MASTER THESIS

Towards a circular economy of critical raw materials: The case of niobium.

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1. Introduction

Raw materials are needed in any producing industry and are thus crucial to the economy and society. The consumption of finite materials such as metals, fossil fuels and minerals is still on the rise and projected to double within the next 60 years (OECD, 2018). Therefore, a responsible handling of raw materials will become more and more important in the near future (European Commission, 2017). One group of materials whose availability is already problematic are critical raw materials (Isildar et al., 2019; European Commission, 2020a). These materials are characterised by their high importance for the economy and by a high risk regarding their supply. Per definition, supply risk of a material is the risk of an interruption in its supply and depends on the governance and trade policy of the raw material's producing countries. The substitution and recycling of a critical raw material can reduce its supply risk. The higher the economic importance and the higher the supply risk of a material, the higher the criticality of this material (European Commission, n.d.). Some models focusing on assessing the criticality of materials such as the Yale method created by Gradel et al. (2012) add to the two dimensions of supply risk and economic importance a third category, the environmental implications on ecosystems and human beings.

One of the 30 critical raw materials identified by the European Commission (EC) is niobium. It was first classified as a critical raw material in 2011 in the European Union's (EU) initial list of critical raw materials and has been confirmed as such in every subsequent EU list of critical raw materials to date (European Commission, 2020a). Its criticality has increased from a score of 2.8 in 2011 to a score of 3.9 in 2020 (European Commission, 2020a, p. 65). Niobium (Nb) with the atomic number 41 is a chemical element and a ductile soft metal of group 5 of the periodic table. It occurs worldwide, however, in higher concentrations it can be mainly found in Nigeria, the Democratic Republic of Congo, Russia, Australia, Canada, and Brazil. Over 90% of the worldwide reserves are located in Brazil; Brazil and Canada are the only two main producers (Institute for Rare Earths and Strategic Metals, 2021; European Commission, 2014). In fact, 85% of the EU supply of niobium originates in Brazil, in a global context 92% of niobium is sourced in Brazil (European Commission, 2020a, pp. 5 & 8). Moreover, 75% of the Brasilian niobium reserves are located in a single mine in Minas Gerais, operated by CBMM (Companhia Brasileira de Metalurgia e Mineração [CBMM], 2019; Dolganova et al., 2020). The supply risk of niobium is based on its high concentration of production in one country, its production being mainly performed by one company, an uncertain recycling rate and a moderate substitutability (Royal Society of Chemistry, 2021; Deloitte, 2015; European Commission, 2014; U.S. Geological Survey, 2015).

Niobium is widely used as a strengthening component for high strength low alloy (HSLA) stainless steels in the form of ferro-niobium (FeNb). Ferro-niobium only contains 65% of pure niobium and accounts for 89% of the worldwide niobium demand (Minerals UK, 2011; Alves & dos Reis Coutinho, 2019). A low concentration of 0.01 to 0.1% of niobium can already significantly enhance the mechanical strength of steel (Institut für seltene Erden und strategische Metalle, n.d.; PROMETIA, 2017). The three main use cases for niobium are infrastructure (45%), energy (17%), and mobility (23%) (European Commission, 2020a). As niobium strengthens stainless steel, it is widely used in the construction industry for beams and girders for buildings, bridges, and other infrastructure. In the energy sector it is mostly used for the construction of oil and gas pipelines (Royal Society of Chemistry, n.d.). However, it is recently also increasingly being implemented in the clean energy sector, e.g., to enhance the performance of solar cells (Baktash et al., 2020; Nunes et al., 2020). Thirdly, niobium is used in the mobility sector, especially in the automotive industry in HSLA steel as a light-weight strengthening material for car parts (European Commission, 2014; Golroudbary et al., 2019).

Finally, superalloys account for approximately 8% of the global niobium demand. Due to its high melting point, it is used in superalloys at a concentration of 5% for thermal turbines, jet engines, rockets, and the nuclear energy industry (European Commission, 2014; Alves & dos Reis Coutinho, 2019; Kurlyak, 2016; Tkaczyk et al., 2018).

Besides being a crucial material to the economy, the use of niobium holds further issues. Niobium is one of the critical raw materials with the highest forecasted demand growth, second only to lithium (European Commission, 2020a) and according to the European Commission its demand will keep rising at an annual growth rate of 8% (European Commission, 2014; European Commission, 2020a). Since 2000, the trade of niobium has already nearly tripled (Dolganova et al., 2020). However, the recycling rate remains relatively low at 20 to 30% (Royal Society of Chemistry, 2021; European Commission, 2014). Additionally, no valid substitute for niobium exists as possible substitute materials imply increased costs and/or a decreased performance (European Commission, 2014, Tkaczyk, 2018). Various studies show that along the whole supply chain of the production of niobium, from mining, processing, production to consumption and finally end of life, greenhouse gases (GHG) are emitted, and the environment is negatively impacted (Golroudbary et al., 2019; Ibn-Mohammed et al., 2016).

In sum, niobium is classified as a highly critical raw material for bearing a high supply risk, being a crucial raw material for various major economic sectors and the negative environmental implications of niobium production.

The objective of this thesis is to investigate an approximation to a circular economy for the use of niobium to analyse how the criticality and the negative environmental impact of the metal can be mitigated. The main research question which shall be answered is:

> *To what extent does the implementation of a circular economy strategy for niobium-containing high-strength low-alloy steel under varying conditions impact niobium's criticality for the European Union as well as the generation of waste and emissions along the supply chain?*

To answer this question, an Input-Output analysis and a criticality assessment integrated in a scenario analysis will be conducted.

1.2 Theoretical and practical contributions

The aim of this thesis is to establish possible future scenarios of a circular use of niobium in HSLA steel to analyse how the criticality of the material is impacted under varying conditions. In these scenarios, the end of life products of the niobium supply chain will be the source of new niobium-containing high-strength steel. The practical contribution consists of elaborating a feasible and sustainable solution for the current issues related to the niobium supply chain and to meet the rising demand for the material in the European Union over the next decades (European Commission, 2014). The focus lies on creating substantiated forecasts of material, waste, and emission flows along the niobium supply chain for the near future to elaborate a feasible supply chain management.

Three different main scenarios based on current developments will be analysed to show different possible future outcomes. These scenarios consider variables which impact the companies operating in the niobium supply chain: a supply shortage of niobium, the introduction of a new recycling technology and governmental policies. The first scenario demonstrates how a sudden shortage of niobium due to an interruption of the niobium supply chain in the processing stage impacts the criticality of niobium. This scenario builds on the already discussed fact that niobium is as a raw material with an exacerbating criticality (Royal Society of Chemistry, 2021; European Commission, 2014; European Commission, n.d.). The European Commission classifies especially the stage in which ferro-niobium is processed as the most critical step to cause a bottleneck for the European Union (European Commission, 2020a). Therefore, it will be assumed that in this stage a halt of exports from Brazil where the majority of ferro-niobium is produced (Alves & dos Reis Coutinho, 2019; Dolganova et al., 2020) occurs. The second scenario examines the implementation of a technological innovation which leads to a higher recyclability of niobium. In the third scenario, the European Union will implement a circular economy strategy. Policies will obligate companies in the niobium supply chain to work towards a circular economy and source more raw materials from secondary sources. This scenario builds on the "European Green Deal", the EU's answer to the growing environmental and climate-related challenges. Part of the Green Deal measures is the implementation of policies to mobilise the economy towards a climate neutral and circular economy (European Commission, 2019).

As a contribution to theory, this thesis adds to the currently existing literature on life cycle assessments of the niobium supply chain (Dolganova et al., 2020; Alves & dos Reis Coutinho, 2019) by assessing how the current challenges related to niobium production may evolve and be addressed in the future. This thesis will not only establish one theoretical forecast but explore three possible future scenarios. In these scenarios, the potential impact of different driving variables for a more circular use of niobium in the European Union will be analysed, the material flows, and emissions related to the supply chains will be calculated. As a contribution to practice, the feasibility and impact of a circular use case of niobium on its criticality under varying circumstances will be evaluated and concrete recommendations for action for companies and European governments will be formulated.

2. Literature review

2.1 Critical raw material classification

One definition of CRMs which is predominantly used in current literature is the definition by the European Commission (Isildar et al., 2019; Massari & Roberti, et al., 2013; Glöser et al., 2015), which defines critical raw materials as follows: “Critical raw materials are those which display a particularly high risk of supply shortage in the next 10 years, and which are particularly important for the value chain.” (European Commission, 2011, p. 12). This definition includes two dimensions by which CRMs can be classified, supply risk and economic importance (European Commission, 2011). According to the European Commission (2011), supply risk (SR) is the risk of a disruption of the supply of a material and is influenced by various factors, among them the global supply concentration, substitutability, import reliance, recycling rate, country governance of the country of origin and possible trade restrictions. The economic importance (EI) of a material reflects to what extent a material is essential for an economy, measured by the value added of sectors using the material (European Commission, 2020a). On a corporate level, the economic importance can be measured by the revenue that is impacted by the material (Graedel et al., 2012).

With these two criteria a criticality matrix is established which is a common tool of raw material criticality assessment. By means of the matrix, both supply risk and economic importance are quantified, and critical raw materials can be ordered in the two-dimensional matrix instead of elaborating a less informative hierarchical risk ranking (Glöser et al., 2015). The threshold for criticality lies at a value of 2.8 for economic importance and 1 for supply risk. When a material scores higher than these threshold values in both dimensions, it is classified as critical. Niobium scores high in both dimensions (EI = 6.0; SR = 3.9) in comparison to other raw materials and is therefore classified as one of the most critical raw materials for the European Union, as can be seen in the following figure (European Commission, 2020a).

In addition to the first two dimensions, a third dimension has gained importance considering critical raw materials, which is environmental implications. Firstly, CRMs are essential for sustainable products and green technology, e.g., for renewable energy and emission-free vehicles, and therefore important in order to reach carbon neutrality (European Commission, 2020a; Isildar et al., 2019). Secondly, the sourcing and processing of CRMs is often related to negative environmental impacts (Graedel et al., 2012; Nuss et al., 2014). Graedel et al. (2012) have elaborated a criticality assessment framework for metals which develops the two-dimensional matrix and considers environmental impacts as a third dimension which has to be taken into account when evaluating the criticality of raw materials. The result is a three-dimensional criticality space with the three axes supply risk, economic importance or as Graedel et al. (2012) phrase it, vulnerability to supply restriction, and environmental implications in which critical raw materials can be positioned (Graedel et al., 2015). This framework addresses not only economic and geopolitical issues but also the environmental implications of using a certain material. The environmental implications are calculated by adding up two damage categories, human health and ecosystems, from the mining stage of a metal to the manufacturing of a first intermediate product which is then used in most end products.

2.4 Circular economy and urban mining for critical raw materials

The central concept in this thesis is circular economy, an economic system in which "the economic and environmental value of materials is preserved for as long as possible by keeping them in the economic system, either by lengthening the life of the products formed from them or by looping them back in the system to be reused" (den Hollander et al., 2017, p. 517). In a circular economy no more waste is produced as all materials are infinitely reused (den Hollander et al., 2017). Opposed to a linear model, in which products are produced, used, and discarded at their end of life, in a circular economy, products are designed in a way that they can be either repaired, reused, returned, or recycled at their end of life (World Economic Forum, 2014). The European Commission has lately published a circular economy action plan in which they strive for a more sustainable but also more competitive European economy by implementing a circular economy. In a circular economy scenario not only the generation of waste is avoided but also the emission of greenhouse gases can be reduced, and economic growth is decoupled from the use of new resources (European Commission, 2020b). In case of critical raw materials, implementing the principles of the circular economy hold a high potential of reducing the dependency on present suppliers and the exploitation of new resources, which has already been highlighted in various recent articles (El Wali et al., 2019; Araya et al., 2020; Ottoni et al., 2020).

Regarding circular economy, the concept of urban mining has become central. Urban mining is a circular economy strategy according to which raw materials are sourced from already existing objects and infrastructure (German Environment Agency, 2020; Ottoni et al., 2020, Tesfaye et al., 2017). Especially durable goods such as cars, technical devices, buildings, and landfill sites are used as "urban mines" to serve the demands of the economy (German Environment Agency, 2020; Giurco et al., 2014). Key studies dealing with urban mining have already emphasized the potential benefits of urban mining, especially to master the rising amount of e-waste (Zeng et al., 2018, Tesfaye et al., 2017) and in this context also to recover critical raw materials from this waste stream (Ottoni et al., 2020). Another advantage of urban mining is the ability to create forecasts of future material flows considering the life span of the goods materials can be sourced from. Through a preceding analysis, products can be efficiently used at their end-of-life stage instead of entering waste management (German Environment Agency, 2020). Due to urban mining, a circular product flow is achieved not by recycling the whole product, but by recovering raw materials from the product at its end-of-life and reintroducing these materials to the market (Ottoni et al., 2020; Tesfaye et al., 2017).

As previously mentioned, the demand for niobium is on the rise (European Commission, 2014) while the criticality regarding its supply and environmental impact is increasing (European Commission, 2020a). In order to meet this rising demand for niobium and reduce the dependency on suppliers and the environmental impact, urban mining can be a feasible strategy as high-strength steel containing niobium is used in goods which are commonly used for urban mining, e.g., infrastructure such as buildings and pipelines or cars (German Environment Agency, 2020; Giurco et al., 2014). Furthermore, most of the niobium-bearing goods show a relatively stable lifespan, e.g., cars with an estimated lifespan of 10 years or pipelines with an estimated lifespan of 60 years (Cunningham, 1998). This enables a more reliable and accurate forecasting of future material streams in the niobium supply chain.

3. Research design

3.1 Data collection

As already pointed out by various articles, data on the supply chain and life cycle of niobium and ferro-niobium is still scarce (Dolganova, 2020; Alves & dos Reis Coutinho, 2019). Therefore, data on energy consumption, greenhouse gas emissions, material use and waste occurring along the niobium supply chain will be retrieved from various sources, for instance from data provided by CBMM, the biggest producer of niobium technology and various scientific papers. To ensure the accuracy of the data included it will be cross-checked from various sources. The import numbers of ferro-niobium into the European Union are taken from PROMETIA's factsheet on niobium and tantalum (PROMETIA, 2017). For the criticality assessment data will be acquired via the ESTAT database which includes the necessary data on the sectors using niobium products in the European Union. Data regarding the shares of the sectors in niobium consumption as well as data on the trade variables and substitution index will be taken from the EC's reports on CRMs. Finally, data on the World Governance Index will be retrieved from World Bank. A detailed overview of all sources for each variable can be found in Appendix I.

3.2 Data analysis

This thesis integrates an input-output analysis and a criticality assessment into a scenario analysis. The scenario analysis is a widely used tool to forecast the economy's development in a defined period of time. Within this framework, the future is constructed in a systematic way (Swart et al., 2004). It is a central planning tool for companies to observe developments relevant for their industry or specifically one company to prepare for an uncertain future (Wack, 1985). Different scenarios manifest varying images of the future described by a set of possible outcomes (Pallottino et al., 2005). Scenarios include the definition of a problem and current conditions, the identification of processes that trigger change and assumptions on how problems can be solved (Swart et al., 2004). In this thesis, each scenario investigates a different process which stresses the need for or catalyses circular economy. Hence, a comprehensive view on possible future developments for a circular use case of niobium can be established and consequently lead to new insights to finally construct solutions on how the criticality of niobium may be mitigated.

To explore the possibility of establishing urban mining as a strategy to improve the current environmental issues related to the niobium supply chain the input-output (I-O) model method will be applied. I-O models have already been used in numerous ways to investigate approaches related to circular economy, e.g., for industrial symbiosis (Yazan & Fraccascia, 2020) or for life cycle impact assessments of recycled materials (Shi et al., 2019), and are a common method to analyse supply chains (Wang et al., 2020). In I-O models, material flows between different sectors of one economy are aligned and interdependencies between the sectors can be analysed (Leontief, 1973). In this paper, the approach of an Enterprise Input-Output (EIO) model will be adapted. The EIO model is a type of I-O models which serves as an accounting and a planning tool that outlines the flows of material, energy, and water as well as monetary flows of production on a company-level, a supply chain-level and for various supply chains. Moreover, EIO models facilitate the analysis of environmental impacts occurring along the supply chain by modelling not only the inputs and primary outputs but also the waste streams and emissions produced in different stages (Yazan & Fraccascia, 2020; Albino & Kühtz, 2004). Here, EIO models will be established to model circular economy cases for the niobium supply chain in different scenarios.

3.2.1 EIO modelling

To achieve this model, the material flows between the sectors will be entered into an enterprise input-output table to compute intermediate flows, final demand, external resources needed in the production process as well as waste and by-products emitted in the process. A basic physical input-output table consists of four main components, two matrices and two vectors, in which n equals the number of sectors. In the intermediate flow matrix Z ($n*n$) the output from one sector i becomes the input for another sector j. The second component is the final demand vector f ($n*1$) which reflects the final demand of sector i. The technical coefficients matrix A ($n*n$) manifests the required main output quantity of sector i to produce one unit of main output of sector j. The total output vector x ($n*1$) condenses the total output of sector j. In the calculation Z, f and x are estimated in order to calculate A (Leontief, 1973).

Table 1: Example of a physical Input-Output table, own depiction

Intermediate Flows Matrix Z	unit	P1: Process 1	P2: Process 2	P3: Process 3	Final Demand f	Total Output x
P1: Process 1	t	z_{11}	z_{12}	z_{13}	f_1	x_1
P2: Process 2	t	z_{21}	z_{22}	z_{23}	f_2	x_2
P3: Process 3	t	z_{31}	z_{32}	z_{33}	f_3	x_3

The EIO table is complemented by further components to enable a sustainability analysis; the primary input coefficient matrix R (s*n where s is the number of primary inputs), the total primary input use vector r (s*1), the waste and by-products matrix W (m*n where m is the number of wastes and by-products) and the total waste and by-product emission vector w (m*1). R contains the quantities of the primary inputs k, these are raw materials, natural resources and energy resources needed to produce one unit of the main output j. W includes the quantities of secondary products l, waste and by-products, generated in the production of main product j. Vector r denotes the quantity of a primary input k needed to produce one unit of the main output and vector w defines the quantity of secondary product l emitted (Yazan & Fraccascia, 2020).

Table 2: Example of an Enterprise Input-Output table, own depiction

Intermediate Flows Matrix Z	unit	P1: Process 1	P2: Process 2	P3: Process 3	Final Demand f	Total Output x
P1: Process 1	t	z_{11}	z_{12}	z_{13}	f_1	x_1
P2: Process 2	t	z_{21}	z_{22}	z_{23}	f_2	x_2
P3: Process 3	t	z_{31}	z_{32}	z_{33}	f_3	x_3

Primary Resources Matrix R	unit	P1: Process 1	P2: Process 2	P3: Process 3	Total Primary
R1: Primary input 1	t	r_{11}	r_{12}	r_{13}	$\sum r_{1j}$
R2: Primary input 2	t	r_{21}	r_{22}	r_{23}	$\sum r_{2j}$
R3: Primary input 3	t	r_{31}	r_{32}	r_{33}	$\sum r_{3j}$

Waste & By-products Matrix W	unit	P1: Process 1	P2: Process 2	P3: Process 3	Total Waste W
W1: Waste 1	t	w_{11}	w_{12}	w_{13}	$\sum w_{1j}$
W2: Waste 2	t	w_{21}	w_{22}	w_{23}	$\sum w_{2j}$

3.2.2 Criticality assessment

In a final step, the criticality of niobium for each scenario will be assessed, to find an answer to the central research question by evaluating how the implementation of a circular economy strategy impacts the criticality of niobium under varying circumstances. For this purpose, the EC's methodology will be adopted, considering the dimensions economic importance and supply risk and focussing on the European Union's market. The evaluation of the supply risk and of the economic importance will be executed as follows:

Economic Importance (EI)

To calculate the Economic Importance, raw material end-use applications are assigned to the EU's manufacturing sectors, which are grouped at the two digit level of NACE (Nomenclature of Economic Activities) Rev.2. The Gross Value-Added (GVA) of each application sector is then weighted by the application share of the respective sector and added up. At first, the unscaled Economic Importance is calculated by multiplying the sum of the weighted GVAs ($Total\_GVA_w$) with the substitute index for EI (SI_{EI}).

$$EI_{unscaled} = Total\_GVA_w \; x \; SI_{EI}$$

In order to obtain the scaled EI, the unscaled EI score is divided by the highest value of the manufacturing sector NACE Rev.2 at the 2-digit level. The result is then multiplied by 10 to obtain the value for EI on a scale from 1 to 10.

$$EI_{scaled} = EI_{unscaled} \, / \, GVA_{max} \; x \; 10$$

Supply Risk (SR)

The supply risk can be calculated for two life-cycle stages, the extraction stage and the processing stage. As the EC assesses the processing stage as the more critical stage for niobium, only this stage will be taken into account for SR calculation. The first step to obtain the value for SR, is to multiply the squared share of production (SOP) of each producing country with the scaled WGI of each producing country (WGI_{scaled}) which can be obtained from the World Bank. The result of this multiplication is the "contribution to the Herfindahl-Hirschmann-Index WGI (HHI_{WGI}). This calculation is conducted with SOP both on global (GS) and EU (EU) supply level for each production country.

$$(HHI_{WGI})_{GS} = (SOP_{GS})^2 \; x \; WGI_{scaled}$$

$$(HHI_{WGI})_{EU} = (SOP_{EU})^2 \; x \; WGI_{scaled}$$

The HHI_{WGI} is then multiplied with the trade variable (t) which reflects the component of trade restrictions such as export taxes, export quotas and export prohibitions, for each production country. The variable t is based on OECD database of export restrictions and EC's database on trade agreements.

$$(HHI_{WGI\text{-}t})_{GS} = (HHI_{WGI})_{GS}\ x\ t$$

$$(HHI_{WGI\text{-}t})_{EU} = (HHI_{WGI})_{EU}\ x\ t$$

The sum of the $HHI_{WGI\text{-}t}$ of the individual production countries equals the total $HHI_{WGI\text{-}t}$.

The supply risk is then calculated as follows:

$$SR = [(HHI_{WGI\text{-}t})_{GS} \text{ x } IR / 2 + (HHI_{WGI\text{-}t})_{EU} \text{ x } (1 - IR / 2)] \text{ x } (1 - EOL_{RIR}) \text{ x } SI_{SR}$$

IR is the import reliance, based on to what extent the EU relies on the import of a certain material. SI_{SR} refers to the substitute index for supply risk and EOL-RIR stands for end-of-life recycling input rate which is used as the recycling indicator in this framework. In contrast to the recycling rate which measures the amount of wastes recycled in relation to waste generated, the EOL-RIR or recycling input rate measures how much of a material's input into the production system comes from secondary raw materials sourced through recycling of end-of-life products (European Commission, 2020a).

5. Discussion of results

In each scenario the supply risk of niobium as well as environmental implications, i.e., emissions and waste generated along the supply chain, could be mitigated in comparison to the linear case. In the resource based scenario, the supply risk could be reduced by 0.5 points, from 3.9 to 3.4. However, niobium's overall criticality is still far from an uncritical state in this scenario. Also, the quantity of all by-products and emissions could be reduced by at least 11.59% due to the increased recycling input rate triggered through the bottleneck scenario. This reduction implies a relief for the direct environment of the niobium mine due to the reduction of landfill waste, such as tailings and overburden (Dolganova et al., 2020) as well as for the global environment due to the reduction of GHG emissions.

In the second scenario which analysed the introduction of an ICP-MS technology which enables a better sorting and recycling of steel scrap from ELVs, a maximum recycling input rate of 20.96% was calculated due to the limiting factor of available ELVs as urban mines. With a recycling rate of 100% of all available HSLA steel in ELVs a recycling input rate of 20.96% can be achieved and the supply risk can be reduced to 3.1 in the year. At a recycling rate of 85%, the EOL-RIR lies at 17.82% and the supply risk drops to 3.2 while at a recycling rate of 70% of all secondary HSLA steel available the EOL-RIR is reduced to 14.67% and the supply risk accounts for 3.4. Also, the quantity of by-products generated along the supply chain was lowered, for instance, GHG emissions declined by 18.91% (100% recycling rate), 16.07% (85% recycling rate) and 13.24% (70% recycling rate). Furthermore, the amount of tailings and overburden, the two by-products of the niobium supply-chain which cannot be reused and are discarded in landfill, could also be reduced by respectively 7.4 tonnes and 4 tonnes (100% recycling rate) 6.3 and 3.4 tonnes (85% recycling rate) and 5.2 and 2.8 tonnes (70% recycling rate) per 100 tonnes of HSLA steel produced.

Finally, the government based scenario had the biggest impact on niobium's supply chain and criticality, lying furthest in the future and implying the highest recycling input rate of all scenarios with an EOL-RIR of 30%. According to the EIO modelling in this scenario the GHG emissions are reduced by 27.06% which implies a total reduction of 50 tonnes of $CO_{2\text{-eq}}$ per 100 tonnes of HSLA steel produced. Tailings and overburden are respectively lowered by 10.7 tonnes and 5.8 tonnes. In the government based scenario, the supply risk drops to a score of 2.75. Even though this result manifests a significant reduction of niobium's supply risk by 1.15

points, niobium remains a critical raw material in this scenario, surpassing the criticality threshold of 1 by far (European Commission, 2020).

The main limitation for this thesis was the lack of current data which takes into consideration the latest developments caused by the Covid-19 pandemic in 2020 and 2021. Due to the resulting effects on the economy and the sectors which use niobium-containing HSLA steel a change in the demand in the European Union is highly probable. Furthermore, Brazil's WGI might have changed due to the political issues which Brazil has been facing as a result of the Covid-19 pandemic which has had a significant impact on the country's economy, society and politics (Zilla, 2020, Santander Trade, 2021, BBC News, 2021). However, newer data which covers the time period of 2020 and 2021 is not yet available and could therefore not be included to reflect on how these developments might have had an impact on niobium's criticality.

6. Conclusion

The central goal of this thesis was to assess how the adoption of a circular economy strategy impacts niobium's criticality as well as the generation of waste and emissions along the supply chain. To find an answer to this question three scenarios for different possible future paths were established to explore imminent developments which impact the niobium supply chain and trigger circular economy. For each scenario a different recycling input rate was assumed which was then incorporated in the EIO analysis. The results of the EIO model showed how the amount of inputs, outputs and by-products changed in each scenario. In a final step, the supply risk was calculated for each scenario according to the EC's criticality assessment framework to evaluate, how circular economy affected niobium's criticality under differing conditions.

In the theoretical framework, after having defined the concept of CRMs, the issues occurring along the niobium supply chain besides supply risk and economic importance were analysed and broken down into two categories: environmental impact and social-economic and geopolitical issues. Firstly, along the entire supply chain, especially during mining of niobium and production of HSLA steel, the environment is negatively impacted due to the generation of wastes which cannot be recycled or reused and the emission of GHGs (Dolganova et al., 2020; Golroudbary et al., 2019; Globe Metals and Mining, 2020; Alves & dos Reis Coutinho, 2019). Secondly, Brazil, the producer of over 90% of all niobium products worldwide, is facing grave economic, social and political issues which were further aggravated by the Covid-19 pandemic since 2020 (Zilla, 2020, Santander Trade, 2021, BBC News, 2021). Additionally, the Brazilian government does not take sufficient measures to protect the environment and to thereby lessen the environmental impact of the niobium supply chain (Caldeira Rodrigues, 2021; Nadibaidze, 2020; Hanke Vela, 2020). As a solution to the increasing criticality of niobium and the issues related to its supply chain, an urban mining strategy was explored. Niobium-containing HSLA steel is mostly used in long-lasting products, in vehicles, infrastructure and pipelines, which are viable urban mines due to their stable life-span and durability (German Environment Agency, 2020; Giurco et al., 2014). Therefore, urban mining was deemed a feasible strategy to tackle the current challenges related to the production of HSLA steel.

While establishing the scenarios it became clear that the main limiting factors for the production of secondary HSLA steel are the lack of a recycling technology which enables adequate sorting of different steel types and the currently limited amount of available urban mines. Firstly, most niobium containing HSLA-steel is recycled, however, due to the lack of sorting, it gets diluted in the recycling process when it is melted together with other steels. As a result, the niobium concentration declines, and the steel loses its strengthening properties (Graedel et al., 2011; Kurlyak, 2016; Deloitte, 2015; Ohno et al., 2015). Secondly, as most buildings and pipelines containing HSLA steel will not become urban mines for the next decade, the only urban mines currently available are ELVs. Consequently, the potential amount of secondary HSLA steel is limited to the amount of HSLA steel in ELVs (Kurlyak, 2016, Cunningham, 1998; Jansto, 2021). Furthermore, the lack of a policy framework to promote the market for secondary CRMs in the European Union was identified as another contributing factor to the low functional recycling rate of niobium (McDowall et al., 2017; Domenech & Bahn-Walkowiak, 2019). Finally, the possibility of a bottleneck due to trade restrictions imposed by the Brazilian government against the European Union was identified as the main current threat to the stability of the niobium supply chain (Nadibaidze, 2020, Hanke Vela, 2020; Caldeira Rodrigues, 2021; Korinek & Kim, 2010). Based on these factors, three scenarios were adopted to respectively explore how the implementation of a new recycling technology, the adoption of circular economy policies as part of the European Green Deal and a sudden bottleneck due to trade restrictions would lead to an increased EOL-RIR and impact the niobium supply chain.

These recycling input rates were then incorporated in the EIO analysis. The results from EIO models have shown that in each scenario the amount of inputs needed as well as waste and emissions generated could be decreased which is due to the strongly reduced resources consumed in the recycling process in comparison to primary production. The further ahead the scenario lies in the future, the higher the recycling input rate and thus, the lower the emissions and wastes created along the supply chain. Therefore, the adoption of an urban mining strategy leads to less tailings and overburden having to be disposed of on a landfill site, which lightens the negative environmental impact on the direct environment of the mine. Also, the generation of CO_2 and other GHGs is significantly decreased when an urban mining strategy is implemented due to which the contribution of the niobium production to climate change on a global level can be reduced.

In a final step, the supply risk and, thus, the change in niobium's criticality was evaluated for each scenario adopting the EC's framework for criticality assessment. In all three scenarios a significant reduction of the supply risk could be observed due to the increase in EOL-RIR. The higher the recycling input rate, the lower the supply risk and the lower niobium's overall criticality. Therefore, the lowest criticality could be achieved in the government-based scenario which implied the highest EOL-RIR of 30% and a decrease in supply risk of 1.15 points from

3.9 in the linear case to 2.75 in the circular model. These results show that the adoption of a circular economy strategy has a strong mitigating impact not only on the environmental implications, but also on the criticality of niobium. Also, through circular economy, the European Union becomes less dependent on Brazil as the main producing country of ferro-niobium. However, even a recycling input rate of 30% is not sufficient to completely offset the criticality of niobium as the criticality threshold of 1 for SR (European Commission, 2020a) is still exceeded.

This thesis contributes to academia by exceeding the scope of the current state of research on niobium which mainly focuses on life cycle assessments (Dolganova et al., 2020; Alves & dos Reis Coutinho, 2019) but rarely goes beyond the end-of-life state of products containing niobium to look for future strategies to improve the status quo (Golroudbary et al., 2019). Furthermore, the need for further research on CRMs is emphasized, as recycling as the only strategy will not solve the issues related to the niobium supply chain. Therefore, future research on the topic of CRMs might focus on the two main measures which can be taken to reduce criticality, recycling and substitution (European Commission, 2020a). In this thesis it has been manifested that a high EOL-RIR is necessary to offset the criticality of niobium. Consequently, further research on strategies, technologies and innovation which lead to a higher recycling input rate is necessary. In addition to recycling, research on possible substitutes for niobium as a strengthening component could further contribute to secure the production and supply of HSLA steel. Currently there is no viable alternative to niobium as all potential substitutes either involve higher costs and/or a lower performance than niobium. However, substitutes are important contributors to decrease a material's criticality and should therefore not be overlooked in research.

Additionally, this thesis constitutes a call for action for both politics and the economy. Until now, little effort has been made to decrease niobium's criticality. Legislators in the European Union should make use of possibilities to implement policies in the context of the European Green Deal to promote the market of secondary CRMs in the EU and thus lower the dependence on producing countries of primary CRMs. In the light of the high projected demand growth for niobium, a decrease in EI below the criticality threshold of 2.8 is extremely unlikely (European Commission, 2020a). Therefore, the legislator should focus on strategies which aim at decreasing SR and help prevent a bottleneck scenario and ensure a stable supply. Also, with the establishment of policies the legislator would not only protect economic growth but also the environment by decreasing the emission of GHGs and the production of wastes as this thesis has highlighted. Thus, a contribution towards the achievement of the United Nation's sustainability goals could be made.

The results have shown that urban mining is a viable strategy to both reduce niobium's criticality and mitigate its supply chain's negative impact on the environment. However, to achieve this goal, joint efforts of the companies acting in the niobium supply chain and the government are needed as not just the government is responsible to ensure the supply chains of CRMs. Also, individual companies should look for strategies which lower their vulnerability to a decline in supply and invest in innovations which increase the recycling input rate of niobium-containing HSLA steel. Furthermore, these companies could lower their carbon footprint by adopting a circular economy strategy for their raw materials.

In conclusion, urban mining is a feasible and sustainable strategy to positively impact niobium's criticality and mitigate its supply chain's environmental implications. Additionally, the European Union would become less dependent on Brazil, a country which faces strong economic, environmental, social and political issues and thus preventing a shortage of supply. However, joint efforts of academia, politics and companies are needed to reduce the supply risk as well as the environmental implications. Even though circular economy has a high potential in all scenarios to reduce SR, an even higher recycling input rate or a mix of a recycling and a substitution strategy is necessary to reduce SR below the criticality threshold of 1 and offset niobium's criticality.