumes, whereas Stuttgart was previously chosen for its central location at lower demand levels.

Additionally, during the 30% increase, the facilities shift more East as waste has to be collected from more waste points located in Eastern Europe. This shift highlights the growing importance of Eastern Europe as a supply source when demand rises. During the 50% and 65% increase, more facilities have to be opened to satisfy demand due to the capacity constraint.

Furthermore, as demand increases, costs rise due to the opening of additional facilities, leading to higher fixed costs. Also, transport costs increase, particularly during smaller demand increases. Notably, the distribution costs peak at the 30% increase scenario before declining at 50% and 65%. This is because, at 30%, fewer facilities handle a larger demand, necessitating longer transport distances, whereas at higher demand increases, additional facilities reduce distribution costs.

The results of the demand increase indicate that the model remains feasible up to a 65% demand increase, beyond which it becomes infeasible due to insufficient copper waste availability. At a 66% increase, the model fails to satisfy demand, leading to an unfulfilled copper demand of 629.29 tons. This confirms that waste supply shortages could be bottlenecks when demand increases significantly.

Table 11.4: Facility capacities sensitivity analysis demand fluctuations

30% decrease		**10% increase**		**30% increase**		**50% increase**		**65% increase**	
Facility i	C_i	**Facility i**	C_i	**Facility i**	C_i	**Facility i**	C_i	**Facility i**	C_i
Bologna_REC	33.638	Barcelona_REC	18.227	Bologna_REC	50.000	Barcelona_REC	28.316	Barcelona_REC	30.061
Geithain_REC	22.909	Bologna_REC	49.205	Dortmund_REC	50.000	Bologna_REC	50.000	Bologna_REC	50.000
Stuttgart_REC	50.000	Dortmund_REC	50.000	Katowice_REC	47.874	Dortmund_REC	50.000	Dortmund_REC	50.000
		Geithain_REC	50.000	Stuttgart_REC	50.000	Katowice_REC	50.000	Freiburg_REC	50.000
						Stuttgart_REC	50.000	Geithain_REC	35.365
								Katowice_REC	35.720

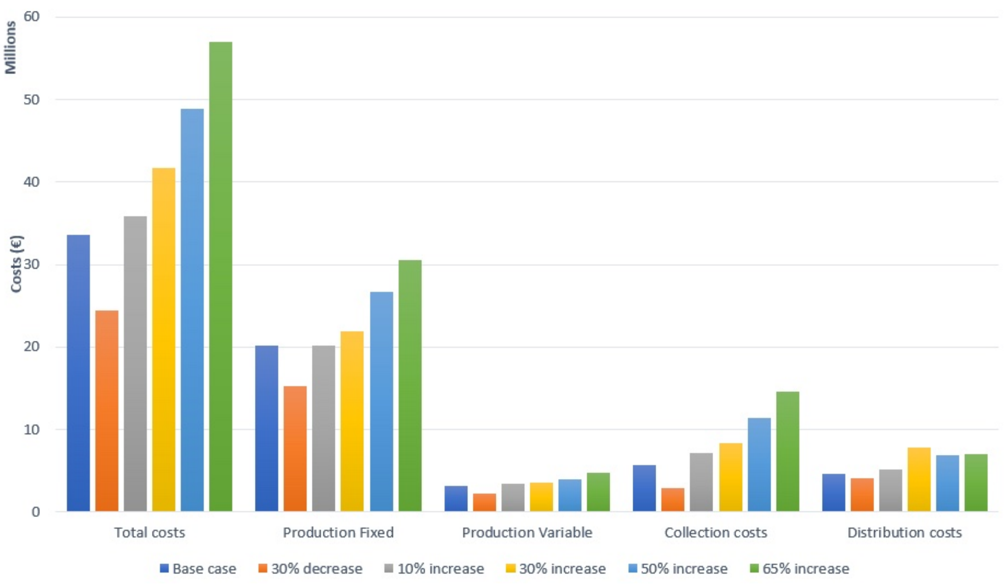


Figure 11.5: Sensitivity analysis demand

11.4.1 Conclusion

The sensitivity analysis on demand fluctuations reveals that a 30% demand decrease results in only three active facilities (Bologna, Geithain, and Stuttgart), eliminating the need for a fourth facility. So, lower demand enables a higher concentration of recycling, reducing fixed costs.

When demand increases by 10%, Dortmund replaces Stuttgart, suggesting that Dortmund's proximity to more waste points and customers makes it more efficient for handling larger volumes. Nevertheless, at a 30% demand increase, the network shifts eastward, adding Katowice, indicating that additional waste must be sourced from East Europe to sustain rising demand.

At 50% and 65% demand increases, more facilities are required due to capacity constraints. Furthermore, distribution costs peak at 30% demand increase but decline at higher demand levels as additional facilities reduce transport distances.

The model remains feasible up to a 65% demand increase, but at 66%, it becomes infeasible due to a supply shortage of 629.29 tons, highlighting that waste supply shortages could be a bottleneck when demand increases significantly.

11.5 Supply fluctuations

The next section presents the sensitivity analysis on evenly decreasing the waste supply. Currently, not all waste is used. Therefore, only an analysis is executed on lowering the supply. The results are given in Table 11.5 and Figure 11.6.

Firstly, as the availability of waste decreases, total costs increase, mainly due to the rising collection costs. The fixed costs remain the same, but collection costs increase significantly due to longer transport distances and lower waste availability, leading to higher per-unit costs. This reflects the need to collect waste from a wider geographical area. In contrast, distribution costs remain relatively stable across all scenarios, indicating that the demand side of the network remains largely unaffected.

From a facility utilization perspective, the facility locations stay the same. The model adapts only slightly by volume. Moreover, Stuttgart was removed from the network, while Dortmund took over as the primary facility. This shift suggests that the model prioritizes facilities located more centrally when supply decreases to decline transport costs.

Critically, supply could be decreased up to 39.5%. Greater reduction led to infeasibility, meaning insufficient copper waste was available to meet demand. Thus, the recycling network is sensitive to supply shortages, and future disruptions in waste availability could impact the network.

Table 11.5: Facility capacities sensitivity analysis supply decrease

10% decrease		**30% decrease**		**39.5% decrease**	
Facility i	C_i	**Facility i**	C_i	**Facility i**	C_i
Barcelona_REC	16.570	Barcelona_REC	16.570	Barcelona_REC	18.454
Bologna_REC	39.231	Bologna_REC	39.231	Bologna_REC	40.757
Geithain_REC	46.410	Dortmund_REC	50.000	Dortmund_REC	50.000
Stuttgart_REC	50.000	Geithain_REC	46.410	Geithain_REC	43.000

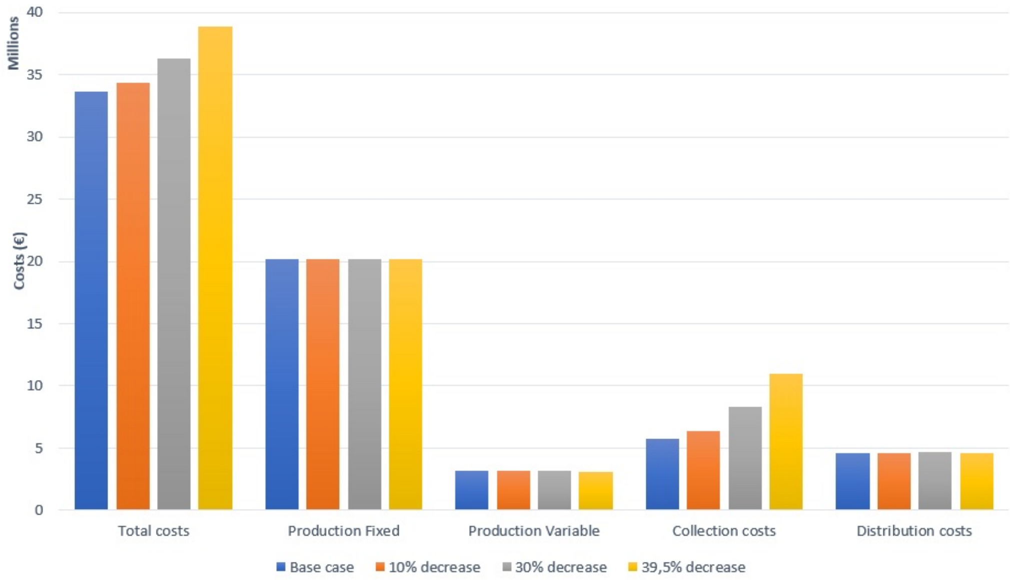


Figure 11.6: Sensitivity analysis supply

11.5.1 Conclusion

The sensitivity analysis on supply fluctuations reveals that reducing available copper waste increases total costs, primarily due to rising collection costs. Since fixed costs remain unchanged and distribution costs are relatively stable, the higher collection costs result from sourcing waste from a broader geographic area, making transport more expensive.

Facility utilization remains largely stable, but Stuttgart is removed from the network as supply decreases, with Dortmund taking over as a more cost-effective alternative. This suggests that when waste supply is limited, the model prioritizes more centrally located facilities to minimize collection costs.

The model remains feasible up to a 39.5% supply decrease, but beyond this, there is insufficient copper waste to meet demand, making the network infeasible. This highlights the recycling network's vulnerability to supply shortages and emphasizes improving waste collection to ensure resilience.

11.6 Conclusion

The sensitivity analyses highlight that facility capacity and fixed costs are the most sensitive parameters, while transport costs and demand fluctuations have a more limited impact on the network.

Firstly, facility capacity strongly affects the number and locations of recycling centers, with higher capacities leading to fewer facilities and lower costs due to reduced fixed costs. Despite increased transport costs when fewer facilities operate, savings from reduced fixed costs outweigh these expenses, making high-capacity facilities the most cost-effective. However, relying on a single facility increases risks.

Secondly, fixed costs are the primary driver, determining facility locations and network structure. When reduced, the model shifts towards a more decentralized structure, adding facilities to minimize transport distances. This demonstrates that high fixed costs discourage decentralization, while lower fixed costs make localized recycling beneficial.

Thirdly, transport costs have a limited impact on facility locations, with the network structure remaining mostly unchanged until a 600% increase. The model prioritizes transport cost increases over opening new facilities, proving that fixed costs dominate location decisions. However, in extreme cases, additional facilities are introduced to shorten transport distances and costs.

Fourthly, demand fluctuations show that lower demand results in a more concentrated network, reducing fixed costs. As demand increases, the network shifts eastward to access additional waste. The model remains feasible up to a 65% demand increase, beyond which supply shortages cause infeasibility, confirming that waste availability is a limiting factor.

Lastly, supply shortages significantly impact costs, primarily through rising collection expenses. As waste supply decreases, more centrally located facilities are prioritized to minimize collection costs. The network remains feasible up to a 39.5% supply reduction; beyond this, demand cannot be met, highlighting the network's vulnerability to supply reduction.

In summary, facility capacity and fixed costs are the most sensitive parameters. Additionally, transport costs and demand fluctuations are less influential, with significant changes occurring only under extreme conditions. Moreover, waste supply is a critical constraint, as lower availability increases costs and can lead to infeasibility.

Furthermore, the findings highlight the importance of balancing cost efficiency with network resilience to ensure a stable recycling network. Cost minimization favors fewer, larger facilities, but this reduces flexibility and increases risks. Ensuring sufficient waste availability and maintaining a decentralized network with multiple facilities improves resilience.

12 Scenario-based testing

This chapter answers the research question: *How does the optimized copper recycling network perform under scenarios such as supply- and demand fluctuations, and disruptions?*

The scenarios presented in this chapter differ from the sensitivity analyses discussed in Chapter 11. The sensitivity analyses allowed the model to adjust the network by opening or closing facilities in response to changing input parameters. This approach focused on identifying the most cost-optimal network structure under varying conditions.

In contrast, this chapter evaluates the robustness of the already optimized network. When disruptions occur in reality, it is often not feasible to change the entire network immediately. Therefore, in all scenario tests presented here, the current set of open and closed facilities remains fixed (so no new facilities can be opened except explicitly mentioned). The aim is to assess how well the existing network can withstand external changes, including normal external developments (such as demand and supply fluctuations) and disruptions.

The costs in this chapter are rounded to hundreds. Refer to Appendix 15.7 for the exact costs.

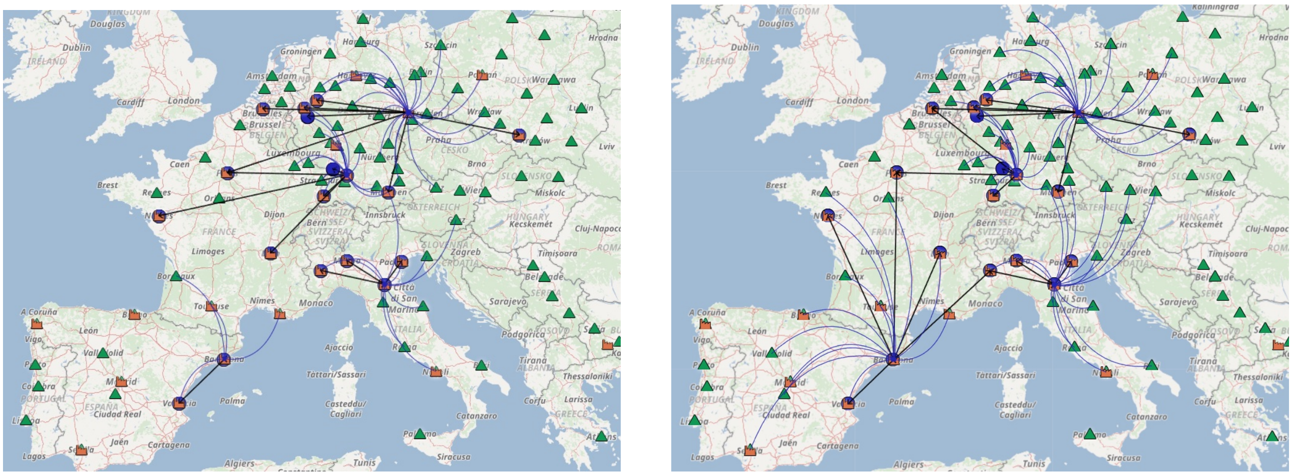
12.1 Demand fluctuation

The first scenario tests a uniform fluctuation in demand, where demand is increased or decreased by the same percentage across all customers. For example, in the case of a 30% increase scenario, the demand of every customer is increased by 30%. In Figure 12.1 and Tables 12.1 and 12.2, the results are depicted. Additionally, the remaining network structures are displayed in Appendix 15.7.

First, an increased demand could result from stricter regulations in the future, and the emergence of even more technologies, due to which more copper is required. Thus, handling rising customer demand is critical in ensuring the networks' long-term resilience. Furthermore. A decrease in demand could be the result of demand shifting to competitors. As one single company will not be the only supplier of customers, this is a risk that has to be considered. Customers could start buying recycled copper from other parties.

The maximum production capacity of the network equals 200.000 tons. After testing, it was concluded that the demand can increase up to 31.5%, for it still to be satisfied. When demand increases, infeasibility occurs. Therefore, scenarios were tested ranging from a 10% to a 31.5% increase in demand. In addition, higher demand increases were tested while relaxing the maximum capacity constraint and allowing the network to expand (as mentioned in Chapter 11.4, there is enough waste available in Europe for a demand increase up to 65%).

As is clearly visible in Figure 12.1, when demand increases, more waste has to be collected from waste points to satisfy demand. It is also noticeable that Barcelona now supplies to an increased number of customers. During the base case, Barcelona provided only to local customers, while in the 30% increase scenario, Barcelona also distributed to multiple customers in France. This is because the facilities in Germany now have to supply to the increased demand of the greater number of customers in Germany. The figures of the other scenarios are given in Appendix 15.7.1.



(a) Base case (b) Demand increase of 30%

Figure 12.1: Change network due to demand increase

As seen in Table 12.1, Barcelona, Bologna, and Geithain operate below their full capacity at lower demand levels, while Stuttgart remains fully utilized. Thus, Stuttgart's role as a central hub in the network remains crucial, even during periods of lower demand. Moreover, when demand increases, facilities have to scale up, with Geithain firstly operating at full capacity, followed by Bologna. During the last scenario, the network is pushed to its limits, with only Barcelona having some production capacity left.

Table 12.1: Facility capacities during fluctuating demand

30% decrease		**10% increase**		**30% increase**	
Facility i	C_i	**Facility i**	C_i	**Facility i**	C_i
Barcelona_REC	11.599	Barcelona_REC	18.227	Barcelona_REC	47.874
Bologna_REC	27.462	Bologna_REC	49.205	Bologna_REC	50.000
Geithain_REC	17.487	Geithain_REC	50.000	Geithain_REC	50.000
Stuttgart_REC	50.000	Stuttgart_REC	50.000	Stuttgart_REC	50.000

As expected, both collection and distribution costs increase when considering the costs in Table 12.2. As more waste has to be collected to satisfy demand, more recycled copper has to be distributed.

Table 12.2: Costs during fluctuating demand (rounded)

Costs Network	**Base Case**	**30% Decrease**	**10% Increase**	**30% Increase**
Production Fixed	20,153,900	20,153,900	20,153,900	20,153,900
Production Variable	3,140,200	2,198,100	3,414,900	3,840,400
Collection Costs	5,718,600	2,597,500	7,284,900	12,862,400
Distribution Costs	4,621,000	2,953,600	5,158,400	6,970,100
Total Costs	33,633,700	27,903,200	36,012,200	43,826,900

Lastly, what happens if the model is allowed to expand its network was tested. This results in adding an extra facility from a 30% increase on. Thus, even when capacity can fulfill demand with four open facilities, the network would expand because of lower costs. Furthermore, during a 50% and 65% increase in demand, the facilities are increased by five and six, respectively. The results can be seen in Table 15.14 and 15.13 and Figures 15.12, 15.13, and 15.14 in Appendix 15.7.1.

Last, it was tested what would happen when the maximum capacity was relaxed. These results are listed in Tables 15.15 and 15.16 in Appendix 15.7.1. In this case, Stuttgart would be expanded significantly. The other facilities show slight increases. Again, this shows the importance of Stuttgart in the network. Also, the network under increased capacity is, as expected, considering the analysis in Chapter 11.1, more cost-efficient as fixed costs are decreased significantly.

12.1.1 Cost comparison sensitivity analysis and scenario demand

This section compares the flexible network during the demand sensitivity analysis and the network during the scenario testing. The results are summarized in Table 12.3.

Table 12.3: Comparison of demand sensitivity vs. scenario analysis

Aspect	Sensitivity Analysis	Scenario Analysis
Network flexibility	Network adapts per demand level; facilities can open/close optimally.	Fixed base network (4 facilities) remains active for all demand levels.
Network feasibility	Feasible up to a 66% demand increase.	Feasible up to a 31.5% demand increase.
Total costs (example: 30% increase)	€41.6M	€43.8M[7]
Cost efficiency	Lower total costs in all cases due to optimized facility selection and capacity scaling.	Higher total costs due to inefficiencies from maintaining a fixed network structure.
Number of facilities	Increases with demand: 5 facilities at 50% increase, 6 at 65% increase.	Constant at four facilities regardless of demand.
Fixed production costs	Scales with number of facilities; increases with demand.	Constant across all scenarios.
Collection and distribution costs	Lower due to facility proximity to waste and customers; transport distances minimized.	Higher due to longer transport routes and inability to open additional facilities.
Capacity allocation	Dynamically distributed across facilities to match demand efficiently.	Capacity spread across fixed facilities, resulting in less optimal utilization.
Scalability	Highly scalable; supports decentralization as demand grows.	Not scalable; fixed structure.
Conclusion	Cost-optimal and resilient under varying demand; supports network expansion and decentralization.	Less efficient under high demand levels; fixed network leads to higher costs and low resilience during large demand increases.

12.1.2 Conclusion

This scenario analysis tested the performance of the optimized network under fluctuating demand, focusing on both constrained and unconstrained network expansion. The results show that the current network can handle up to a 31.5% increase in demand before reaching capacity limits. Beyond this threshold, infeasibility occurs unless additional facilities are introduced.

As demand increases, more waste must be collected from more spread-out waste points, resulting in rising collection costs. Barcelona's role expands, supplying customers beyond its local region due to capacity constraints in Germany. Meanwhile, Stuttgart remains fully utilized across all demand levels, highlighting its crucial role as a central hub in the network.

When network expansion is allowed, the model selects additional facilities from a 30% demand increase onward, reducing transport distances and lowering overall costs. Furthermore, if maximum facility capacities are relaxed, Stuttgart will significantly expand.

As expected, collection and distribution costs increase due to greater transport distances when demand increases. The large increase in collection costs highlights the limited availability of waste nearby.

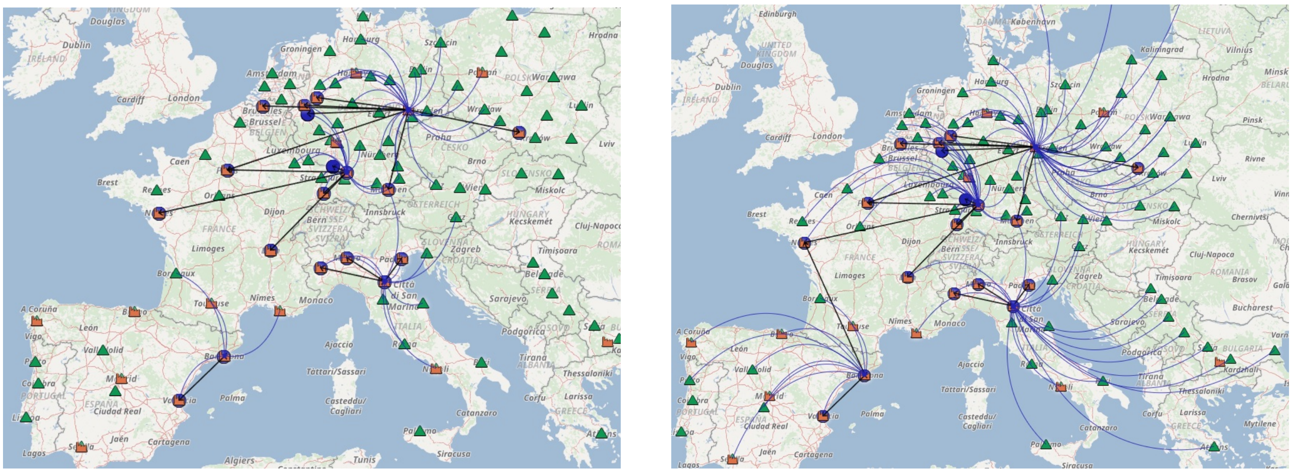
The scenario analysis is less cost-efficient than the sensitivity analysis due to its fixed structure and limited flexibility. While the sensitivity model dynamically adapts facility locations and capacities based on demand, the scenario model shows higher costs.

[7] €42.7M if network expansion would be allowed as explained in the last part of the previous section (see Appendix 15.14, 15.13). Also, as seen in the analysis in Section 11.1, relaxing the maximum capacity is most cost-efficient.

12.2 Supply fluctuation

The second scenario tests a uniform decrease in supply, similar to the previous scenario, where the same percentage across all waste points decreases the supply. As the network already does not use all the waste supplied, only decreased supply scenarios were tested. The results are visible in Figure 12.2 and Figures 15.15, 15.16 and 15.17 in Appendix 15.7.2. Moreover, Tables 12.4 and 12.5 provide the results.

As is clearly visible in Figure 12.2, when supply decreases, waste still has to be collected from an increased number of waste points to satisfy demand. All the facilities now have to collect waste from many waste points. This is very inefficient for the network as collection transport costs increase. This cost increase is given in Table 12.4. As expected, the collection costs rise remarkably. All the other costs do not show or show small changes.



(a) Base case

(b) Supply decrease of 39,5%

Figure 12.2: Change network due to supply decrease

Table 12.4: Costs during decreased supply (rounded)

Costs Network	**Base Case**	**10% Decrease**	**30% Decrease**	**39.5% Decrease**
Production Fixed	20,153,900	20,153,900	20,153,900	20,153,900
Production Variable	3,140,200	3,140,200	3,140,200	3,122,400
Collection Costs	5,718,600	6,409,500	8,544,600	11,135,600
Distribution Costs	4,621,000	4,621,000	4,621,000	4,632,200
Total Costs	33,633,700	34,324,600	36,459,700	39,044,200

Furthermore, the facility utilisation is given in Table 12.5. Only a slight increase occurs at the facility in Barcelona. This is because waste now also has to be collected from Central Spain, which is why it is more efficient to increase operations in Barcelona. As a result, Barcelona now also distributes to Nantes.

Table 12.5: Facilities during decreased supply

10% decrease		**30% decrease**		**39.5% decrease**	
Facility i	C_i	**Facility i**	C_i	**Facility i**	C_i
Barcelona_REC	16.570	Barcelona_REC	16.570	Barcelona_REC	18.454
Bologna_REC	39.231	Bologna_REC	39.231	Bologna_REC	39.231
Geithain_REC	46.410	Geithain_REC	46.410	Geithain_REC	44.526
Stuttgart_REC	50.000	Stuttgart_REC	50.000	Stuttgart_REC	50.000

12.2.1 Cost comparison sensitivity analysis and scenario supply

This section compares the flexible network during the supply sensitivity analysis and the network during the scenario testing. The results are summarized in Table 12.6.

Table 12.6: Comparison of supply sensitivity vs. scenario analysis

Aspect	Sensitivity Analysis	Scenario Analysis
Network flexibility	Model adapts facility selection to limited supply by switching locations and reallocating capacities.	Fixed network of 4 facilities remains active, regardless of available supply.
Network feasibility	Remains feasible down to 39.5% supply decrease.	Remains feasible down to 39.5% supply decrease.
Total costs (example: 39.5% supply decrease)	€38.9M	€39.0M
Cost efficiency	Slightly more efficient at high supply shortage; avoids expensive transport from distant locations.	Slightly higher costs due to limited flexibility.
Facility configuration	Facility mix changes with supply: Dortmund replaces Stuttgart at 30% decrease.	Facilities remain fixed; the same set is active under all scenarios.
Fixed costs	Constant, no new facilities opened.	Constant, network fixed.
Collection and distribution costs	Collection costs increase as supply becomes scarcer nearby; distribution costs vary slightly.	Collection costs increase similarly; distribution costs are more stable due to fixed customer allocation.
Capacity allocation	Reallocates capacity across optimal facilities under different supply levels.	Reallocates capacity across optimal facilities under different supply levels.
Resilience to supply loss	Moderately resilient; adapts by shifting demand to more available waste points.	Resilient but less adaptive; maintains structure with slight performance loss.
Conclusion	Slightly more efficient under supply reduction due to adaptive reallocation.	Performs acceptably under supply decrease, but lacks flexibility to respond optimally.

12.2.2 Conclusion

This section evaluated how the network performs under evenly decreased waste supply scenarios. As supply decreases, facilities must source waste from more waste points, significantly increasing collection costs as facilities must collect from distant locations. Moreover, facility utilization remains largely unchanged, with only Barcelona experiencing a slight increase in production as it becomes more efficient to collect waste from Central Spain. This also leads to Barcelona supplying additional customers, such as those in Nantes.

The network remains feasible up to a 39.5% supply reduction. Beyond this point, demand cannot be satisfied, making the network infeasible. Again, these findings highlight the vulnerability of the recycling network to waste shortages and emphasize the importance of securing waste availability.

When comparing the sensitivity analysis with the scenario, it becomes evident that the flexible network slightly outperforms the fixed network in terms of cost efficiency at high levels of supply reduction. While both remain feasible up to the same threshold, the sensitivity model shows better adaptability by reallocating supply to the most efficient facilities (e.g. switching from Stuttgart to Dortmund).

12.3 Disruptions

With the current global state, disruptions become a greater risk. Disruptions can cause the outage of (a part of) the supply chain. Recognizing and understanding these risks is important for developing resilient strategies. Examples of disruptions are for example natural disasters, pandemics and geopolitical shifts.

For instance, natural disasters such as floods can severely disrupt supply chains by damaging infrastructure. This was the case during the 2021 floods in Germany that led to widespread devastation, affecting transportation networks and industrial facilities (Cuddy, 2021).

In addition, the COVID-19 pandemic shows how health crises can lead to global supply chain disruptions. Lockdowns and restrictions resulted in labor shortages, factory closures, and transportation challenges (Guardian, 2025).

Also, incidents affecting key transportation routes can greatly affect supply chains. The 2021 blockage of the Suez Canal is an important example, where a single event led to significant delays in global shipping (Jack Barnett, 2024).

Therefore, this section presents the impact of three disruptions on the recycling network. The aim was to choose realistic, diverse, and relevant scenarios that align with potential future risks in the European copper recycling context. The first disruption tested is a facility outage, resulting from operational failures, regulatory constraints, or extreme weather events. This is one of the most critical and realistic disruption types, directly impacting production capacity. This type of disruption has been observed frequently in practice and directly impacts the continuity of supply.

The second disruption tested is a local disruption that affects transportation routes. This type of disruption was chosen to reflect regional challenges such as flooding, as happened last year in France, Belgium and Germany (NOS, 2024a). It reflects the network's sensitivity to changes in accessibility.

The third and final disruption involves a regional demand increase. This was selected to evaluate the network's responsiveness to regional increases in customer demand, which policy shifts, economic growth, or industrial transitions in specific areas may drive. Unlike uniform demand growth tested earlier, regional demand surges may occur unevenly across Europe. For example, if the German automotive sector accelerates its production of electric vehicles, this could significantly increase the demand for recycled copper in Germany.

These three scenarios were selected because they each target a distinct part of the network: production capacity, transport infrastructure, and customer dynamics. Together, they offer a realistic assessment of the network's ability to perform under unforeseen disruptions. They also reflect past events such as the 2021 floods, the COVID-19 pandemic, and the Suez Canal blockage.

12.3.1 Facility outages

First of all, the scenario of a facility outage is tested. One or more recycling facilities become temporarily or permanently unavailable.

To ensure a specific facility is closed, a binary constraint is added to enforce the closure of the production of a specific facility. When a facility is out of operation due to a disruption, most fixed costs still apply. Therefore, rather than fully closing the facility in the model, the outage is modeled by restricting the production volume to zero. This ensures that fixed costs are still incurred during the disruption, reflecting real-world conditions more accurately.

Moreover, the demand constraint is adjusted to ensure that the model remains solvable while still tracking the exact amount of unmet demand. Instead of strictly enforcing that all demand must be met, an unmet demand variable u_k is introduced:

$$\sum_{i \in I} y_{ik} + u_k = \lambda \cdot D_k, \quad \forall k \in K \tag{12.1}$$

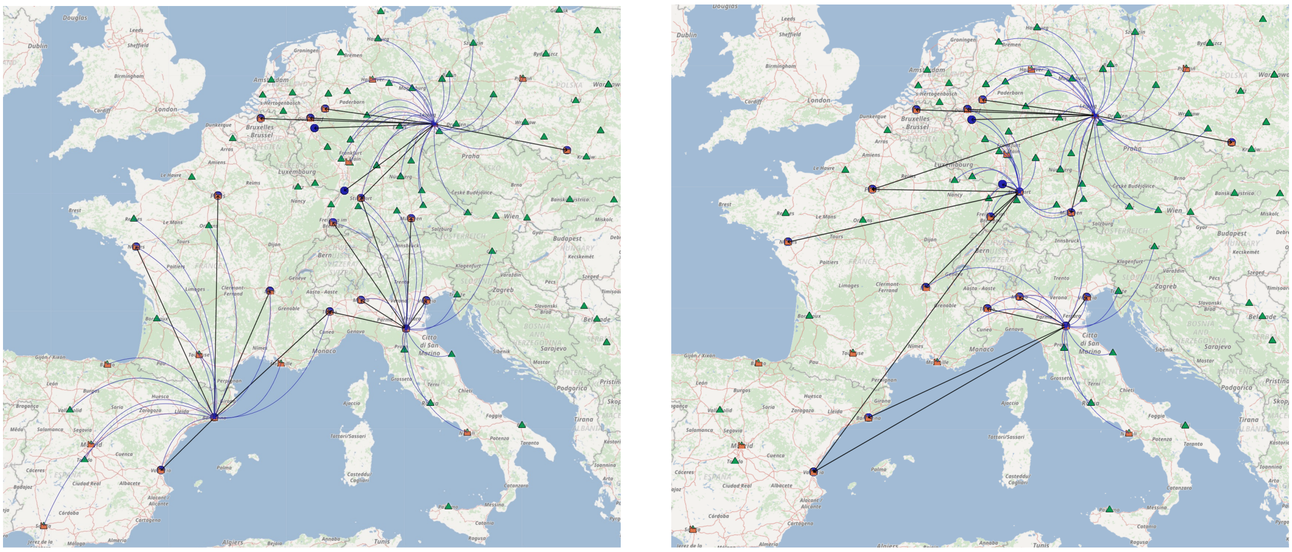
where:

- u_k represents the unmet demand at customer k;
- If all demand is fulfilled, u_k=0;
- If the available production capacity is insufficient, u_k>0, indicating a demand violation.

As the maximum capacity of a facility is 50.000 and the demand is more than 150.000 tons, the outage of a facility will definitely lead to unfulfilled demand. Moreover, the remaining facilities will operate at full capacity.

Stuttgart's closure leads to an unmet demand of 2210 tons in Antwerp, while Geithain's outage causes a shortage of 2110 tons in Katowice. Similarly, the closure of Bologna and Barcelona results in unmet demand in Bologna and Valencia, respectively. This highlights that each facility primarily serves a specific geographical area.

Furthermore, in Figure 12.3 it is visible that, during the outage of Stuttgart, Barcelona now collects and distributes to multiple locations instead of locally. Additionally, during the outage in Barcelona, Stuttgart and Bologna have to distribute very far to reach customers in Southern Europe. Nevertheless, demand can still not be completely satisfied. Appendix 15.7.3 shows the networks during the outage of Geithain and Bologna.



(a) Stuttgart outage

(b) Barcelona outage

Figure 12.3: Comparison of Stuttgart and Barcelona outages

The cost impacts of each facility outage scenario are detailed in Table 12.7. Total costs increase significantly when major facilities are inactive. The fixed costs stay the same, as these costs still occur when a facility is disrupted. Variable costs decrease slightly, as some demand is unfulfilled. Nevertheless, transport costs increase remarkably.

The outage in Stuttgart leads to the highest costs, highlighting that Stuttgart has the most important role in the network. Collection costs rise greatly due to longer transport distances from the waste points to the remaining facilities. For Geithains' outage, the collection costs also increase significantly, leading to the second most critical facility in the network.

Notably, the distribution costs during the outage of Bologna are higher than those of the Geithain outage. This is due to the regional customers located near Bologna, leading to higher costs for the other facilities when Geithain or Stuttgart needs to serve this demand.

Last, Barcelona's outage leads to the lowest total costs among the outage scenarios. Thus, Barcelona is the least critical to the overall network, because of its non-central location.

Table 12.7: Cost impact of facility outage (rounded)

Costs Network	**Base Case**	**Stuttgart Outage**	**Geithain Outage**	**Bologna Outage**	**Barcelona Outage**
Production Fixed	20,153,900	20,153,900	20,153,900	20,153,900	20,153,900
Production Variable	3,140,200	2,703,500	2,703,500	3,028,000	3,175,000
Collection Costs	5,718,600	11,698,300	10,829,500	9,975,500	6,277,900
Distribution Costs	4,621,000	7,418,400	6,510,600	7,255,400	5,926,400
Total Costs	33,633,700	42,004,100	40,917,500	40,412,800	35,533,200

12.3.2 Local disruption

Secondly, the impact of a local disruption will be tested. As central Europe is the most important part of the network, considering most waste points and the most important customers are located there, the disruption occurs in that area. Waste points in the Netherlands, Belgium, Central Germany, and Eastern France have become unreachable and are therefore forced to be closed. Also, a Wiggle Factor increase of 5% is added as detours must be made to reach customers. The increase leads to higher transport distances, contributing to rising transport costs. The results are depicted in Figure 12.4 and in Tables 12.8 and 12.9 .

As shown in Figure 12.4, waste must now be collected from further locations, including waste points in Poland and Serbia. The waste points in central Europe are not utilized.

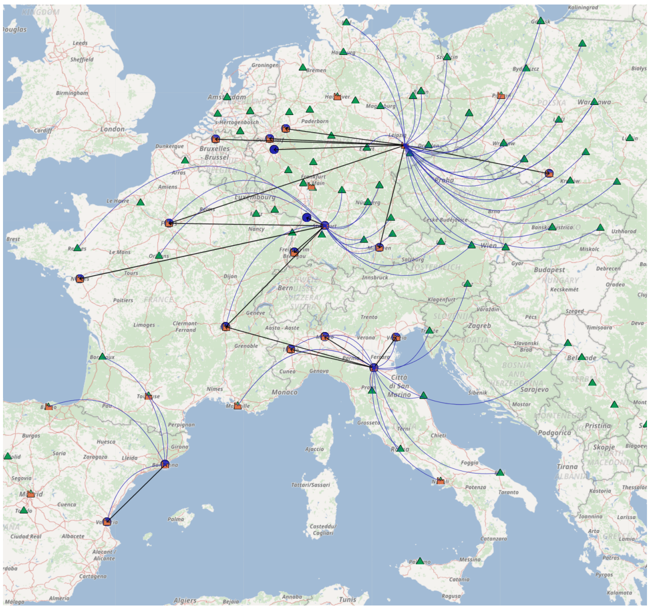


Figure 12.4: Local disruption

Moreover, as seen in Table 12.8, Stuttgart and Barcelona operate at the same capacity. Nevertheless, Bologna increases in processing volumes and Geithain decreases in processing volume as Bologna is closer to alternative waste sources (e.g., Italy or South Europe). In contrast, Geithain relied more on the now-unavailable Central European waste points.

Table 12.8: Facility capacities during local disruption

Facility i	C_i **Base Case**	C_i **Local disruption**
Barcelona_REC	16,570	16,570
Bologna_REC	39,230	41,910
Geithain_REC	46,410	43,731
Stuttgart_REC	50,000	50,000

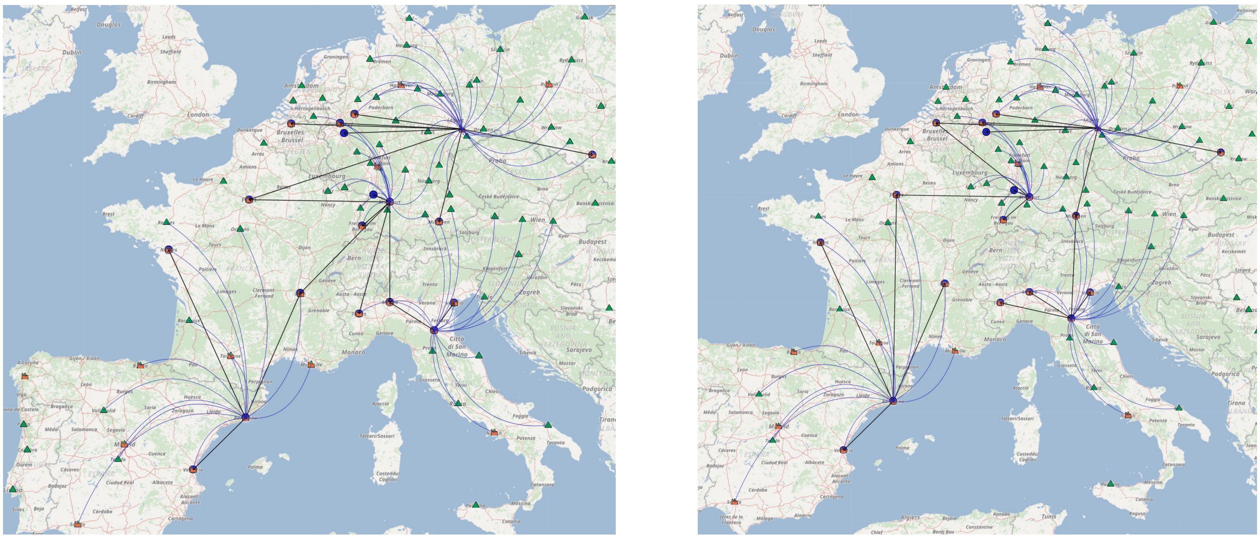
In addition, Table 12.9 shows that total costs increase significantly from €33M to €36M. This is mainly the cause of rising collection points, which is, as mentioned before, because waste now needs to be transported from alternative, more distant locations. In addition, distribution costs rise slightly, reflecting the additional transport costs (modeled through the WF) necessary to maintain customer deliveries.

Table 12.9: Costs during local disruption (rounded)

Costs	**Base Case**	**Local Disruption**
Production Fixed	20,153,900	20,153,900
Production Variable	3,140,200	3,122,800
Collection Costs	5,718,600	8,395,400
Distribution Costs	4,621,000	4,758,800
Total Costs	33,633,700	36,430,900

12.3.3 Regional demand increase

The third disruption includes the increase of regional demand, both in South and Central Europe. The results are indicated in Figure 12.5 and Tables 12.10 and 12.11.



(a) Demand increase in South Europe (b) Demand increase in Central Europe

Figure 12.5: Comparison of demand increases in South and Central Europe

In the South Europe demand increase case, the customer demand in Barcelona, Valencia, Nantes, Lyon, Turin, Milan, Venice and Bologna has increased by 60%. Furthermore, in the Central demand increase case, the demand is increased by 60% in Antwerp, Stuttgart, Munich, Düsseldorf, Cologne, Dortmund, and Paris.

As seen in the results, in both cases, the network becomes more reliable on Barcelona. Also, when demand in Central Europe increases, the network must rely on the Barcelona facility to fulfill demand. This is because Barcelona operates below full capacity in the base case, making it the only facility with great excess capacity to absorb higher demand. In contrast, central facilities already operate at or near their capacity limits, preventing them from scaling up as effectively.

Table 12.10: Facility capacities across regions

Facility i	C_i **(Base Case)**	**South Europe**	**Central Europe**
Barcelona_REC	16,570	46,246	49,501
Bologna_REC	39,230	50,000	50,000
Geithain_REC	46,410	50,000	50,000
Stuttgart_REC	50,000	50,000	50,000

Table 12.11: Cost comparison of different regions (rounded)

Costs	**Base Case**	**South Europe**	**Central Europe**
Fixed Costs	20,153,900	20,153,900	20,153,900
Variable Costs	3,140,200	3,817,800	3,760,300
Collection Costs	5,718,600	12,471,300	11,493,100
Distribution Costs	4,621,000	6,830,700	7,349,500
Total Costs	33,633,700	43,273,700	42,756,800

The primary cost driver in both scenarios is the increase in collection costs, which more than doubled from the base case (€5.7M) to €12.5M in the South Europe scenario and €11.5M in the Central Europe scenario. This indicates that additional waste had to be sourced from a broader geographic area, increasing transport costs. Logically, distribution costs also increase as an increased demand has to be distributed.

Barcelona emerges as a crucial facility in managing regional demand. Central facilities become dependent on Barcelona to meet rising demand from nearby customers, leading to higher distribution costs, especially in the Central Europe scenario.

12.4 Balancing costs, and resilience

Designing an optimal recycling network requires more than minimizing total costs. While a centralized network may yield lower costs, it is more vulnerable to disruptions and lacks flexibility during unforeseen events. This section reflects on the trade-off between cost-efficiency and resilience by comparing the results of key scenarios, including an additional test where an extra facility is proactively added to improve robustness. This analysis aims to evaluate whether the corresponding improvements in network resilience offset the higher costs associated with an additional facility.

12.4.1 Trade-off insights

The base case network, consisting of four facilities, has a total cost of €33.6M and satisfies demand under regular conditions. However, it relies on key facilities such as Stuttgart and Geithain. In disruption scenarios, especially during facility outages, the network faces unmet demand or rising costs. For instance, the outage of Stuttgart results in a total cost increase of €42M and an unmet demand of 2.210 tons.

An additional test was executed to explore whether adding another facility improves resilience, and a fifth facility was added in Katowice and Dortmund. The effect of a facility outage on the new network was tested. Moreover, the effect of increased demand in South Europe was tested as these disruptions have the highest impacts. The results are indicated in Table 12.12.

Table 12.12: Comparison of network cost and resilience with added facilities

Scenario	**Base Case**	**+ Katowice**	**+ Dortmund**
Total Costs (no disruption)	€33.6M	€36.7M	€37.0M
Stuttgart outage	€42.0M (unfulfilled demand)	€41.9M (demand fulfilled)	€40M (demand fulfilled)
Geithain outage	€40.9M (unfulfilled demand)	€39.7M (demand fulfilled)	€38.3M (demand fulfilled)
South Europe demand increase	€43.2M (demand fulfilled)	€43.7 (demand fulfilled)	€43.7 (demand fulfilled)

The results demonstrate that both additional facilities improve network resilience, as demand can be fully satisfied in the outage scenarios where the base case results in unmet demand. The base case, which operates with four facilities, shows significant vulnerabilities: the outage of Stuttgart or Geithain leads to unfulfilled demand and total costs of €42.0M and €40.9M, respectively.

Adding a facility in Katowice increases the normal (non-disruption) total costs to €36.7M, but ensures that full demand is met during the Stuttgart and Geithain outages. In the case of a Geithain outage, the total cost is €39.7M, which is lower than the base case under disruption, and thus reflects a more resilient and cost-effective solution under risk. However, during a Stuttgart outage, the cost is €41.9M, slightly lower than the disrupted base case. This is because Stuttgart remains the most central facility, and Katowice alone cannot fully offset its outage.

Similarly, adding a facility in Dortmund results in slightly higher total costs in regular conditions due to higher fixed costs. However, Dortmund provides better coverage in Central Europe. With Dortmund included, total costs during the Stuttgart and Geithain outages are €40.0M and €38.3M, respectively. These are both lower than the disrupted base case and slightly more cost-effective than the Katowice case.

In the South Europe demand increase scenario, the added facilities do not lead to lower costs. However, when even higher demand increases, the network will be more resilient in absorbing additional demand.

In conclusion, adding a fifth facility enhances the network's resilience, enabling the model to absorb disruptions without unfulfilled demand cost-effectively. While Katowice and Dortmund offer resilience benefits, their effectiveness varies by disruption type. Katowice is more cost-efficient under normal conditions, while Dortmund provides stronger resilience against Central European outages. The final decision between the two depends on the company's priorities and expected disruptions.

12.5 Overview of key scenarios and conclusion

This chapter answered the sub-question *How does the optimized copper recycling network perform under scenarios such as supply- and demand fluctuations, and disruptions?*

Table 12.13 presents an overview of the most important scenarios, highlighting the trade-offs between cost, efficiency, and resilience. Scenarios are compared on total costs, number of facilities, unmet demand, and resilience level.

Table 12.13: Comparison of costs and resilience across scenarios

Scenario	**Costs (€M)**	**Facilities**	**Unmet Demand**	**Resilient**	**Comment**
Base Case	33.6	4	0	Moderate	Cost-efficient solution
Facility outage scenarios					
Stuttgart outage	42.0	3	2210	Low	Most critical facility, high costs
Geithain outage	40.9	3	2210	Low	Eastern demand unfulfilled, high costs
Bologna outage	40.4	3	2210	Low	Regional demand impact
Barcelona outage	35.5	3	2210	Moderate	Least critical facility
Transport disruption					
Local disruption	36.4	4	0	Moderate	Central waste inaccessible, detours required
Regional demand increase					
Demand increase South Europe	43.3	4	0	Low	High transport costs
Demand increase Central Europe	42.8	4	0	Low	High transport costs
Demand fluctuation scenarios					
Demand +30%	43.8	4	0	Low	No flexibility, demand still met
Demand +30% (network expansion)	42.7	5	0	Moderate	Expansion reduces costs
Flexible network (demand +30%)	41.6	5	0	High	Flexible and scalable
Supply fluctuation					
Supply –39.5%	39.0	4	0	Moderate	Network feasible, but approaching limit
Extra facility (Base)					
Extra facility Katowice (base)	36.7	5	0	High	Low-cost region, improves resilience
Extra facility Dortmund (base)	37.0	5	0	High	Higher cost, stronger central support
Extra facility (Outages)					
Katowice + Stuttgart outage	41.9	4	0	High	Slight cost reduction, demand fulfilled
Dortmund + Stuttgart outage	40.0	4	0	High	Most cost-effective resilient outcome
Katowice + Geithain outage	39.7	4	0	High	Improved resilience for Eastern demand
Dortmund + Geithain outage	38.3	4	0	High	Most cost-effective resilient outcome
Extra facility (regional demand)					
Dortmund + South demand increase	43.7	4	0	High	Higher costs, but more resilient

Across most tested disruptions, the network remained operational, reflecting a certain degree of robustness. However, in the event of facility outages and high demand increases, the network failed to satisfy all demand. While cost-efficient under regular conditions, the base network lacks flexibility in the face of unexpected events.

First, the impact of facility outages on the recycling network's ability to meet demand was considered. When a facility is closed, unmet demand arises, with Stuttgart's outage affecting Antwerp, Geithain impacting Katowice, Bologna impacting demand in Bologna, and Barcelona leading to unfulfilled demand in Valencia. Therefore, during a facility outage, the network shows low resilience.

Stuttgart and Geithain are the most critical hubs in the network, as their outages lead to the highest cost increases and demand violations. While Barcelona's closure results in the lowest cost impact, confirming that it is the least critical facility.

Secondly, a local disruption scenario was tested. The results show that waste collection shifts to alternative locations, including Poland and Serbia, leading to significantly higher collection costs. While Stuttgart and Barcelona maintain their processing levels, Bologna increases its processing due to its proximity to alternative waste sources, while Geithain experiences a decrease. Despite the higher costs, the network remains operational, showing moderate resilience.

Last, a regional demand increase of 60% was tested in both South and Central Europe. In both cases, Barcelona was critical in absorbing additional demand, even when the rise occurred in Central Europe. Barcelona operates below full capacity in the base case, whereas central facilities already operate at or near capacity limits.

As a result, total costs increased significantly. The primary cost driver was the increase in collection costs, which more than doubled due to the need to source waste from further locations. This indicates low resilience, not only due to the high costs but also because the network is operating at the edge of its capacity. This demonstrates that network resilience depends not only on facility capacity but also on waste availability. Ensuring waste availability at all times is crucial for the networks' performance, especially during periods of increased demand.

It can be concluded that the network's resilience is closely linked to the availability of waste and the efficiency of collection and distribution. In cases of supply disruptions or local transport disruptions, the model had to rely on more distant waste points, which significantly increased collection costs. Similarly, regional demand increases pushed the network to its limits.

Two additional scenarios were tested to test the improved resilience, in which a fifth facility was added in Katowice or Dortmund. These cases show that the robustness during scenarios is increased significantly, as is indicated in Table 12.13. For instance, demand can be fulfilled in all outage scenarios when an additional facility is available, while total costs remain lower than the disrupted base case. Dortmund provides better resilience for central disruptions, while the addition of Katowice is more cost-efficient under normal conditions. The demand increase scenario shows slightly higher costs but does offer more resilience. This supports the idea that a decentralized network structure enhances robustness and lowers costs during disruptions.

13 Conclusion

This chapter provides the answers to the main research question and sub-questions. This research aimed to determine how the Critical Raw Materials Act (CRMA) impacts the copper supply chain, and how the copper recycling network of natural resource companies can be optimized to ensure compliance while minimizing costs. Eventually, the research question can be answered:

How does the CRMA impact the copper supply chain, and how can the copper recycling network of a natural resource company be optimized to comply with the regulation while minimizing costs?

Through an analysis of the CRMA requirements, the copper supply chain, Mixed Integer Linear Programming (MILP), and scenario-based testing, this thesis provided an assessment of how the CRMA reshapes copper supply chains, what the optimal copper recycle network of natural resource companies looks like, and how resilient this network is.

13.1 Answers to the sub-questions

To conclude on the main research question, each sub-question is addressed:

1. What are the key requirements of the CRMA, and how do they translate into constraints and opportunities for a supply chain network?

The CRMA addresses the EU's growing concerns regarding the security and sustainability of Critical Raw Materials (CRMs). CRMs are essential for the energy transition, yet their supply chains are highly vulnerable due to global demand and reliance on external suppliers.

First, the research evaluated the key requirements of the CRMA and how they translate into constraints and opportunities for a supply chain network. The CRMA introduces extraction, processing, and recycling requirements, aiming to reduce dependency on third countries and enhance supply chain resilience and sustainability. The requirements are as follows:

1. At least 10% of the CRMs used in the EU must be sourced from EU-based extraction sites;
2. A minimum of 40% of CRMs should be processed within the EU;
3. **At least 25% of CRMs must come from EU-based recycling efforts** (focus area of the research);
4. No more than 65% of any CRM should be imported from a single third country;

This will necessitate a shift towards more EU-based and sustainable practices. Additionally, the regulation mandates greater environmental transparency and risk and conformity assessments while offering financial support, joint purchasing mechanisms, and strategic stockpiling incentives for companies aligning with CRMA goals.

Due to the long timeline required to establish new mines (10–20 years) and the impact mining has on the environment, alternative solutions such as recycling and efficient product design are essential to meet future CRM demand. Innovation in recycling technologies and product efficiency will play a key role, while the EU must balance increased mining efforts with sustainable and responsible practices. Ultimately, mining, efficient product design, and innovative recycling methods will be necessary to secure the raw materials required for Europe's energy transition.

2. What are the processes and structure of a general copper supply chain of natural resource companies, and which parts are most impacted by the CRMA?

Copper supply chains consist of multiple stages: mining, processing, manufacturing, waste collection, and recycling. Copper is a highly recyclable material with extensive industrial applications, particularly in electronics, renewable energy, and transportation. However, despite its recyclability, only 45% of copper is recycled, indicating room for improvement in circularity.

Natural resource companies supply copper to automotive, electronics, and renewable energy industries. The CRMA mandates that 25% of CRMs must come from EU-based recycling, which will increase demand for recycled copper.

A supply gap is created with copper demand set to exceed supply by 2026. Expanding EU mining is not a short-term solution, as new mines take 10–20 years to develop, highlighting the necessity of recycling to meet demand.

Therefore, enhancing recycling operations in Europe is the most feasible (time-wise) and effective approach (when comparing changing a natural resource company's mining, processing and recycling operations) to meeting CRMA requirements. Optimizing the copper recycling network allows these companies to strengthen their market position, lower emissions, and ensure CRMA compliance while fostering a more sustainable and resilient supply chain.

Table 13.1 summarizes the copper supply chain before and after the implementation of the CRMA, serving as an answer to the first part of the research question "*How does the CRMA impact the copper supply chain?*"

Table 13.1: Copper supply chain before and after the CRMA

	Before CRMA	**After CRMA**
Sourcing and processing (*Section 5.4.2*)	Mining and processing mostly outside EU (Wincewicz-Bosy et al., 2021; Flores et al., 2020).	10% of copper must be sourced from EU-based extraction; 40% processed in EU. (EU, 2023a)
Recycling share and location (*Section 5.4.2*)	Only 45% of copper globally recycled; significant EU scrap exported to low-cost countries (Henckens and Worrell, 2020).	At least 25% of copper must be recycled within the EU; focus on recycling scrap locally (Henckens and Worrell, 2020; Hool et al., 2023).
Strategic focus (*Sections 5.1, 5.4.2*)	Supply chain optimized for cost efficiency and global competitiveness (Glencore, 2024b).	Focus on EU autonomy, circularity, emission reduction, and CRM compliance benchmarks (EU, 2023a; Hool et al., 2023; Tröster et al., 2024).
Design and disassembly (*Section 5.4.4*)	Devices designed for durability and efficiency, not for recyclability; complex disassembly.	Shift towards recyclability of products to meet CRMA goals.
Emissions and transport (*Section 5.4.2*)	High emissions from long-distance transport and global recycling (Teske et al., 2022).	Reduced emissions due to local, short-distance EU-based recycling (Teske et al., 2022).
Permitting and implementation (*Section 5.2*)	Long permitting timelines, fragmented national processes, low EU coordination (Hool et al., 2023).	Strategic projects enjoy shortened permitting; streamlined coordination (Tröster et al., 2024).
Market opportunities (*Section 5.2.2*)	Limited regulatory incentives for recycling.	CRMA offers a competitive advantage through compliance, EU funds, strategic stockpiling, and joint purchasing (Commission, 2023d).
Stakeholder involvement (*Section 5.2.2*)	Limited involvement of companies in raw material governance (Hool et al., 2023).	Increased transparency obligations, environmental footprint declarations, and CRM conformity assessments required (Hool et al., 2023).
Recycling costs (*Section 5.4.4*)	Priority for cost-efficiency by exporting copper scrap to lower cost countries.	Potentially higher costs due to domestic recycling (Tröster et al., 2024).

3. How can the copper recycling network of natural resource companies be optimized while adhering to the CRMA?

Given that the recycling network is the most affected part of the supply chain, this study developed a Mixed-Integer Linear Programming (MILP) model to find the optimal copper recycling facilities. The model performs cost minimization by considering transport costs, in-transit costs, unit costs, fixed costs (divided by a depreciation factor), the internal rate, risks, subsidies, waste, and customer locations. Distances are corrected with a Wiggle Factor to represent real-world transport lanes.

The optimization problem is structured around three key decisions:

1. The optimal number of recycling facilities;
2. The optimal facility locations;
3. The capacity distribution across facilities.

The optimization focuses on ensuring that EU-based recycled copper can fulfill 25% of every customer's demand. AIMMS SC Navigator solves the MILP model, providing a user-friendly interface for optimization and testing multiple scenarios.

It is important to note that these customers do not solely rely on one supplier. This means customers could shift to competitors, suggesting an uncertainty factor.

4. What is the optimal design of the copper recycling network under CRMA requirements?

A dummy dataset was created to test the model. Through a case study, for which a leading global natural resource company was selected, the model is explained. Data was used from publicly available datasets, such as Statista and Eurostat, as well as literature. Moreover, the demand data of the selected natural resource company was used. The Center of Gravity tool in AIMMS is used for the set of potential recycling facilities, resulting in 30 candidate recycling facility locations.

After implementing the cost-minimizing objective, constraints and all data points in AIMMS, the MILP identified four optimal recycling facility locations for this specific use case. The facilities were located in Stuttgart, Geithain, Bologna, and Barcelona, with a total processing capacity of 152.210 tons. The optimal network is displayed in 13.1.

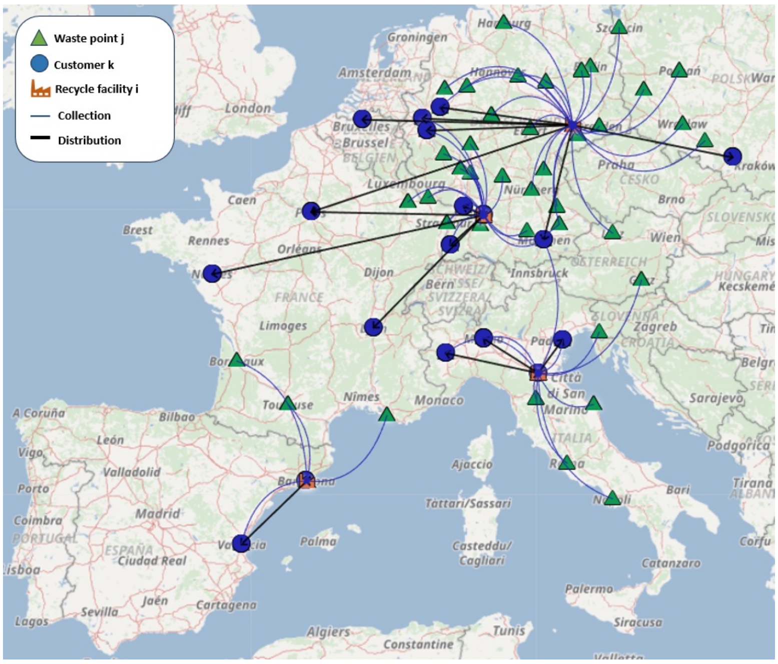


Figure 13.1: Optimal recycling network, active nodes

The results indicate that facility capacity and location decisions are primarily driven by fixed costs, which account for 60% of total costs, followed by transportation costs (30.7%), and variable costs (9.3%). Stuttgart is the most critical hub, operating at full capacity due to its central position, minimizing transport costs. Geithain serves key European customers but faces higher transport costs, while Bologna and Barcelona operate at lower capacities, primarily fulfilling regional demand.

Several sensitivity analyses were conducted to test the behavior of the model. The sensitivity analyses reveal that facility capacity is the most sensitive parameter in optimizing the recycling network, while transport costs have a more limited impact.

Higher facility capacities lead to fewer locations and lower costs, but relying on a single facility increases risks. Furthermore, fixed costs primarily drive location decisions, with lower fixed costs enabling a more decentralized network. Transport costs have a low impact, only resulting in network changes under extreme increases.

Moreover, demand fluctuations impact network concentration, with lower demand leading to a more concentrated network. The network was feasible up to a 65% increase before waste supply shortages occur. Additionally, supply reductions significantly raise collection costs, with feasibility maintained up to a 39.5% decrease. Waste availability is a key constraint, affecting network feasibility. The findings highlight the need to balance cost efficiency with resilience, as fewer, larger facilities lower costs but reduce flexibility. A decentralized structure with multiple facilities and secure waste sourcing enhances network robustness.

5. How does the optimized copper recycling network perform under scenarios such as supply- and demand fluctuations, and disruptions?

The robustness of the model was scenario tested with three disruptions, as well as demand and supply fluctuations. The key difference with the sensitivity analyses was that during the sensitivity analyses, the model was allowed to adjust the network by opening or closing facilities. In contrast, during the scenario testing, the network was fixed. When comparing the demand and supply fluctuations during the scenarios with the sensitivity analyses, it can be concluded that logically, during the sensitivity analyses, the model is more flexible and cost-efficient.

Table 13.2 summarizes the key scenarios, their costs, efficiency and resilience. It can be concluded that the current recycling network shows operational robustness under most disruptions, but shows low resilience during facility outages and high demand increases. Stuttgart and Geithain are the most critical hubs, as outages cause the largest cost increases. In contrast, Barcelona is the least critical, with minimal impact when closed.

Local disruptions shift waste collection to distant sites like Poland and Serbia, increasing costs but maintaining operations, showing moderate resilience. Moreover, regional demand surges stress the network, with Barcelona absorbing excess demand due to its spare capacity.

The main cost driver in disruption scenarios is the sharp rise in collection costs, highlighting the importance of waste availability. Overall, network resilience depends on both facility capacity and efficient waste collection.

Adding a fifth facility in Katowice or Dortmund significantly improves resilience. Both Dortmund and Katowice enhance cost-effective robustness during disruptions. These results support a more decentralized network design to improve flexibility and lower disruption costs.

Table 13.2: Comparison of cost, efficiency and resilience across scenarios

Scenario	Costs (€M)	Facilities	Unmet Demand	Resilient	Comment
Base Case	33.6	4	0	Moderate	Cost-efficient solution
Facility outage scenarios					
Stuttgart outage	42.0	3	2210	Low	Most critical facility, high costs
Geithain outage	40.9	3	2210	Low	Eastern demand unfulfilled, high costs
Bologna outage	40.4	3	2210	Low	Regional demand impact
Barcelona outage	35.5	3	2210	Moderate	Least critical facility
Transport disruption					
Local disruption	36.4	4	0	Moderate	Central waste inaccessible, detours required
Regional demand increase					
Demand increase South Europe	43.3	4	0	Low	High transport costs
Demand increase Central Europe	42.8	4	0	Low	High transport costs
Demand fluctuation scenarios					
Demand +30%	43.8	4	0	Low	No flexibility, demand still met
Demand +30% (network expansion)	42.7	5	0	Moderate	Expansion reduces costs
Flexible network (demand +30%)	41.6	5	0	High	Flexible and scalable
Supply fluctuation					
Supply –39.5%	39.0	4	0	Moderate	Network feasible, but approaching limit
Extra facility (Base)					
Extra facility Katowice (base)	36.7	5	0	High	Low-cost region, improves resilience
Extra facility Dortmund (base)	37.0	5	0	High	Higher cost, stronger central support
Extra facility (Outages)					
Katowice + Stuttgart outage	41.9	4	0	High	Slight cost reduction, demand fulfilled
Dortmund + Stuttgart outage	40.0	4	0	High	Most cost-effective resilient outcome
Katowice + Geithain outage	39.7	4	0	High	Improved resilience for Eastern demand
Dortmund + Geithain outage	38.3	4	0	High	Most cost-effective resilient outcome
Extra facility (regional demand)					
Dortmund + South demand increase	43.7	4	0	High	Higher costs, but more resilient

13.2 Policy implications

From a policy perspective, the results of this study highlight several important implications. First, regulations such as the CRMA should encourage recycling targets and motivate the design of resilient and diversified recycling networks. The findings demonstrate that while a centralized network is cost-efficient under normal conditions, it becomes vulnerable when disruptions occur, particularly when critical facilities such as Stuttgart or Geithain are impacted.

Policymakers could expand recycling infrastructure in underutilized regions like Eastern and Southern Europe. Although these areas are limited in the base case, they show strong potential for enhancing resilience, as demonstrated in the added facility scenario with Katowice. While central locations like Dortmund also contribute to improved performance, they share the same geographical risk exposure as existing sites and may further reinforce centralization rather than promote decentralization.

Introducing buffer stocks is another way to help companies manage shocks. The results show that facility outages lead to unmet demand, which could be mitigated through strategic stockpiling. These buffers would be particularly effective in central hubs that face high demand and limited short-term redundancy.

To support resilient and cost-effective recycling networks, it is important first to explore how existing CRM recycling infrastructure in Europe can be leveraged more effectively. Mapping the current network would help identify where capacity already exists and where upgrades or expansions are possible. This approach reduces the need for new investments and builds on existing capabilities.

Furthermore, investment in digitization and advanced logistics systems could improve network adaptability and performance. For instance, establishing real-time waste flow monitoring systems within the EU could serve as coordination and warning tools, enabling action when supply issues arise. Policies could also stimulate collaboration between public and private actors to increase data availability and alignment. Reliable insights into waste availability would allow better recycling throughout Europe.

In addition, to support circular and secure CRM supply chains, domestic recycling must become economically viable. Today, modern devices are not designed for recyclability, making disassembly complex and often unprofitable. Separating copper from mixed waste streams remains a technical challenge, underscoring the need for investment in more effective sorting and pre-separation technologies and highlighting the need for different product designs.

Ultimately, natural resource companies must align their operations with CRMA requirements. An optimized recycling network ensures regulatory compliance, enhances competitiveness, reduces environmental impact, and strengthens Europe's position in the copper industry. However, for this to succeed, policymakers and industry players must address challenges related to waste collection and recycling efficiency. Only then can the copper recycling network evolve into a sustainable and future-proof solution for securing Europe's copper supply.

14 Discussion and future research

This research developed an optimization model for the copper recycling network in Europe under the Critical Raw Materials Act (CRMA). While the model delivers valuable insights, it is built on some assumptions and simplifications that influence the results, both in data and methodology. This section highlights a reflection of the fundamental limitations of this study as well as the most critical data limitations.

14.1 Fundamental limitations

1. Policy interpretation and translation into constraints

The Critical Raw Materials Act (CRMA) is a new regulation that leaves room for interpretation for how targets (e.g. the 25% recycle requirement) will be applied across different industries. As the regulation is still in its early stages, it is unclear how the targets will be precisely enforced in practice or how they will translate into constraints for companies. The translation of these goals into constraints introduces some uncertainty. Implementing the policy more strictly or flexibly could alter companies' optimal networks.

This research, a simplified constraint was used: 25% of every customer's demand must be fulfilled with recycled content. However, this target applies at a broader market level and may be spread across multiple suppliers and customers within the EU. Therefore, it is uncertain to what extent a single company would be held individually accountable for the constraint.

Future research should explore the results of different interpretations of the CRMA and how they translate into constraints for companies. For example, executing research on how the recycling requirement would be divided over other companies and using that outcome for network optimization.

More advanced approaches, such as fuzzy or probabilistic constraints, could be applied to better capture the policy implementation's uncertainty. This would allow for a more robust model. Executing this robust approach would be an interesting topic for a thesis intern at KPMG.

2. Assumption of centralized waste control

The model assumes a single company with full control over waste sourcing. The waste control is fragmented, involving other parties, such as other firms and local governments. This centralization assumption oversimplifies the real-world complexity and limits the model's ability to reflect real waste flows.

In reality, copper waste is often owned, handled, or regulated by different actors, making it unlikely that one company can independently access or process all waste from a given region. Additionally, access to waste can depend on local contracts or public-private partnerships. As a result, the flow of waste in reality may be more constrained.

Future models could incorporate a setup involving multiple actors to improve realism. All actors influencing copper waste flows in Europe should be mapped to reflect better how waste is managed and shared between stakeholders. Also, data management on waste flows should be improved. Developing a more transparent system for tracking copper waste could enhance the accuracy and applicability of future models.

3. Technological feasibility and market conditions

The model does not consider technologies and innovations. Recovering copper from modern devices can be challenging and costly due to complex product design. These factors directly impact recycling efficiency, processing costs, and operational feasibility. Furthermore, delays caused by technical limitations can affect lead times, potentially influencing customer satisfaction and overall performance.

Additionally, the model excludes market conditions such as copper pricing, competition, and profitability. While the model focuses on minimizing costs, it does not capture the impact of these fluctuating conditions or the potential benefits of fulfilling additional demand. For example, customers might rely on multiple suppliers, resulting in competition, which is not incorporated in the model. Also, in the model, total costs remained unchanged when a facility outage was simulated and an additional facility was added. However, the network was able to fulfill more demand during the disruption compared to the base case, suggesting higher profitability, which the current model did not include.

Future research could focus on integrating technological differentiation into the model by incorporating variable recycling efficiencies based on technologies and product complexity. This would allow for a more realistic evaluation of efficiency.

Also, future models could shift from cost minimization to profit optimization. This includes incorporating dynamic copper pricing, carbon credits, environmental taxes, and potentially the customer's willingness to pay for recycled versus non-recycled copper. This could also be a sufficient subject for a next thesis intern at KPMG.

4. Deterministic and simplified model

Lastly, the current model is static and based on deterministic inputs. However, in reality, recycling flows are dynamic and uncertain. A more advanced model could incorporate uncertainty through stochastic or robust programming to test the network's resilience under disruption scenarios. For example, fluctuations in copper availability, demand shifts, and potential disruptions could be included.

In addition, the model assumes that decisions are made only based on cost and availability. Customer preferences, supplier trust, and regulatory constraints can influence outcomes. Future research should reflect these aspects to improve the model's realism. Uncertain factors such as customer behavior could be modeled as probabilistic variables to reflect these aspects within a robust or stochastic model.

14.2 Discussion on data limitations

The data collection process for this research faced limitations, primarily due to the unavailability of many data points. A dummy dataset was created based on reasonable assumptions and publicly available sources to test the model. The assumptions were carefully considered. Nevertheless, they introduce certain limitations that should be considered when interpreting the outcomes of this research. The most critical assumptions are summarized below:

- **Waste availability:** Copper waste locations and quantities were estimated using consumption data from industrial zones, neglecting dispersed sources like Waste of Electrical and Electronic Equipment (WEEE) and construction waste. Also, as mentioned in the previous section, the assumption that all waste at one location is available to a single company oversimplifies reality;
- **Recycling facilities:** Due to the unavailability of data on the existing recycling network of the natural resource company, the research only focused on opening new recycling facilities. In reality, also expanding existing facilities would be interesting;
- **Customer demand:** Customer locations and volumes were, just as the waste points, approximated based on industrial zones. Moreover, only very high-consuming cities were selected, which may miss medium-sized customers and does not fully reflect the actual distribution of demand;
- **Fixed- and variable costs, risks, and subsidies:** Fixed and variable costs were estimated based on literature and proportional scaling, lacking specificity. Risk costs were generalized using the INFORM Risk Index and tied to facility locations, not to transport routes. Also, subsidies are generalized, while in reality they may vary by country;
- **Transport costs, VoT:** Costs were based on average values for full truckloads and straight-line distances adjusted by a wiggle factor. This ignores arc-specific variations in infrastructure, congestion, and actual load sizes. Moreover, the Value of Time (VoT) parameter was based on an average of different commodities; however, this might not fully represent the VoT of copper.

Based on these data limitations, the next step would be integrating real-world data on copper waste availability and customer demand (and potential existing recycling network) from a natural resource company to enhance the model's accuracy and applicability.

14.3 Final reflections

This thesis provided academic and practical contributions. From an academic perspective, it improves supply chain optimization literature by integrating Mixed Integer Linear Programming (MILP) and the CRMA constraint into one framework. It also contributes to the understanding of how the CRMA impacts supply chains. Moreover, on a practical level, this study provided natural resource companies with a framework for optimizing their recycling network under the CRMA constraint.

Despite the limitations, the study provides a foundation for analyzing the optimal copper recycle network considering the CRMA. The insights from this research can help guide further studies and provide decision-makers with an initial understanding of key trade-offs of the CRMA and optimization possibilities. Future research can drive innovation in how Europe optimizes circular CRM supply chains, and companies like KPMG are uniquely positioned to spread the word about the importance of this topic.

Attention should be paid to how CRM recycling facilities can collaborate across regions and industries to optimize recycling operations. By prioritizing cooperation over competition, facilities can better align with the broader EU goal. Such collaboration will be important to meeting CRMA targets and ensuring long-term sustainability and will help drive Europe toward a greener and more self-sufficient future.

Bibliography

AIMMS (2023a). AIMMS Development — aimms.com. https://www.aimms.com/platform/aimms-development/. [Accessed 23-10-2024].

AIMMS (2023b). Linear Programming &x2014; AIMMS Documentation — documentation.aimms.com. https://documentation.aimms.com/platform/math-program/linear-programming.html. [Accessed 23-10-2024].

AIMMS (2024). AIMMS SC Navigator Documentation — scnavigator-manual.aimms.com. https://scnavigator-manual.aimms.com/index.html. [Accessed 04-01-2025].

Ala, A., Goli, A., Mirjalili, S., and Simic, V. (2024). A fuzzy multi-objective optimization model for sustainable healthcare supply chain network design. *Applied Soft Computing*, 150:111012.

Arabi, M., Gholamian, M. R., Teimoury, E., and Mirzamohammadi, S. (2024). A robust bi-level programming model to enhance resilience in supply chain network considering government role, taxing, and raw sale: An iron ore case study. *Computers & Industrial Engineering*, 193:110322.

Arcadis (2023). New horizons - international construction costs 2023. Technical report.

Association, I. C. (2022). Copper Recycling - International Copper Association — internationalcopper.org. https://internationalcopper.org/resource/copper-recycling/. [Accessed 02-01-2025].

Aurubis (2024). E-scrap and Complex Raw Materials — aurubis.com. https://www.aurubis.com/en/products/recycling/e-scrap-and-complex-raw-materials. [Accessed 26-02-2025].

Baghalian, A., Rezapour, S., and Farahani, R. Z. (2013). Robust supply chain network design with service level against disruptions and demand uncertainties: A real-life case. *European journal of operational research*, 227(1):199–215.

Bank, E. I. (2024). Spain: EIB and Cunext sign €30 million loan for the production of eco-friendly recycled copper in Córdoba — eib.org. https://www.eib.org/en/press/all/2024-483-eib-and-cunext-sign-eur30-million-loan-for-the-production-of-eco-friendly-recycled-copper-in-cordoba. [Accessed 23-01-2025].

Capitalist, V. (2024). Infographic: Visualizing Copper's Global Supply Chain — visualcapitalist.com. https://www.visualcapitalist.com/sp/coppers-supply-chain/. [Accessed 20-11-2024].

Carrara, S., Bobba, S., Blagoeva, D., Dias, P. A., Cavalli, A., Georgitzikis, K., Grohol, M., Itul, A., Kuzov, T., Latunussa, C. E., et al. (2023). *Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU: A foresight study*. Publications Office of the European Union Luxembourg.

Christofyllidis, S. (2023). Copper recycling in europe: Waste from electrical and electronic equipment (weee). Technical report, International Copper Association.

Cia, H. E. M. and Cunha, C. B. (2024). Sustainable supply chain design using a multi objective linear optimization approach for solid bulk products. *Cleaner Logistics and Supply Chain*, page 100170.

Commission, E. (2020). Construction and demolition waste — environment.ec.europa.eu. https://environment.ec.europa.eu/topics/waste-and-recycling/construction-and-demolition-waste_en. [Accessed 05-12-2024].

Commission, E. (2023a). Critical Raw Materials: ensuring secure and sustainable supply chains for EU's green and digital future — ec.europa.eu. https://ec.europa.eu/commission/presscorner/detail/en/ip_23_1661. [Accessed 08-11-2024].

Commission, E. (2023b). End-of-Life Vehicles — environment.ec.europa.eu. https://environment.ec.europa.eu/topics/waste-and-recycling/end-life-vehicles_en. [Accessed 05-12-2024].

Commission, E. (2023c). *Study on the Critical Raw Materials for the EU 2023 - Final Report*. Publications Office of the European Union.

Commission, E. (2023d). Voorstel voor een verordening van het europees parlement en de raad tot vaststelling van een kader om een veilige en duurzame voorziening van kritieke grondstoffen te waarborgen, en tot wijziging van de verordeningen (eu) nr. 168/2013, (eu) 2018/858, (eu) 2018/1724 en (eu) 2019/1020. *European Commission*.

Commission, E. (2024a). Batteries — environment.ec.europa.eu. https://environment.ec.europa.eu/topics/waste-and-recycling/batteries_en. [Accessed 16-10-2024].

Commission, E. (2024b). Carbon Border Adjustment Mechanism — taxation-customs.ec.europa.eu. https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism_en. [Accessed 16-10-2024].

Commission, E. (2024c). Circular economy and quality of life — cinea.ec.europa.eu. https://cinea.ec.europa.eu/programmes/life/circular-economy-and-quality-life_en. [Accessed 23-01-2025].

Commission, E. (2024d). Corporate sustainability due diligence — commission.europa.eu. https://commission.europa.eu/business-economy-euro/doing-business-eu/sustainability-due-diligence-responsible-business/corporate-sustainability-due-diligence_en. [Accessed 16-10-2024].

Commission, E. (2024e). Corporate sustainability reporting — finance.ec.europa.eu. https://finance.ec.europa.eu/capital-markets-union-and-financial-markets/company-reporting-and-auditing/company-reporting/corporate-sustainability-reporting_en. [Accessed 16-10-2024].

Commission, E. (2024f). Ecodesign for Sustainable Products Regulation — commission.europa.eu. https://commission.europa.eu/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/ecodesign-sustainable-products-regulation_en. [Accessed 04-10-2024].

Commission, E. (2024g). INFORM - Global, open-source risk assessment for humanitarian crises and disasters — drmkc.jrc.ec.europa.eu. https://drmkc.jrc.ec.europa.eu/inform-index#:~:text=The%20INFORM%20Risk%20Index%20is,about%20prevention%2C%20preparedness%20and%20response. [Accessed 22-01-2025].

Commission, E. (2024h). Strategic projects under the CRMA — single-market-economy.ec.europa.eu. https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials/strategic-projects-under-crma_en. [Accessed 23-01-2025].

Cuddy, A. (2021). Germany floods: How a country was taken by surprise — bbc.com. https://www.bbc.com/news/world-europe-57867773. [Accessed 09-03-2025].

Davis, J. (2024). Cunext Secures €30 Million for Green Copper Production Project - METALS WIRE — metalswire.net. https://metalswire.net/commodities/cunext-secures-e30-million-for-green-copper-production-project/. [Accessed 23-01-2025].

Domínguez-Caamaño, P., Benavides, J. A. C., and Prado, J. C. P. (2016). An improved methodology to determine the wiggle factor: An application for spanish road transport. *Brazilian Journal of Operations & Production Management*, 13(1):52–56.

Dulia, E. F. and Shihab, S. A. (2024). An integrated supply chain network design for advanced air mobility aircraft manufacturing using stochastic optimization. *arXiv preprint arXiv:2406.07766*.

EU (2023a). Critical raw materials — single-market-economy.ec.europa.eu. https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials_en. [Accessed 08-10-2024].

EU (2023b). Critical Raw Materials Act — single-market-economy.ec.europa.eu. https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials/critical-raw-materials-act_en#overview-of-the-critical-raw-materials-act. [Accessed 02-10-2024].

Eurostat (2024). Hourly labour costs — ec.europa.eu. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Hourly_labour_costs. [Accessed 22-01-2025].

Flores, G. A., Risopatron, C., and Pease, J. (2020). Processing of complex materials in the copper industry: Challenges and opportunities ahead. *Jom*, 72(10):3447–3461.

Fonseca, M. V. A. (2024). *Dynamics of Peru's Position in the Global Copper Ore Trade: A Social Network Analysis*. PhD thesis, .

Forum, W. E. (2023). The global risks report 2023 18th edition. Technical report, World Economic Forum.

Francisco Saldanha-da Gama, S. W. (2024). *Facility Location Under Uncertainty*. International Series in Operations Research Management Science.

Glencore (2023). Glencore resources and reserves report 2023. Technical report, Glencore.

Glencore (2024a). 2024-2026 climate action transition plan. Technical report, Glencore.

Glencore (2024b). At a glance — glencore.com. https://www.glencore.com/who-we-are/at-a-glance. [Accessed 04-12-2024].

Glencore (2024c). Copper — glencore.com. https://www.glencore.com/what-we-do/metals-and-minerals/copper. [Accessed 04-12-2024].

Glencore (2024d). Glencore annual report 2023. Technical report, Glencore.

Glencore (2024e). Recycling — glencore.com. https://www.glencore.com/what-we-do/recycling. [Accessed 04-12-2024].

GROUP, I. C. S. (2024). The world factbook 2024. Technical report, INTERNATIONAL COPPER STUDY GROUP.

Guardian, T. (2025). Five years on from the pandemic, how has Covid changed our world? | The panel — theguardian.com. https://www.theguardian.com/commentisfree/2025/mar/01/five-years-covid-first-lockdown-lives-changed. [Accessed 09-03-2025].

Henckens, M. and Worrell, E. (2020). Reviewing the availability of copper and nickel for future generations. the balance between production growth, sustainability and recycling rates. *Journal of Cleaner Production*, 264:121460.

Hishamuddin, H., Sarker, R. A., and Essam, D. (2013). A recovery model for a two-echelon serial supply chain with consideration of transportation disruption. *Computers & Industrial Engineering*, 64(2):552–561.

Hool, A., Helbig, C., and Wierink, G. (2023). Challenges and opportunities of the european critical raw materials act. *Mineral Economics*, pages 1–8.

ICSG, I. C. S. G. (2024). What Is Copper — icsg.org. https://icsg.org/what-is-copper/. [Accessed 20-11-2024].

International Copper Association (2023). Copper: The pathway to net zero - focus on europe. https://internationalcopper.org/wp-content/uploads/2023/03/Copper_The-Pathway-to-Net-Zero_Focus-on-Europe_final.pdf. Accessed: January 2, 2025.

Ivanov, D. (2022). Viable supply chain model: integrating agility, resilience and sustainability perspectives—lessons from and thinking beyond the covid-19 pandemic. *Annals of operations research*, 319(1):1411–1431.

Jack Barnett, Economics Correspondent | Isabella Fish, R. E. (2024). How supply chain shocks have changed the face of global trade — thetimes.com. https://www.thetimes.com/business-money/markets/article/how-supply-chain-shocks-have-changed-the-face-of-global-trade-0vl9vk3bl?region=global. [Accessed 09-03-2025].

Khalili-Fard, A., Sabouhi, F., and Bozorgi-Amiri, A. (2024). Data-driven robust optimization for a sustainable steel supply chain network design: Toward the circular economy. *Computers & Industrial Engineering*, 195:110408.

Klose, S. and Pauliuk, S. (2023). Sector-level estimates for global future copper demand and the potential for resource efficiency. *Resources, Conservation and Recycling*, 193:106941.

Konstantaras, I., Skouri, K., and Benkherouf, L. (2021). Optimizing inventory decisions for a closed–loop supply chain model under a carbon tax regulatory mechanism. *International Journal of Production Economics*, 239:108185.

Kouwenhoven, M., Muller, J., Thoen, S., Willigers, J., and de Jong, G. (2023). Values of time, reliability and comfort in the netherlands 2022 - new values for passenger travel and freight transport. Technical report, Significance quantitative research.

Li, B., Li, H., Dong, Z., Lu, Y., Liu, N., and Hao, X. (2021). The global copper material trade network and risk evaluation: A industry chain perspective. *Resources Policy*, 74:102275.

Longo, M. C. and Cardillo, E. (2024). Chapter two - eu sdg goals: Content and monitoring for sustainable business. In Longo, M. C. and Cardillo, E., editors, *Being a Sustainable Firm*, pages 19–31. Academic Press.

Lotfi, R., Mehrjerdi, Y. Z., Pishvaee, M. S., Sadeghieh, A., and Weber, G.-W. (2020). A robust optimization model for sustainable and resilient closed-loop supply chain network design considering conditional value at risk. *Numerical Algebra, Control and Optimization*, 11(2):221–253.

Lotfi, R., MohajerAnsari, P., Nevisi, M. M. S., Afshar, M., Davoodi, S. M. R., and Ali, S. S. (2024). A viable supply chain by considering vendor-managed-inventory with a consignment stock policy and learning approach. *Results in Engineering*, 21:101609.

Lotfi, R., Rajabzadeh, M., Zamani, A., and Rajabi, M. S. (2022). Viable supply chain with vendor-managed inventory approach by considering blockchain, risk and robustness. *Annals of Operations Research*, pages 1–20.

Luo, R., Zhou, L., Song, Y., and Fan, T. (2022). Evaluating the impact of carbon tax policy on manufacturing and remanufacturing decisions in a closed-loop supply chain. *International Journal of Production Economics*, 245:108408.

Mackenzie, W. (2024). Infographic | The future of the copper market — woodmac.com. https://www.woodmac.com/news/opinion/infographic-the-future-of-the-copper-market/. [Accessed 15-01-2025].

Manupati, V. K., Kulatunga, A., Ray, P., and Rofin, T. (2024). Sustainable management of eol tyres: A remanufacturing supply chain network design. *Journal of Cleaner Production*, 434:140115.

Mathieux, F., Ardente, F., Bobba, S., Nuss, P., Blengini, G. A., Dias, P. A., Blagoeva, D., De Matos, C. T., Wittmer, D., Pavel, C., et al. (2018). Critical raw materials and the circular economy. *Publications Office of the European Union: Bruxelles, Belgium*.

Nations, U. (2015). Transforming our world: The 2030 agenda for sustainable development. *New York: United Nations, Department of Economic and Social Affairs*, 1:41.

Nations, U. (2024). unfccc.int. https://unfccc.int/cop28/5-key-takeaways#:~:text=COP%2028%20closed%20with%20an,cuts%20and%20scaled%2Dup%20finance. [Accessed 30-10-2024].

NOS (2024a). Ook storm en hoge waterstanden in Frankrijk, België en Duitsland — nos.nl. https://nos.nl/artikel/2503583-ook-storm-en-hoge-waterstanden-in-frankrijk-belgie-en-duitsland. [Accessed 10-03-2025].

NOS (2024b). Servië gaat lithium winnen voor EU, inwoners vrezen 'vuilnisbelt' te worden — nos.nl. https://nos.nl/nieuwsuur/artikel/2540411-servie-gaat-lithium-winnen-voor-eu-inwoners-vrezen-vuilnisbelt-te-worden. [Accessed 16-03-2025].

Paul, S. K., Sarker, R., and Essam, D. (2015). Managing disruption in an imperfect production–inventory system. *Computers & Industrial Engineering*, 84:101–112.

Peck, D. and Sprecher, B. (2023). Stories of Team Science | Kritieke grondstoffen — tudelft.nl. https://www.tudelft.nl/kritieke-grondstoffen/stories-of-team-science-kritieke-grondstoffen. [Accessed 12-11-2024].

Persyn, D., Díaz-Lanchas, J., and Barbero, J. (2022). Estimating road transport costs between and within european union regions. *Transport Policy*, 124:33–42.

Reuters, T. (2024). Copper at a glance — graphics.thomsonreuters.com. https://graphics.thomsonreuters.com/15/chile-copper/index.html. [Accessed 20-11-2024].

Saeedi, M., Parhazeh, S., Tavakkoli-Moghaddam, R., and Khalili-Fard, A. (2024). Designing a two-stage model for a sustainable closed-loop electric vehicle battery supply chain network: A scenario-based stochastic programming approach. *Computers & Industrial Engineering*, 190:110036.

Statista (2023). Europe: refined copper consumption by country 2020 | Statista — statista.com. https://www.statista.com/statistics/1236706/europe-annual-refined-copper-consumption-by-country/. [Accessed 03-01-2025].

Sunaryo, S., Hanura, A. R., and Hussein, F. (2020). Feasibility study on the financial aspect of green ship recycling yard business model. In *AIP Conference Proceedings*, volume 2227. AIP Publishing.

Tadaros, M., Migdalas, A., Samuelsson, B., and Segerstedt, A. (2022). Location of facilities and network design for reverse logistics of lithium-ion batteries in sweden. *Operational Research*, pages 1–21.

Teske, S., Nagrath, K., Niklas, S., Talwar, S., Atherton, A., Orbe, J. G., Assaf, J., and Giurco, D. (2022). Scopes 1, 2, and 3 industry emissions and future pathways. In *Achieving the Paris Climate Agreement Goals: Part 2: Science-based Target Setting for the Finance industry—Net-Zero Sectoral 1.5 C Pathways for Real Economy Sectors*, pages 315–336. Springer.

Today, R. (2024). recyclingtoday.com. https://www.recyclingtoday.com/news/lindner-loacker-recycling-germany-copper-cable-wire-recycling-shredder/. [Accessed 22-01-2025].

Tröster, B., Papatheophilou, S., and Küblböck, K. (2024). In search of critical raw materials: What will the eu critical raw materials act achieve. *An analysis of legal and factual implications of the CRMA*.

Turken, N., Carrillo, J., and Verter, V. (2017). Facility location and capacity acquisition under carbon tax and emissions limits: To centralize or to decentralize? *International Journal of Production Economics*, 187:126–141.

Turken, N., Carrillo, J., and Verter, V. (2020). Strategic supply chain decisions under environmental regulations: When to invest in end-of-pipe and green technology. *European Journal of Operational Research*, 283(2):601–613.

Union, E. (2024a). Overview - NUTS - Nomenclature of territorial units for statistics - Eurostat — ec.europa.eu. https://ec.europa.eu/eurostat/web/nuts. [Accessed 01-03-2025].

Union, E. E. (2024b). Employment (thousand persons) by nuts 3 region. https://ec.europa.eu/eurostat/databrowser/view/nama_10r_3empers__custom_14888937/default/table?lang=en. [Accessed 09-01-2025].

Verschuren, P. and Doorewaard, H. (2010). Designing a research project. Second edition.

voor Ondernemend Nederland, R. (2025). DEI+: Circulaire economie — rvo.nl. https://www.rvo.nl/subsidies-financiering/dei/circulaire-economie. [Accessed 13-02-2025].

Waltho, C., Elhedhli, S., and Gzara, F. (2019). Green supply chain network design: A review focused on policy adoption and emission quantification. *International Journal of Production Economics*, 208:305–318.

Wang, M., Li, Y., Li, M., Shi, W., and Quan, S. (2019). Will carbon tax affect the strategy and performance of low-carbon technology sharing between enterprises? *Journal of cleaner production*, 210:724–737.

Wang, Z. and Wu, Q. (2021). Carbon emission reduction and product collection decisions in the closed-loop supply chain with cap-and-trade regulation. *International Journal of Production Research*, 59(14):4359–4383.

Wincewicz-Bosy, M., Dymyt, M., and Wasowska, K. (2021). The supply chain of the mining industry: the case of copper mining.

Wu, D., Ding, H., and Cheng, Y. (2024). How does environmental policy affect operations and supply chain management: A literature review. *Computers & Industrial Engineering*, page 110580.

Xie, S., Lim, Y. T., Wang, H., Yi, W., and Antwi-Afari, M. F. (2024). Location and capacity optimization of waste recycling centers: Mathematical models and numerical experiments. *Applied Sciences*, 14(16):7039.

15 Appendix

15.1 Global risk landscape

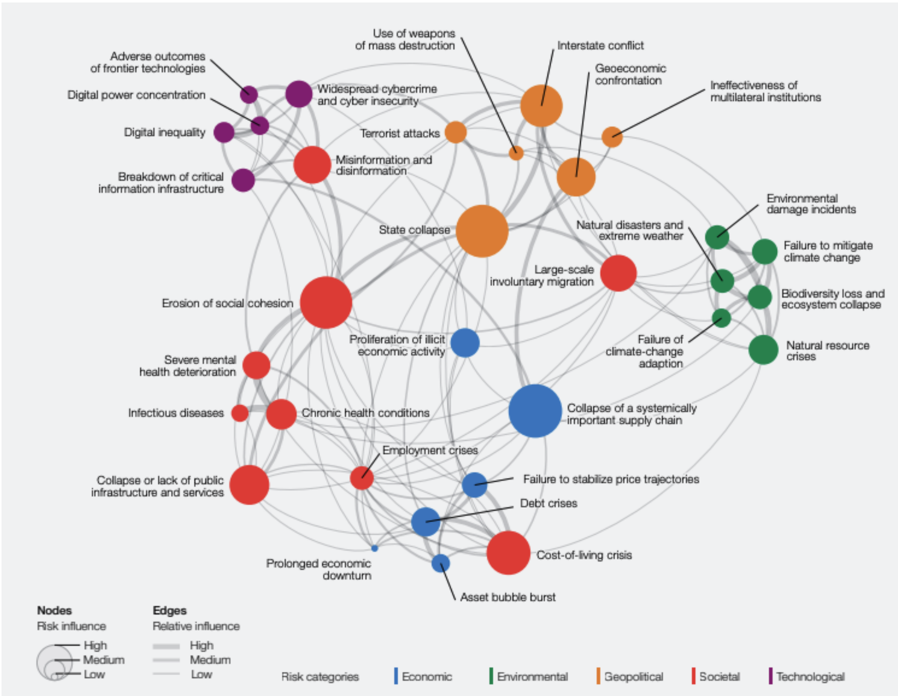


Figure 15.1: Global risks landscape: an interconnections map (Forum, 2023)

15.2 Global CRM suppliers and producers

This Appendix provides some background knowledge in the global supply of CRMs as well as the EU suppliers of CRMs.

An analysis of global supply reveals that China is the largest supplier of several critical raw materials. However, other countries also play significant roles as global suppliers of specific materials. For example, Russia and South Africa are the leading suppliers of platinum group metals, Australia is the primary source of lithium, the USA supplies beryllium and helium, and Brazil is known for niobium. Figure 15.2 illustrates the global map of primary CRM suppliers to the EU (Commission, 2023c).

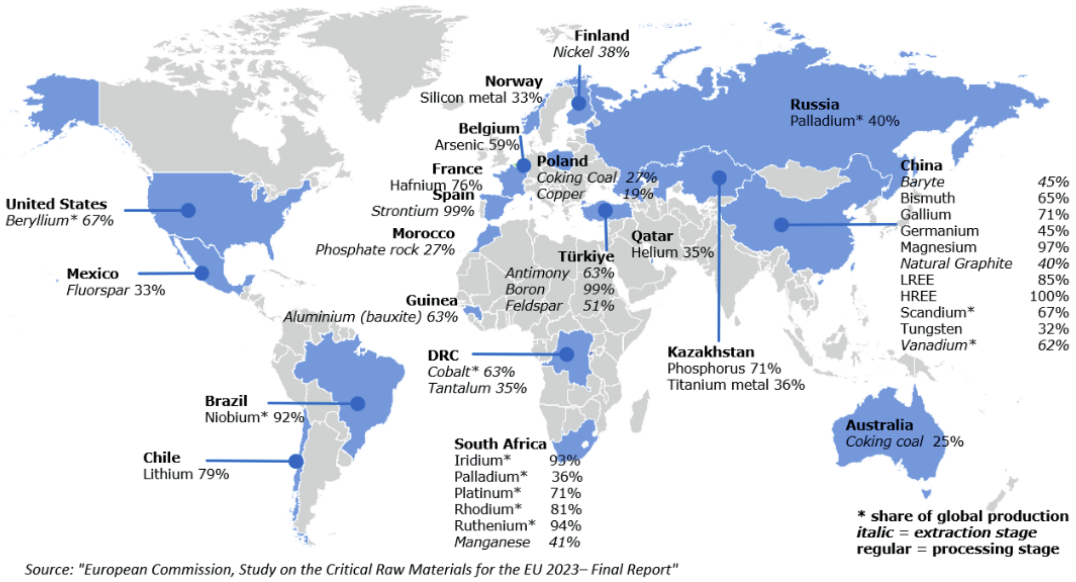


Figure 15.2: Major EU suppliers CRMs (Commission, 2023c)

Furthermore, Figure 15.3 provides an overview of EU producers of CRMs that hold a global market share of over 0.5% (Commission, 2023c).

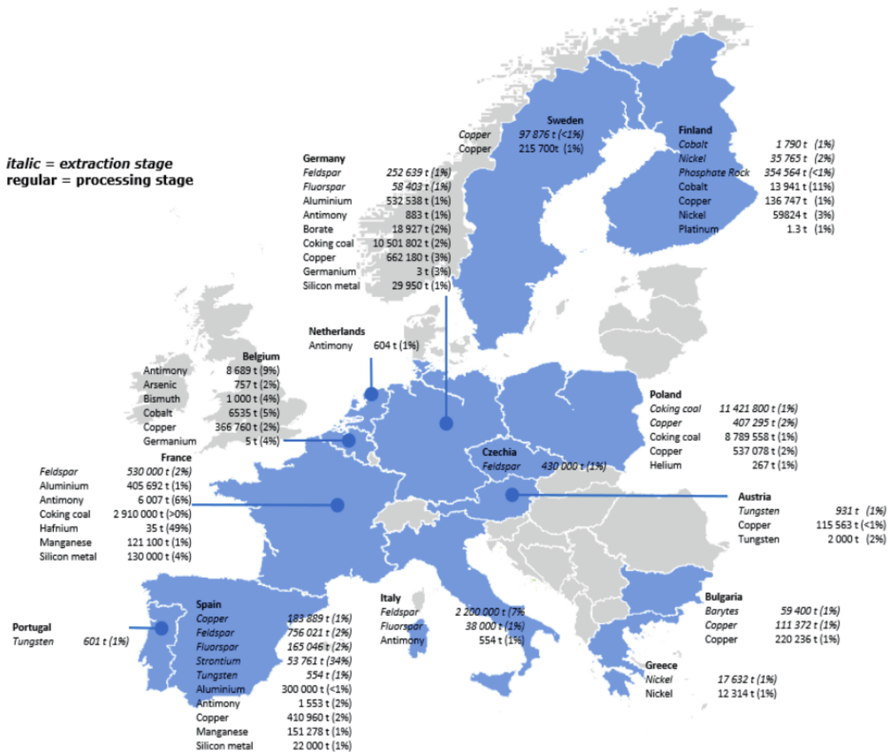


Figure 15.3: EU producers of CRMs, in brackets shares of global supply, 2016-20207 (Commission, 2023c)

15.3 Global copper suppliers, importers and exporters

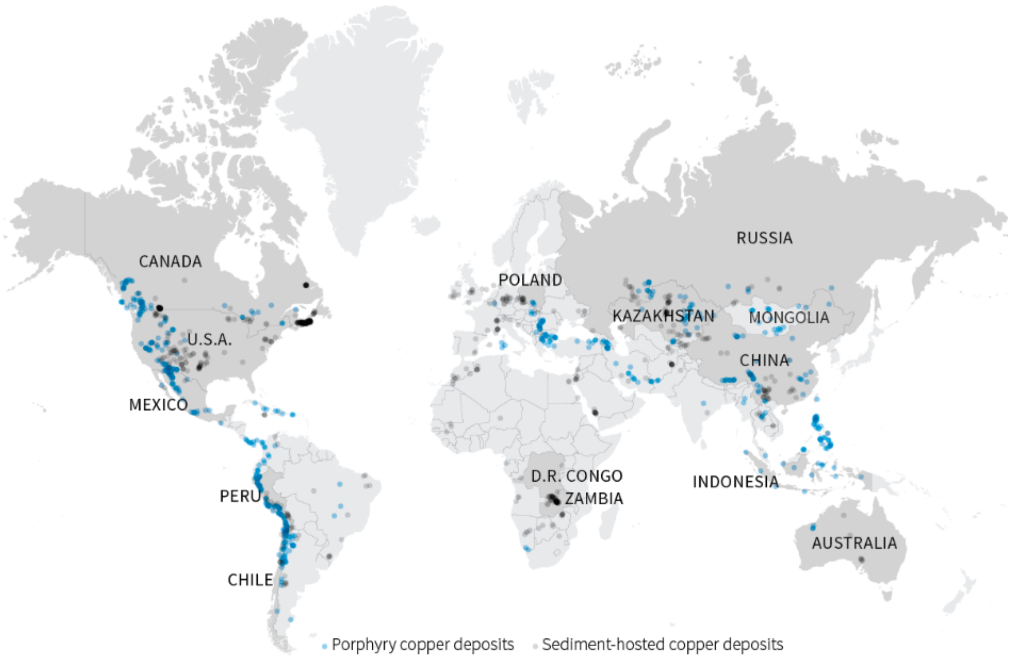


Figure 15.4: Global Copper suppliers (Reuters, 2024)

Table 15.1: Major importers and exporters of copper (Wincewicz-Bosy et al., 2021)

Importers and exporters	**Countries**
Major exporters of refined copper	Chile, Russia, Congo, Japan, Australian, Kazakhstan, China, Poland, South Korea, Peru
Major importers of refined copper	China, United States, Germany, Italy, Taiwan, UAE, Thailand, Turkey, Malaysia, Vietnam
Major exporters of copper ores and concentrates	Chile, Peru, Australia, Canada, United States, Brazil, Mexico, Mongolia, Spain, Indonesia
Major importers of copper ores and concentrates	China, Japan, South Korea, Spain, Germany, Bulgaria, India, Taiwan, Brazil, Finland

15.4 WEEE copper waste

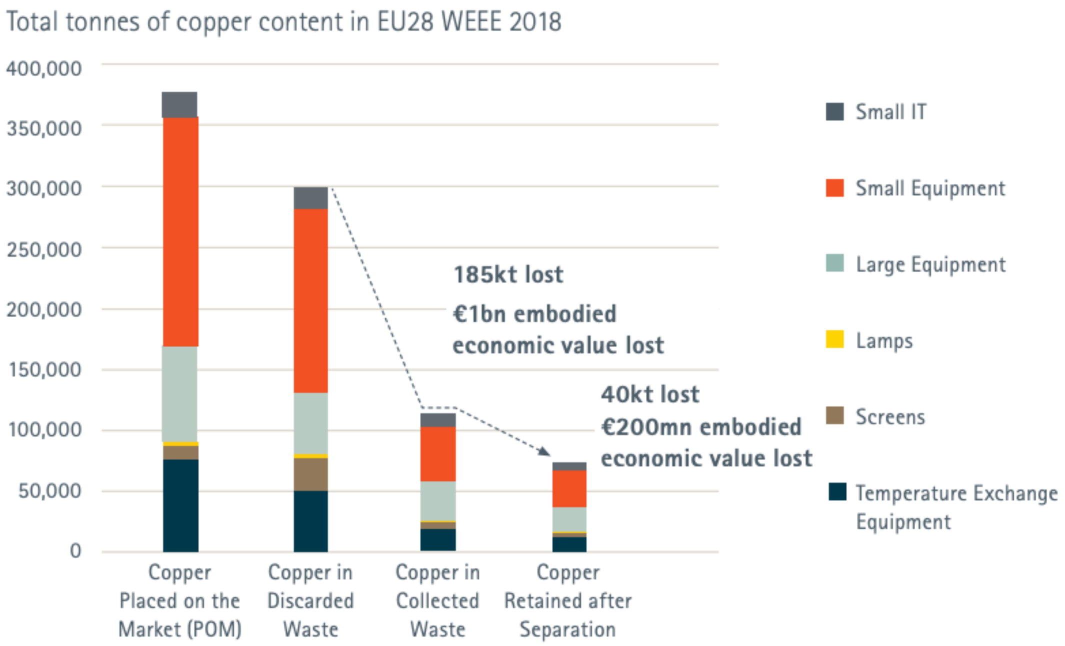


Figure 15.5: Estimated mass and embodied economic value of copper contained in 2018 WEEE flows (total tons of copper content) (Christofyllidis, 2023)

15.5 Datasets

Table 15.2: Datapoints Customers

Customer	Country	Longitude	Latitude	Demand Recycled Copper (tonnes)
Antwerp	Belgium	4.4028	51.2194	6.872,788
Stuttgart	Germany	9.1829	48.7758	12.042,669
Karlsruhe	Germany	8.4037	49.0069	6.391,189
Freiburg im Breisgau	Germany	7.8522	47.9990	5.937,112
Munich	Germany	11.5761	48.1374	9.009,136
Düsseldorf	Germany	6.7735	51.2277	7.584,976
Cologne	Germany	6.9603	50.9375	6.076,975
Dortmund	Germany	7.4660	51.5136	7.483,414
Barcelona	Spain	2.1734	41.3851	10.575,768
Valencia	Spain	-0.3763	39.4699	5.994,105
Paris	France	2.3522	48.8566	11.023,570
Nantes	France	-1.5536	47.2184	6.775,660
Lyon	France	4.8357	45.7640	10.815,568
Turin	Italy	7.6869	45.0703	6.331,185
Milan	Italy	9.1900	45.4642	15.836,071
Venice	Italy	12.3155	45.4408	9.240,546
Bologna	Italy	11.3426	44.4949	7.823,165
Katowice	Poland	19.0238	50.2649	6.396,520

Table 15.3: Dataset recycling facilities

Recycling facility	Long	Lat	City	Country
Stuttgart_REC	9.17702	48.78232	Stuttgart	Germany
Sevilla_REC	-5.97317	37.38283	Sevilla	Spain
Düsseldorf_REC	6.77616	51.22172	Düsseldorf	Germany
Paris_REC	2.3488	48.85341	Paris	France
Nantes_REC	-1.55336	47.21725	Nantes	France
Lyon_REC	4.84671	45.74846	Lyon	France
Milan_REC	9.18951	45.46427	Milan	Italy
Venice_REC	12.33265	45.43713	Venice	Italy
Katowice_REC	19.02754	50.25841	Katowice	Poland
Freiburg_REC	7.85222	47.9959	Freiburg	Germany
Darmstadt_REC	8.58874	49.9039	Darmstadt	Germany
Hannover_REC	9.73322	52.37052	Hannover	Germany
Dortmund_REC	7.466	51.51494	Dortmund	Germany
Geithain_REC	12.69674	51.05528	Geithain	Germany
Rakitovo_REC	24.0873	41.99012	Rakitovo	Bulgaria
Santiago de Compostela_REC	-8.54569	42.88052	Santiago de Compostela	Spain
Bilbao_REC	-2.92528	43.26271	Bilbao	Spain
Madrid_REC	-3.70256	40.4165	Madrid	Spain
Valencia_REC	-0.37739	39.46975	Valencia	Spain
Toulouse_REC	1.44367	43.60426	Toulouse	France
Marseille_REC	5.37034	43.29664	Marseille	France
Turin_REC	7.68682	45.07049	Turin	Italy
Naples_REC	14.26811	40.85216	Naples	Italy
Bologna_REC	11.33875	44.49381	Bologna	Italy
Poznań_REC	16.92993	52.40692	Poznań	Poland
Uppsala_REC	17.63889	59.85882	Uppsala	Sweden
Göteborg_REC	11.96679	57.70716	Göteborg	Sweden
Antwerpen_REC	4.40346	51.21989	Antwerpen	Belgium
Munich_REC	11.57549	48.13743	Munich	Germany
Barcelona_REC	2.17628	41.38364	Barcelona	Spain

Table 15.4: Transport costs data ($tc_{j1} = tc_{1k}$) - 25 ton load (Persyn et al., 2022)

City	Transport costs (€/km)	Transport costs (€/ton/km)
Stuttgart	1.596	0.0638
Sevilla	5.921	0.2368
Düsseldorf	1.596	0.0638
Paris	2.046	0.0818
Nantes	2.279	0.0912
Lyon	2.046	0.0818
Milan	2.046	0.0818
Venice	2.046	0.0818
Katowice	1.596	0.0638
Freiburg	1.746	0.0698
Darmstadt	1.596	0.0638
Hannover	1.596	0.0638
Dortmund	1.596	0.0638
Geithain	1.746	0.0698
Rakitovo	2.514	0.1006
Santiago de Compostela	2.893	0.1157
Bilbao	2.893	0.1157
Madrid	2.514	0.1006
Valencia	2.893	0.1157
Toulouse	2.510	0.1004
Marseille	2.046	0.0818
Turin	2.046	0.0818
Naples	2.279	0.0912
Bologna	2.046	0.0818
Poznań	1.746	0.0698
Uppsala	5.921	0.2368
Göteborg	5.921	0.2368
Antwerpen	1.746	0.0698
Munich	1.746	0.0698
Barcelona	2.893	0.1157

Table 15.5: Unit costs data

Country	Labour costs	Costs (€/ton
Germany	€41.3/hour	23.33/ton
Bulgaria	€9.3/hour	5.25/ton
Spain	€24.6hour	13.90/ton
France	€42.2/hour	23.84/ton
Italy	€29.8/hour	16.84/ton
Poland	€14.5/hour	8.19/ton
Belgium	€47.1/hour	26.61/ton
Sweden	€38.9/hour	21,98/ton

Table 15.6: Fixed Costs, Subsidies, and Internal Rate Data

Location	**Fixed Costs (€)**	**Subsidy (10%) (€)**	**Internal Rate (9%) (€)**
Stuttgart	189.000.000	18.900.000	17.010.000
Sevilla	145.300.000	14.530.000	13.077.000
Düsseldorf	218.000.000	21.800.000	19.620.000
Paris	261.600.000	26.160.000	23.544.000
Nantes	145.300.000	14.530.000	13.077.000
Lyon	189.000.000	18.900.000	17.010.000
Milan	218.000.000	21.800.000	19.620.000
Venice	218.000.000	21.800.000	19.620.000
Katowice	116.300.000	11.630.000	10.467.000
Freiburg	189.000.000	18.900.000	17.010.000
Darmstadt	189.000.000	18.900.000	17.010.000
Hannover	189.000.000	18.900.000	17.010.000
Dortmund	189.000.000	18.900.000	17.010.000
Geithain	116.300.000	11.630.000	10.467.000
Rakitovo	87.200.000	8.720.000	7.848.000
Santiago de Compostela	145.300.000	14.530.000	13.077.000
Bilbao	145.300.000	14.530.000	13.077.000
Madrid	145.300.000	14.530.000	13.077.000
Valencia	145.300.000	14.530.000	13.077.000
Toulouse	145.300.000	14.530.000	13.077.000
Marseille	189.000.000	18.900.000	17.010.000
Turin	189.000.000	18.900.000	17.010.000
Naples	145.300.000	14.530.000	13.077.000
Bologna	145.300.000	14.530.000	13.077.000
Poznań	116.300.000	11.630.000	10.467.000
Uppsala	218.000.000	21.800.000	19.620.000
Göteborg	218.000.000	21.800.000	19.620.000
Antwerpen	218.000.000	21.800.000	19.620.000
Munich	218.000.000	21.800.000	19.620.000
Barcelona	145.300.000	14.530.000	13.077.000

Table 15.7: Generalised Risk Including Hazard & Exposure, Vulnerability, and Lack of Coping Capacity (Commission, 2024g)

Location	Inform Risk	Risk Class	Risk Percentage	Risk Costs (€)
Stuttgart	2.4	Low	1.0%	1.890.000
Sevilla	2.4	Low	1.0%	1.453.000
Düsseldorf	2.4	Low	1.0%	2.180.000
Paris	2.9	Low	2.0%	5.232.000
Nantes	2.9	Low	2.0%	2.906.000
Lyon	2.9	Low	2.0%	3.780.000
Milan	2.5	Low	1.2%	2.616.000
Venice	2.5	Low	1.2%	2.616.000
Katowice	2.5	Low	1.2%	1.395.600
Freiburg	2.4	Low	1.0%	1.890.000
Darmstadt	2.4	Low	1.0%	1.890.000
Hannover	2.4	Low	1.0%	1.890.000
Dortmund	2.4	Low	1.0%	1.890.000
Geithain	2.4	Low	1.0%	1.163.000
Rakitovo	2.7	Low	1.6%	1.395.200
Santiago de Compostela	2.4	Low	1.0%	1.453.000
Bilbao	2.4	Low	1.0%	1.453.000
Madrid	2.4	Low	1.0%	1.453.000
Valencia	2.4	Low	1.0%	1.453.000
Toulouse	2.9	Low	2.0%	2.906.000
Marseille	2.9	Low	2.0%	3.780.000
Turin	2.5	Low	1.2%	2.268.000
Naples	2.5	Low	1.2%	1.743.600
Bologna	2.5	Low	1.2%	1.743.600
Poznań	2.5	Low	1.2%	1.395.600
Uppsala	1.9	Very Low	0.5%	1.090.000
Göteborg	1.9	Very Low	0.5%	1.090.000
Antwerpen	2.1	Low	0.8%	1.744.000
Munich	2.4	Low	1.0%	2.180.000
Barcelona	2.4	Low	1.0%	1.453.000

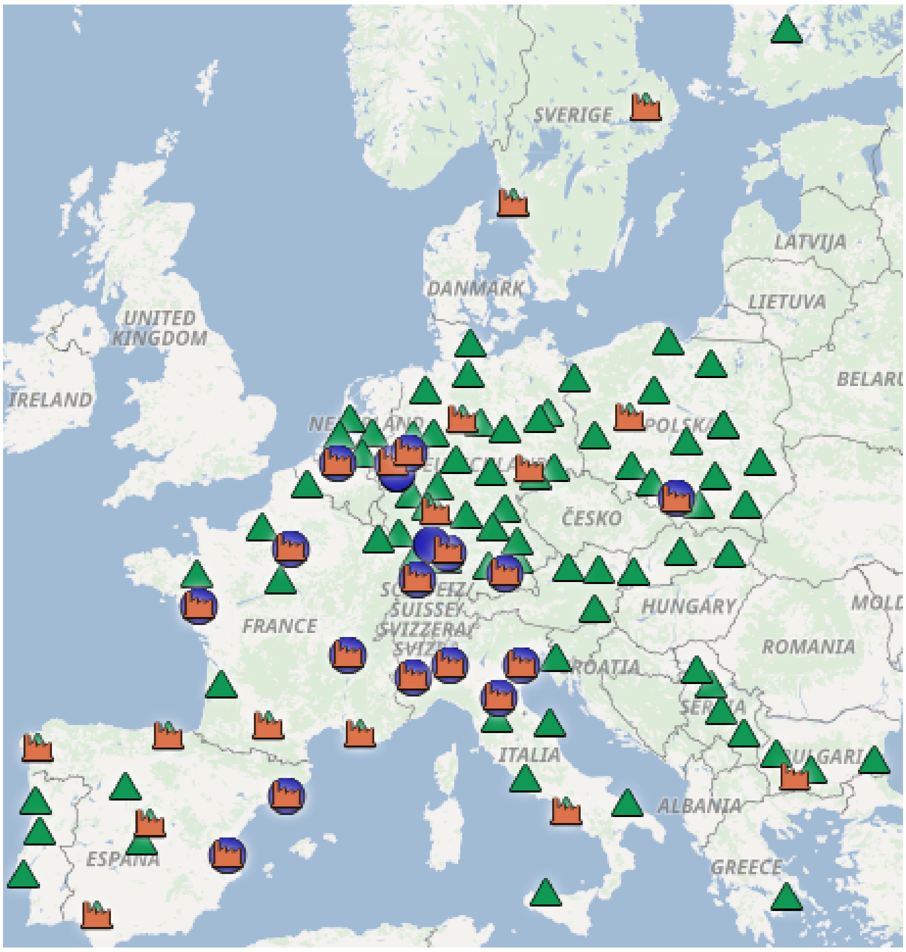


Figure 15.6: Overview of datapoints on map

15.6 Results

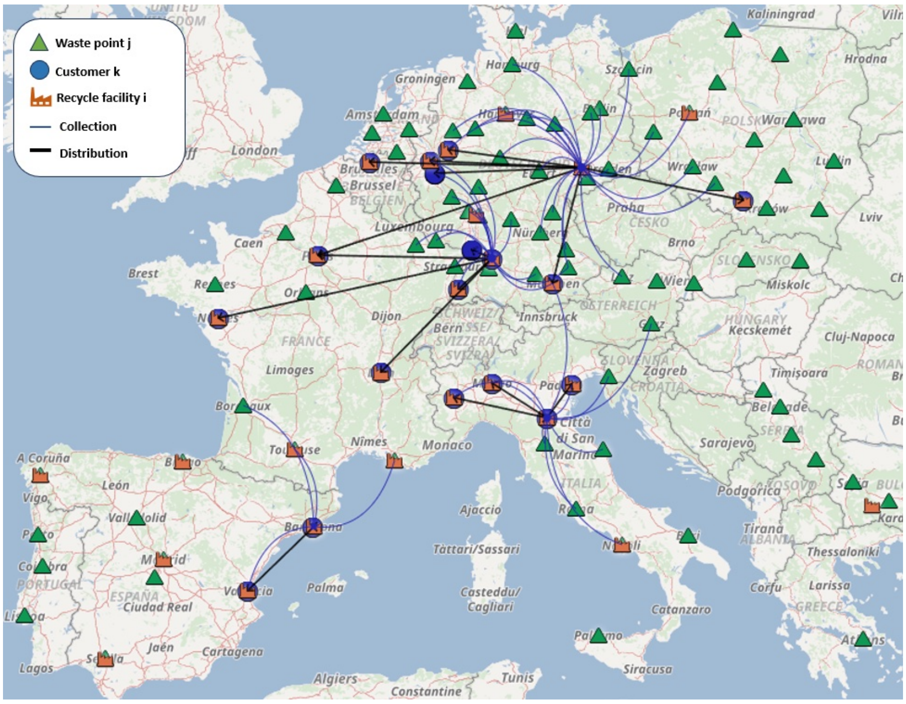


Figure 15.7: Optimal recycling network, all nodes

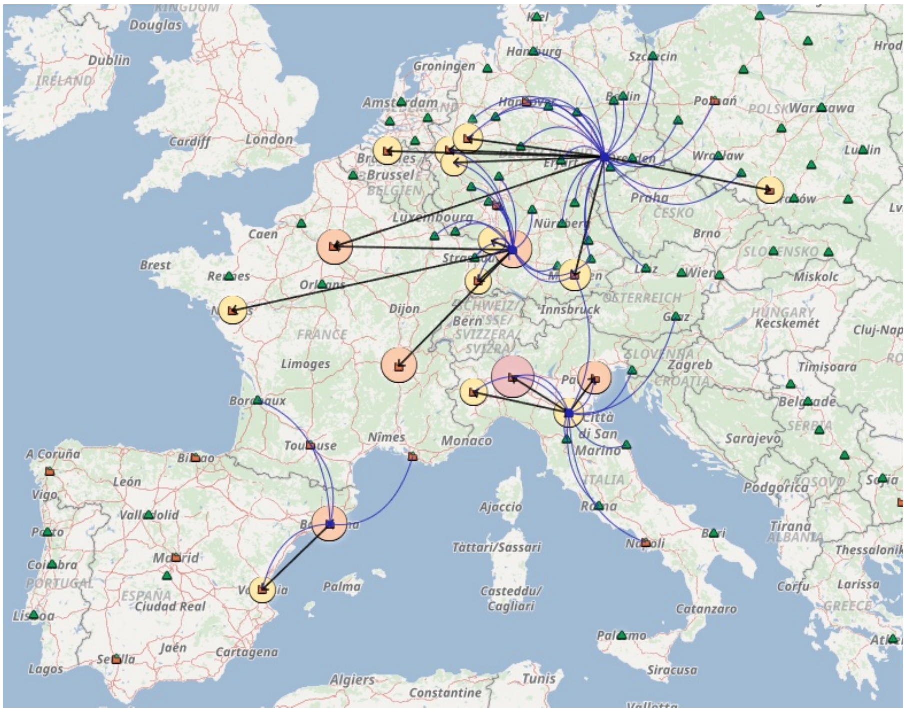


Figure 15.8: High (red), medium (orange), small (yellow) demand areas

Table 15.8: Unrounded costs per facility i

Facility i	C_i	**Fixed Costs**	**Variable Costs**	**Sum** t_{ji}	**Sum** t_{ik}	**Total costs**
Barcelona_REC	16.570	4.843.333	230.321	862.449	294.605	6.230.708
Bologna_REC	39.231	5.133.933	660.649	1.681.191	736.228	8.212.002
Geithain_REC	46.410	3.876.667	1.082.735	2.043.622	2.099.112	9.102.136
Stuttgart_REC	50.000	6.300.000	1.166.500	1.131.365	1.491.013	10.088.878
Total	152.210	20.153.933	3.140.206	5.718.627	4.620.958	33.633.724

Table 15.9: Unrounded primary transport costs per location

Facility i	y_{ji}	$Distance_{ji}$	t_{ji}	**In-Transit costs**	**Total transport costs**
Barcelona_REC	29.660	1.742	801.820	60.628	862.449
Bologna_REC	70.223	3.568	1.518.806	162.385	1.681.191
Geithain_REC	83.073	7.072	1.816.091	227.531	2.043.622
Stuttgart_REC	89.500	3.498	994.990	136.375	1.131.365
Total	272.457	15.880	5.131.708	586.919	5.718.627

Table 15.10: Unrounded secondary transport costs per location

Facility i	y_{ik}	$Distance_{ik}$	t_{ik}	**In-Transit costs**	**Total transport costs**
Barcelona_REC	16.570	143	273.895	20.710	294.605
Bologna_REC	39.231	207	665.117	71.112	736.228
Geithain_REC	46.410	576	1.865.403	233.710	2.099.112
Stuttgart_REC	50.000	411	1.311.286	179.727	1.491.013
Total	152.210	1.336	4.115.700	505.258	4.620.958

Table 15.11: Output of y_{ij} and y_{ik}

From	To	Product	y_{mn}	Distance	t_{mn}	In-Transit
Alsace	Stuttgart_REC	Copper	3685	139	32777	4492
Aquitaine	Barcelona_REC	Copper	640	578	42809	3237
Arnsberg	Geithain_REC	Copper	8642	477	288149	36101
Berlin	Geithain_REC	Copper	2844	221	43889	5499
Brandenburg	Geithain_REC	Copper	3314	196	45317	5678
Braunschweig	Geithain_REC	Copper	4331	262	79235	9927
Campania	Bologna_REC	Copper	4543	612	227379	24310
Cataluña	Barcelona_REC	Copper	12213	0	533	40
Chemnitz	Geithain_REC	Copper	3622	39	9779	1225
Comunitat Valenciana	Barcelona_REC	Copper	6922	394	315757	23875
Darmstadt	Stuttgart_REC	Copper	6170	165	65069	8918
Detmold	Geithain_REC	Copper	6066	400	169291	21210
Dolnośląskie	Geithain_REC	Copper	3675	394	101197	12679
Dresden	Geithain_REC	Copper	3337	95	22038	2761
Düsseldorf_SUP	Stuttgart_REC	Copper	3706	418	98898	13555
Emilia-Romagna	Bologna_REC	Copper	9034	0	316	34
Freiburg	Stuttgart_REC	Copper	6856	170	74526	10215
Friuli-Venezia Giulia	Bologna_REC	Copper	2159	300	52968	5663
Gießen	Stuttgart_REC	Copper	2443	265	41277	5657
Hamburg	Geithain_REC	Copper	2605	433	78723	9863
Hannover	Geithain_REC	Copper	3648	327	83314	10438
Karlsruhe_SUP	Stuttgart_REC	Copper	7380	80	37855	5189
Kassel	Geithain_REC	Copper	2849	294	58462	7324
Koblenz	Stuttgart_REC	Copper	3205	272	55660	7629
Köln	Stuttgart_REC	Copper	7018	374	167447	22951
Lazio	Bologna_REC	Copper	3511	394	113194	12102
Lombardia	Bologna_REC	Copper	18287	261	390111	41709
Lorraine	Stuttgart_REC	Copper	3327	289	61384	8413
Lubuskie	Geithain_REC	Copper	1324	283	26171	3279
Marche	Bologna_REC	Copper	3116	260	66210	7079
Midi-Pyrénées	Barcelona_REC	Copper	4737	330	181123	13695
Mittelfranken	Geithain_REC	Copper	4953	276	95430	11956
Münster	Geithain_REC	Copper	5046	474	167189	20946
Niederbayern	Geithain_REC	Copper	279	367	7149	896
Niederbayern	Stuttgart_REC	Copper	3388	286	61891	8483
Oberbayern	Bologna_REC	Copper	4448	527	191918	20519
Oberbayern	Stuttgart_REC	Copper	5956	248	94346	12931
Oberfranken	Geithain_REC	Copper	3290	191	43878	5497
Oberpfalz	Geithain_REC	Copper	3722	300	78082	9783
Oberösterreich	Geithain_REC	Copper	1543	424	45722	5728
Opolskie	Geithain_REC	Copper	1296	480	43495	5449
Piemonte	Bologna_REC	Copper	7311	384	229650	24553
Provence-Alpes	Barcelona_REC	Copper	5148	439	261598	19780
Rheinhessen-Pfalz	Stuttgart_REC	Copper	4124	196	51530	7063

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From	**To**	**Product**	y_{mn}	**Distance**	t_{mn}	**In-Transit**
Saarland	Stuttgart_REC	Copper	2246	217	31119	4265
Sachsen-Anhalt	Geithain_REC	Copper	3897	181	49388	6188
Schwaben	Stuttgart_REC	Copper	5769	175	64457	8835
Steiermark	Bologna_REC	Copper	1020	556	46443	4966
Stuttgart_SUP	Stuttgart_REC	Copper	13907	1	973	133
Thüringen	Geithain_REC	Copper	4926	152	52262	6548
Toscana	Bologna_REC	Copper	6122	105	52627	5627
Tübingen	Stuttgart_REC	Copper	6542	40	16509	2263
Unterfranken	Stuttgart_REC	Copper	3778	163	39272	5383
Veneto	Bologna_REC	Copper	10671	169	147991	15823
Wielkopolskie	Geithain_REC	Copper	5995	426	178314	22340
Zachodniopomorskie	Geithain_REC	Copper	1868	380	49618	6216
Geithain_REC	Antwerp	Recycled copper	6873	752	361073	45237
Barcelona_REC	Barcelona	Recycled copper	10576	0	461	35
Bologna_REC	Bologna	Recycled copper	7823	0	273	29
Geithain_REC	Cologne	Recycled copper	6077	522	221559	27758
Geithain_REC	Dortmund	Recycled copper	7483	477	249526	31262
Geithain_REC	Düsseldorf	Recycled copper	7585	538	284799	35681
Stuttgart_REC	Freiburg	Recycled copper	5937	170	64537	8845
Stuttgart_REC	Karlsruhe	Recycled copper	6391	80	32781	4493
Geithain_REC	Katowice	Recycled copper	6397	591	263900	33063
Stuttgart_REC	Lyon	Recycled copper	10816	609	420806	57676
Bologna_REC	Milan	Recycled copper	15836	261	337821	36118
Geithain_REC	Munich	Recycled copper	9009	435	273479	34263
Stuttgart_REC	Nantes	Recycled copper	6776	1061	459065	62920
Geithain_REC	Paris	Recycled copper	2986	1012	211066	26444
Stuttgart_REC	Paris	Recycled copper	8038	649	333254	45676
Stuttgart_REC	Stuttgart	Recycled copper	12043	1	843	116
Bologna_REC	Turin	Recycled copper	6331	384	198868	21262
Barcelona_REC	Valencia	Recycled copper	5994	394	273433	20675
Bologna_REC	Venice	Recycled copper	9241	169	128154	13702

15.7 Scenarios

15.7.1 Demand fluctuations

Table 15.12: Costs during fluctuating demand unrounded

Costs network	Base case	30% decrease	10% increase	30% increase
Production Fixed	20.153.930	20.153.933	20.153.933	20.153.933
Production Variable	3.140.210	2.198.144	3.414.959	3.840.442
Collection costs	5.718.630	2.597.545	7.284.914	12.862.425
Distribution costs	4.620.960	2.953.550	5.158.404	6.970.126
Total costs	33.633.730	27.903.173	36.012.211	43.826.926

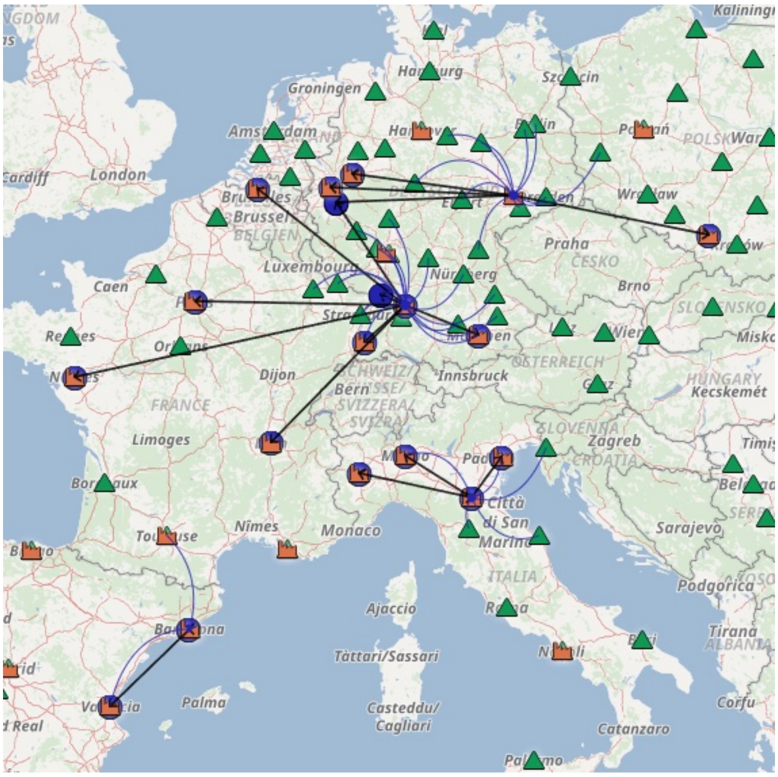

Figure 15.9: Demand decrease of 30%

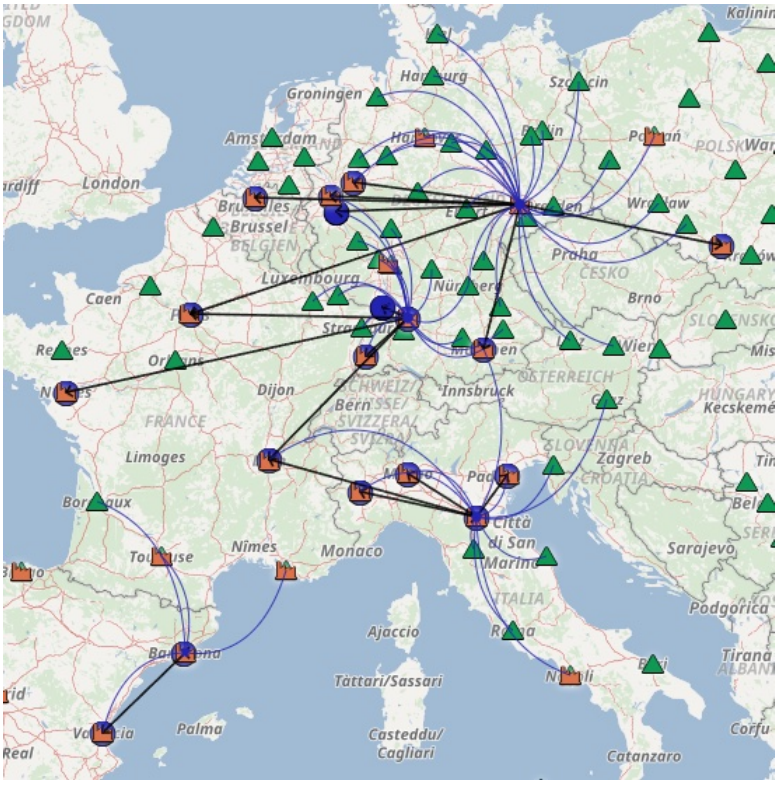

Figure 15.10: Demand increase of 10%

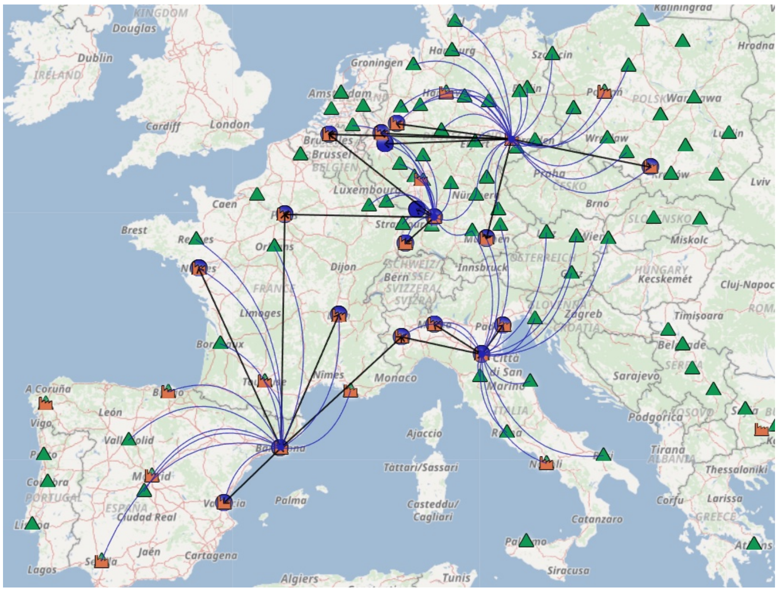

Figure 15.11: Demand increase of 30%

Table 15.14: Costs during fluctuating demand scenario if facility expansion is allowed

Costs expansion network	**Base case**	**30% decrease**	**10% increase**	**30% increase**	**50% increase**	**65% increase**
Production Fixed	20.153.930	20.153.933	20.153.933	24.263.200	26.453.933	30.563.200
Production Variable	3.140.210	2.198.144	3.414.959	3.686.481	4.735.087	4.686.155
Collection costs	5.718.630	2.597.545	7.284.914	8.839.010	11.711.038	14.623.124
Distribution costs	4.620.960	2.953.550	5.158.404	5.882.667	6.285.212	7.479.680
Total costs	33.633.730	27.903.173	36.012.211	42.671.358	49.185.270	57.352.158

Table 15.13: Optimal facilities during fluctuating demand scenario if facility expansion is allowed

30% increase expansion		**50% increase**		**65.5% increase**	
Facility i	C_i	**Facility i**	C_i	**Facility i**	C_i
Barcelona_REC	21.541	Barcelona_REC	28.316	Barcelona_REC	30.822
Bologna_REC	49.584	Bologna_REC	50.000	Bologna_REC	50.000
Geithain_REC	50.000	Dortmund_REC	50.000	Dortmund_REC	50.000
Katowice_REC	26.749	Geithain_REC	50.000	Geithain_REC	33.060
Stuttgart_REC	50.000	Stuttgart_REC	50.000	Katowice_REC	38.026
				Stuttgart_REC	50.000

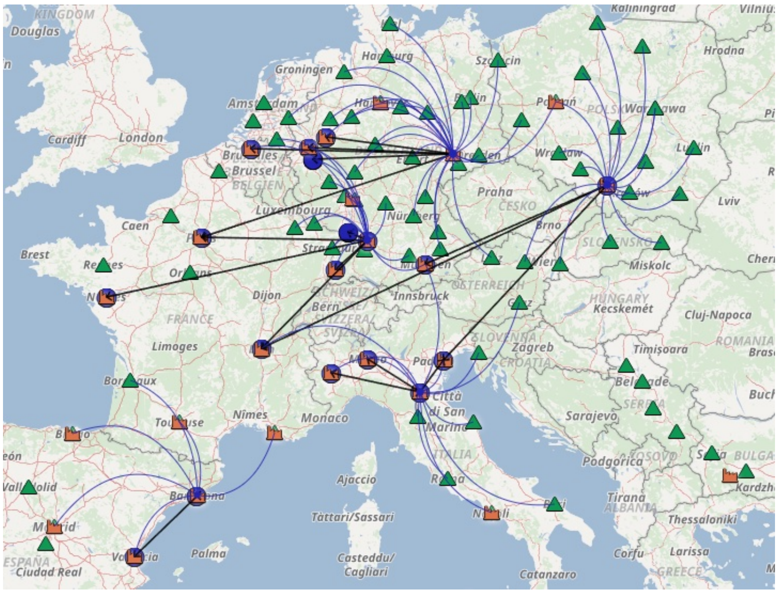

Figure 15.12: Demand increase of 30%, facility expansion network

Figure 15.13: Demand increase of 50%, facility expansion network

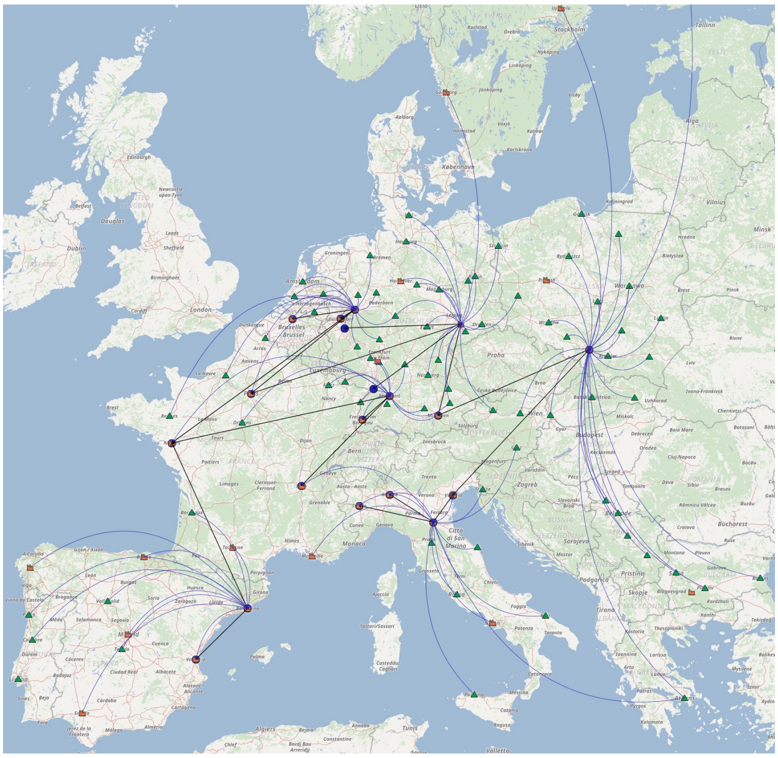

Figure 15.14: Demand increase of 65%, facility expansion network

Table 15.15: Costs comparison of expansion network and relaxed capacity

Costs network	65% increase (expansion network)	65% increase (relaxed capacity)
Production Fixed	30.563.200	20.153.933
Production Variable	4.686.155	5.289.067
Collection costs	14.623.124	17.937.128
Distribution costs	7.479.680	6.472.280
Total costs	57.352.158	49.852.409

Table 15.16: Facility comparison of expansion network and relaxed capacity

65.5% increase (expansion network)		65% increase (capacity relaxed)	
Facility i	C_i	**Facility i**	C_i
Barcelona_REC	30.822	Barcelona_REC	27.423
Bologna_REC	50.000	Bologna_REC	50.748
Dortmund_REC	50.000	Geithain_REC	54.581
Geithain_REC	33.060	Stuttgart_REC	119.157
Katowice_REC	38.026		
Stuttgart_REC	50.000		

15.7.2 Supply decrease

Table 15.17: Costs during decreased supply unrounded

Costs network	Base case	10% decrease	30% decrease	39.5% decrease
Production Fixed	20.153.930	20.153.933	20.153.933	20.153.933
Production Variable	3.140.210	3.140.206	3.140.206	3.122.443
Collection costs	5.718.630	6.409.503	8.544.625	11.135.635
Distribution costs	4.620.960	4.620.958	4.620.958	4.632.204
Total costs	33.633.730	34.324.601	36.459.723	39.044.216

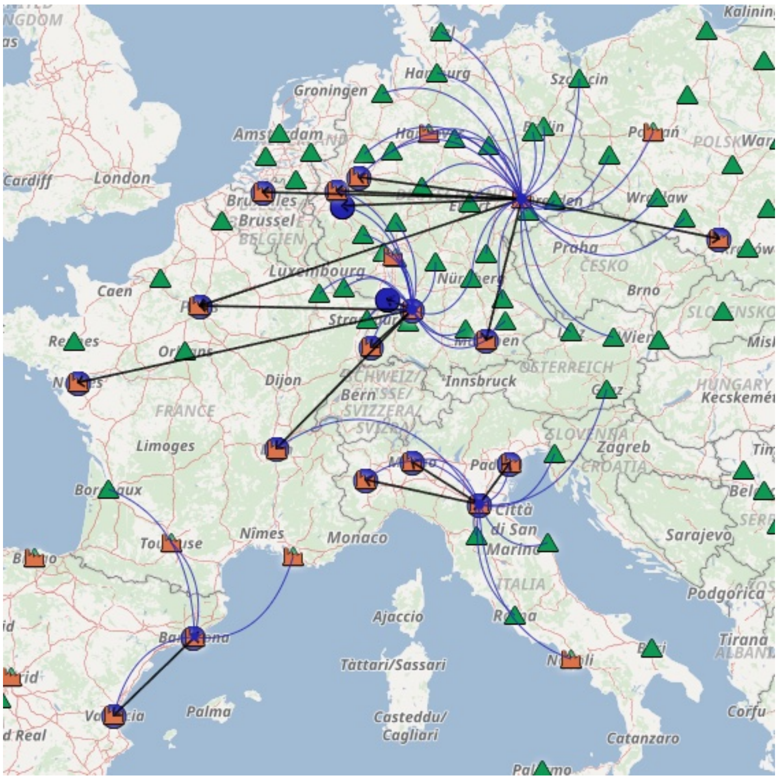

Figure 15.15: Supply decrease of 10%

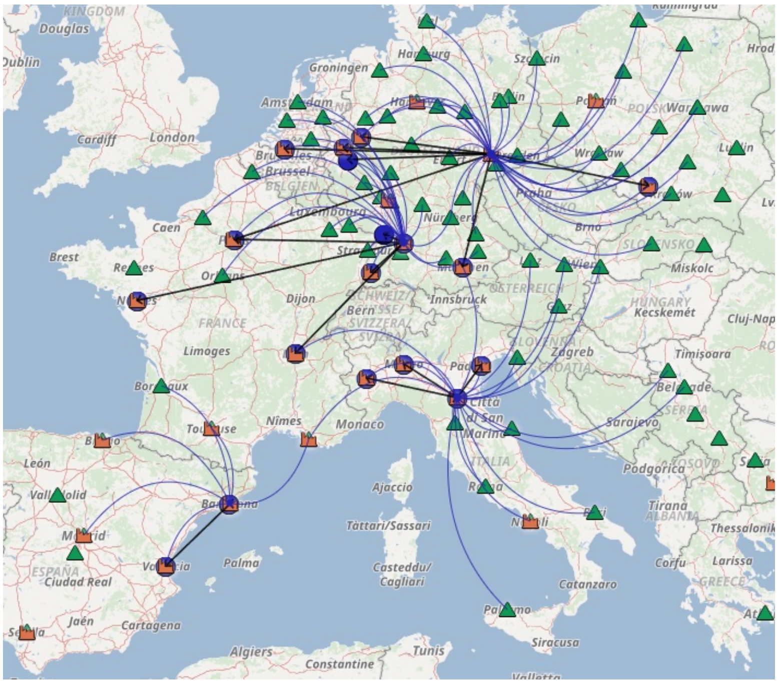

Figure 15.16: Supply decrease of 30%

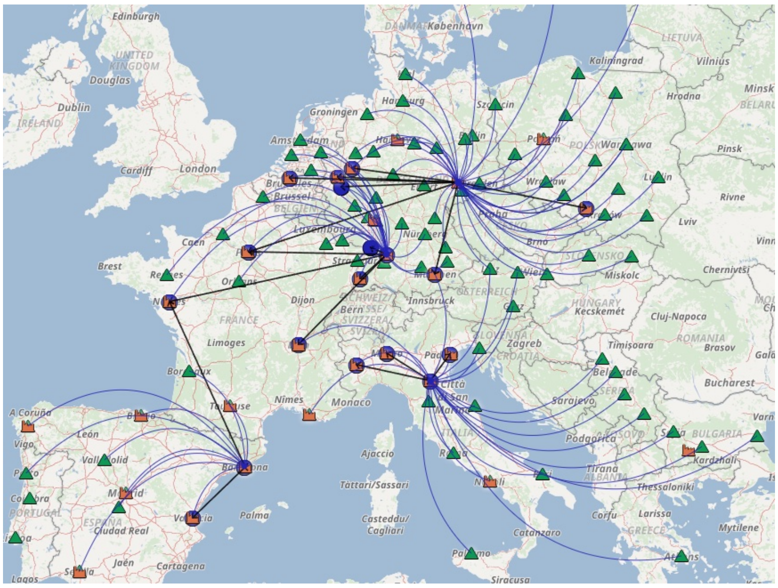

Figure 15.17: Supply decrease of 39,5%

15.7.3 Disruptions

Table 15.18: Cost impact of facility outage, unrounded

Costs Network	Base Case	Stuttgart Outage	Geithain Outage	Bologna Outage	Barcelona Outage
Production Fixed	20,153,930	20,153,930	20,153,930	20,153,930	20,153,930
Production Variable	3,140,210	2,703,500	2,703,500	3,028,000	3,175,000
Collection Costs	5,718,630	11,698,269	10,829,491	9,975,536	6,277,916
Distribution Costs	4,620,960	7,418,367	6,510,605	7,255,375	5,926,409
Total Costs	33,633,730	42,174,066	40,688,526	40,412,841	35,533,255

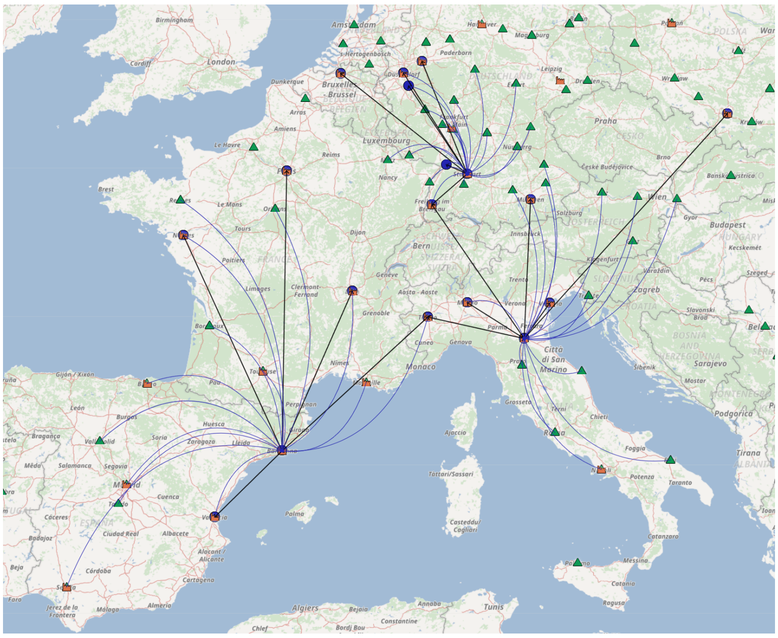

Figure 15.18: Geithain outage

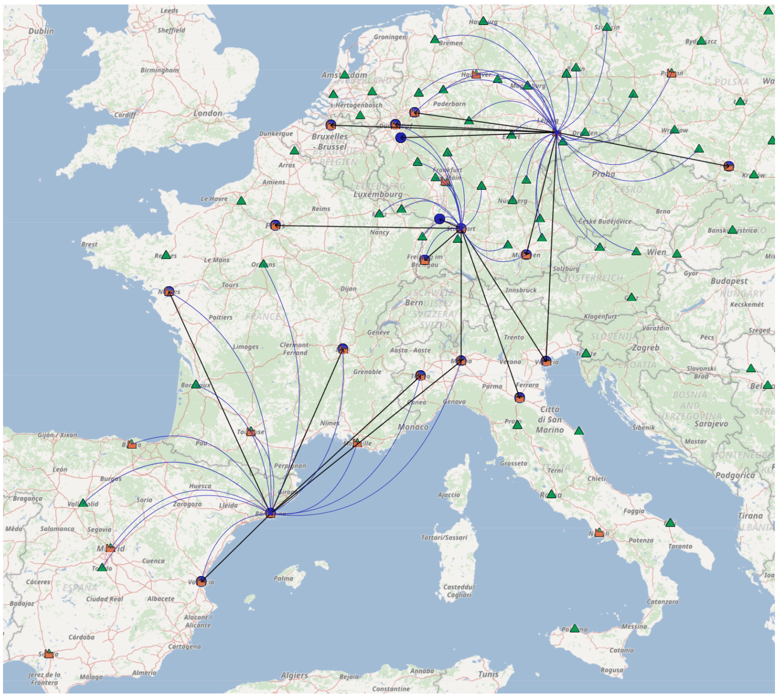

Figure 15.19: Bologna outage

Table 15.19: Costs during local disruption unrounded

Costs	Base Case	Local disruption
Production Fixed	20,153,930	20,153,933
Production Variable	3,140,210	3,122,819
Collection Costs	5,718,630	8,395,355
Distribution Costs	4,620,960	4,758,836
Total Costs	33,633,730	36,430,943

Table 15.20: Cost comparison of different regions unrounded

Costs	Base Case	Southern Europe	Middle Europe
Fixed Costs	20,153,930	20,153,933	20,153,933
Variable Costs	3,140,210	3,817,815	3,760,252
Collection Costs	5,718,630	12,471,266	11,493,099
Distribution Costs	4,620,960	6,830,710	7,349,494
Total Costs	33,633,730	43,273,724	42,756,777

15.8 Personal interview Steef Steeneken: CRM professional, owner of Butter Bridge

This semi-structured interview was conducted by phone on 7 February 2025.

Interview notes:

- The problem of recycling is not solved and is left to the market. Since there is limited market available or business case, nothing happens. No money is provided to companies for recycling;
- Subsidies are small and difficult to obtain. Investors are also cautious as the payback time is large. These are different for all EU countries but it is tied with the EU regulations. Furthermore, it is difficult for start-ups to fund their part as they usually do not have sufficient cash. To be successful a much higher percentage of subsidy is required;
- Recycling becomes difficult as modern devices are hard to disassemble. Disassembly is often not profitable or mixed materials cannot be reused;
- All scrapstreams in Europe have to be identified and it has to be evaluated if it is worth it to invest in a stream;
- Steams are often exported to other countries such as Cambodia and Vietnam because it is cheaper. These streams should be recycled within the EU and should be focused on;
- EU should ban materials being exported. If it is too expensive to recycle materials so they are exported. It is always about money;
- Copper scrap is often going directly to factories, such as Aurubis;
- Companies should not think in product groups, but think how you can win a certain material from a used product instead of making the exact same product again. E.G. Product A is broken, win copper from product and bring back to copper network;
- It is hard to win specific raw materials from mixed materials. Pre-separation is important;
- When producers sell products for more money because it is recycled, it should be brought back to the chain to promote supply of recycled materials. Now this is not the case.