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MASTER'S THESIS

ECONOMIC AND ENVIRONMENTAL ASPECTS OF NIOBIUM RECYCLING

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ABSTRACT

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The issues of sustainable consumption and usage of raw materials attract more and more attention among business, academia, and governmental structures worldwide due to the increasing pressure on the environment. Besides, the situation is being reinforced by the growth of population and constant increase in level of life standards, which lead to a further extension of a demand for materials. On the other hand, the modern economy strongly depends on access to raw materials. Therefore, in order to secure it from possible supply shortages and ensure opportunities for further development, different countries have adopted lists of critical raw materials. For instance, in the EU the materials have been selected taking into risks with regard to access to it and its economic importance. Thus, the development and establishment of sustainable consumption patterns are of high importance. Materials recycling represents a promising way and may be viewed sustainable from economic, environmental, and social viewpoints.

The purpose of this study is to evaluate possible to achieve economic and environmental benefits from an implementation of an innovative recycling technology for a case study material niobium, which has been assessed critical in different countries and regions, such as European Union, United States, and Japan. The research implies a holistic case study of niobium life cycle specifics as well as a study of modern metal recycling. The study includes quantitative assessment of niobium material flow utilizing system dynamics modelling and simulation.

The study provides several major results. First of all, the study provides a comprehensive analysis of niobium life cycle specifics and the developed conceptual model of the global niobium material flow. Secondly, the gained results have been translated into system dynamics, which allowed to conduct a quantitative assessment of niobium material flow via its simulation. Finally, the developed primary system dynamics model has been extended to evaluate possible to achieve economic and environmental benefits from implementation of an innovative niobium recycling technology. In order to achieve reliable results, various scenarios have been considered. Since there is no precise information available on the current situation, the study has considered various collection fractions for the disposed material, as well as the various recovery rates describing different innovative recycling technologies. Thus, possible to achieve economic and environmental benefits from an implementation of innovative niobium recycling technologies have been evaluated.

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Nikita Krekhovetckii
March 2018

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1. INTRODUCTION

1.1. *Structure of Introduction*

In order to deliver a message contained in this chapter of the study in a clear and explicit way, Introduction has been divided into several subchapters starting with a research background and followed by research gap, research scope and objectives, delimitations, and structure of the Master's Thesis itself.

1.2. *Research Background*

Materials have always been essential for humanity in different areas. Moreover, they enable the progress and availability of those ensures opportunities for future development. (Savage 2012) However, the necessity of providing the growing level of living standards and the overall development of economies over the world have led to the constantly increasing demand for resources. (Mancini et al., 2012)

In general, demand for materials can be met in three different ways: traditional extraction, substitution, and recycling. Taking into account the obvious fact that the reserves of any material are limited, the first two methods, ultimately, will lead to a depletion of materials' reserves. Besides, for some applications material's substitution is not always possible or may result in a higher price or a lower quality of a final product.

The third option is a recycling, which may simultaneously fulfill the demand for a material and reduce the need for its extraction as well as to reduce carbon dioxide emissions. Nowadays, environmental advantages of recycling are explicit and clear. For instance, (Eckelman 2014; Broadbent 2016) illustrate remarkable environmental benefits of recycling. Moreover, well-established recycling industry speaks for itself in terms of economic feasibility, which is also shown in (Warringa et al. 2013). In addition, the study demonstrates another benefit which lies in the employment area, as recycling activities lead to a creation of new workplaces. As a result, recycling can be considered sustainable from economic, environmental, and social perspectives.

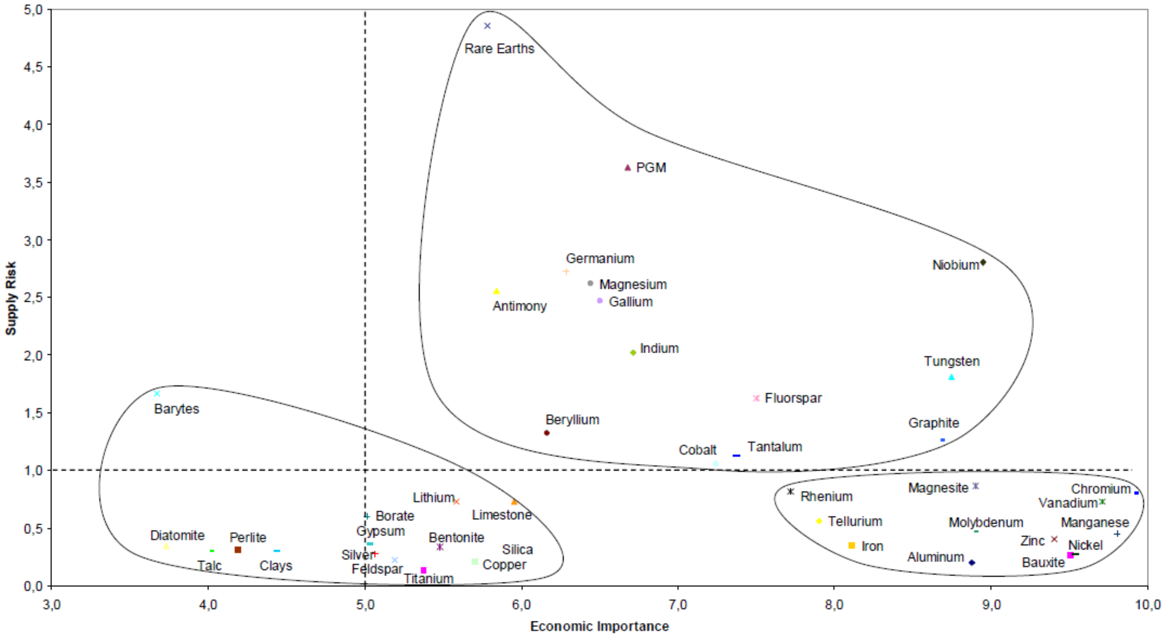
Development of sustainable consumption models including all stages of materials' lifecycle is one of the major challenges of our time. According to (United Nations General Assembly 2015), modern Sustainable Development Agenda was internationally adopted on September 25^{th}, 2015 with the purpose of ending poverty, protecting the planet and ensuring prosperity.

The Agenda includes 17 global goals with specific targets which are to be achieved over the next 15 years. (United Nations 2017a)

One of the global goals is devoted to responsible consumption and production. Moreover, among its targets, one has been set as “by 2030, achieve the sustainable management and efficient use of natural resources,” while another is “by 2030, achieve the sustainable management and efficient use of natural resources.” (United Nations 2017b)

Thus, the establishment of efficient systems of materials’ recycling is an important step towards the transition to sustainable models of materials’ production and consumption. Although the modern achievements of the world recycling industry, recycling rates vary significantly according to the different materials, industries, and regions. (Graedel 2011; DSM Environmental Services, Inc. 2015) For instance, the recycling rate of structural steel, which was claimed by the Institute of Scrap Recycling Industries to be the most recycled material in the world, in 2013 has reached remarkable 97.5%. (Institute of Scrap Recycling Industries, Inc., 2017) However, due to the steadily growing demand for materials, even in a theoretical case of materials’ full recycling and recovery, the need for extraction of raw materials cannot be eliminated.

Furthermore, among all materials, it is possible to distinguish a group of critical raw materials which are vital for industries and countries’ economies as lack of those may lead to the significant severe consequences and negative effects. According to the report of the Ad-hoc Working Group on defining critical raw materials (European Commission 2010) “to qualify as critical, a raw material must face high risks with regard to access to it, i.e. high supply risks or high environmental risks, and be of high economic importance.”



Source: European Commission 2010

Figure 1. Results of Raw Materials Criticality Assessment for the EU in 2010

For instance, figure 1 above illustrates the results of the assessment on materials' criticality conducted by the European Commission in 2010. Raw materials have been assessed by two factors: supply risk and economic importance. Ultimately, the group of materials situated in the top right corner has been adopted as critical raw materials which included 14 materials, while the rare earth materials have been assessed as one element.

The importance of CRM has greatly raised in recent years evidenced through a large number of studies relevant to materials' criticality which have been conducted in different regions and countries, such as European Union (European Commission 2010; 2014a), United States (U.S. Government Accountability Office 2010; U.S. Department of Defense 2001, 2008, 2009a, 2009b, 2009c, 2011; Commission on Engineering and Technical Systems 1999; Committee on Assessing the Need for a Defense Stockpile 2008; Humphries 2011; Grasso 2012; Bauer et al., 2010; McGroarty et al., 2012), Japan (Hatayama et al., 2015), and others. The broader and more detailed review of materials' criticality assessments can be found in the study of Erdmann et al. (2011).

Notwithstanding the differences between the methodologies utilized for evaluation of materials' criticality in different countries and diversity of unique conditions related to country's political, economic, industrial, environmental, geographic, and logistical situation, several materials have been assessed critical in different independent studies. Moreover, some materials are continued to be reported critical in sequential studies. The described outcome may indicate material's multicriticality or, in other words, a global pattern of criticality.

One of the materials which have been gradually assessed critical in different studies is niobium. Niobium is a chemical element with atomic number 41. The material was previously known as Columbium, while, nowadays, the old name is mainly used only in Americas. It is gray and lustrous paramagnetic ductile metal highly resistant to abrasion and heat. Prominent properties of niobium have caused its wide application in different industries. The substitution for some application is not possible, for other leads to significant loss of final product's quality and its higher price.

1.3. *Research Gap*

In order to increase recycling efficiency, innovative technologies should be developed, implementation of which will allow, for instance, a higher recovery rate of a material. Although the results of the development of innovative recycling technologies may appear clear and obvious, the real output should be assessed in a holistic way with regards to system's behavior and trends.

Nowadays, one may find theoretical studies including conceptual frameworks and models which have been developed to define waste reduction process or to suggest a new way for optimization of waste or material lifecycles. Besides, there can be found case studies conducted for a variety of materials connected to a precise industry or included in a specific product. Moreover, other studies are devoted to one material but inside limiting boundaries of a state, country or region. Finally, there also may be found reports including description and evaluation of a whole lifecycle of a product or material.

However, despite the intensity of modern research activity connected to the area of critical raw materials, the studies of a particular material flow and its lifecycle connected to the evaluation of the conditions of implementation of innovative recycling technologies are of a scarce amount. Moreover, it is further exacerbated for materials which have a narrow and specific field of application.

Thus, this master's thesis implies to fill this gap with an aim to determine economic and environmental conditions for implementation of innovative recycling technologies for a case study material niobium.

1.4. *Research Scope and Objectives*

The fundamental goal of this research is to determine what economic and environmental benefits can be achieved through implementation of innovative recycling technologies for material niobium. In order to achieve the desired outcome, the material flow of niobium should be accurately modeled.

Thus, the main research question of this study is "*What are the economic and environmental benefits possible to achieve from an implementation of an innovative niobium recycling technology?*"

Table 1. Research Questions, Objectives and Appropriate Research Methods

#	Research Question	Research Objective	Research Method
RQ 1	What is the structure of niobium material flow?	Reveal the structure of the niobium material flow	Multi-method study
RQ 2	What niobium recycling technologies are available?	Investigate niobium recycling technologies	
RQ 3	What amount of niobium scrap is (theoretically) available?	Evaluate the amount of niobium scrap (theoretically) available	Multi-method quantitative study
RQ 4	What are the possible economic benefits of an implementation of innovative recycling technologies for niobium?	Determine economic benefits possible to obtain from an implementation of innovative niobium recycling technologies	
RQ 5	What are the possible environmental benefits of an implementation of innovative recycling technologies for niobium?	Determine environmental benefits possible to obtain from an implementation of innovative niobium recycling technologies	

In order to answer the main research question and conduct the study systematically and in a sequential way, the main research question can be translated into a series of specific research questions, which are presented in the table 1 above.

The described research framework is applied in this research by means of a case study. Since the case study implies a deep and thorough understanding of the research object in order to clarify the structure of niobium material flow, the available niobium recycling technologies, and the systematic relationships regarding the material lifecycle of niobium, the study will utilize a combination of quantitative and qualitative approaches. Besides, with the purpose to accurately estimate the particular attributes of the research object, mainly will be employed quantitative methods. This research is based on a case study of a particular critical raw material named niobium (columbium).

1.5. *Delimitations*

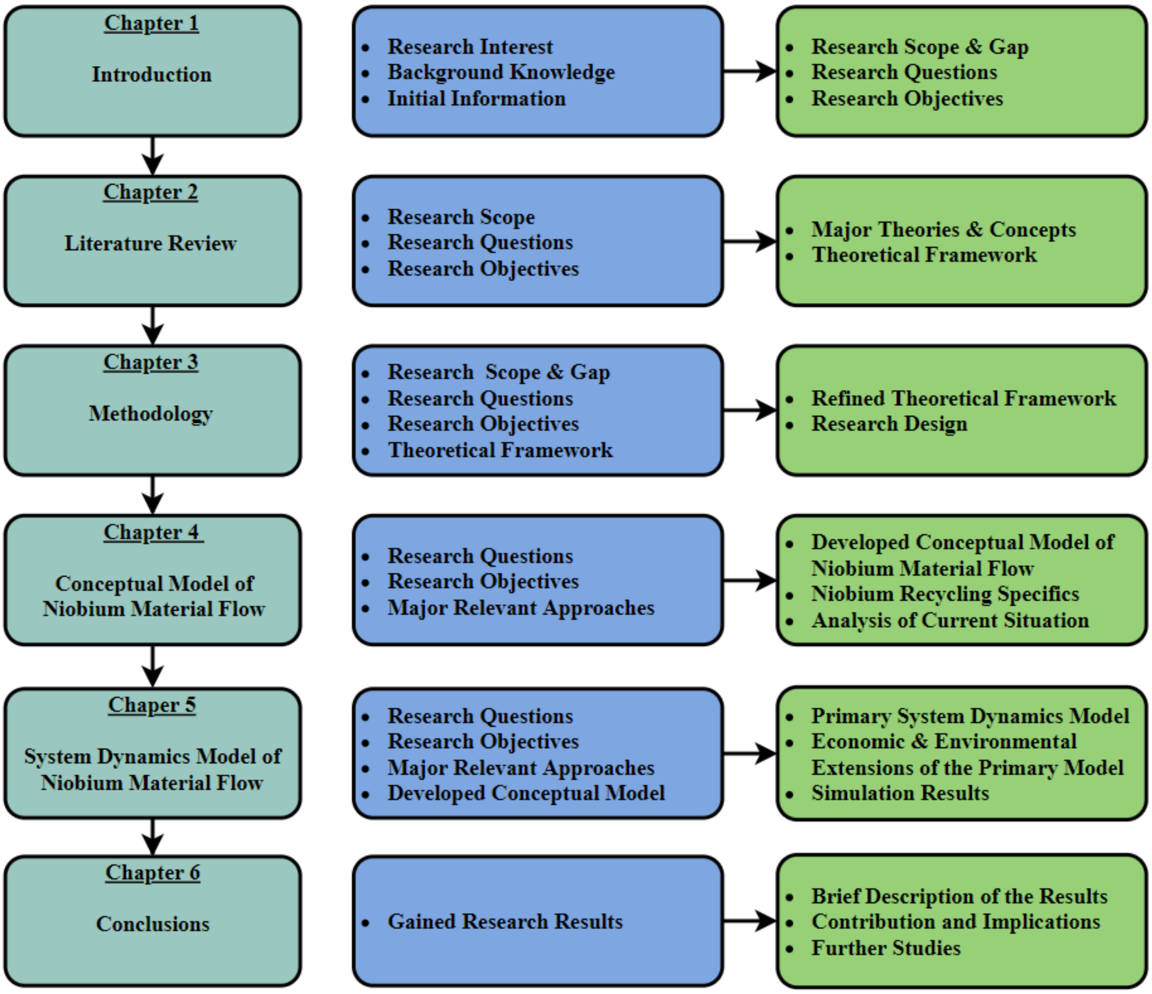
First of all, this research is focused on one case material niobium. Although the lifecycles of raw materials may be seen at some point similar to each other, the study includes in the assessment niobium specifics related to its mining, refinery, production, usage, and utilization stages. Besides, the evaluation is based on the particular limitation connected to the modern technological development regarding the niobium recycling technologies and its collection.

Secondly, the main focus of the study lies in the area of material's recycling. Therefore, the research does not tend to comprise thorough assessment of reduction, remanufacturing, and reuse aspects related to niobium lifecycle as long as it does not affect the main research focus. The main aim is to evaluate recycling area and its further opportunities for development.

Finally, this study entails an evaluation of niobium recycling only in terms of economic and environmental utility. Although material's recycling may be as well perceived sustainable from a social point of view, this study does not include determination of social conditions for implementation of innovative niobium recycling technologies.

1.6. *Report Structure*

In order to present the gained results of the research in a holistic way, the Master's Thesis has been divided into six chapter. Each of the chapters provides a representation of the findings related to a particular part of the research conducted. The illustration of the structure may be found in the figure 1 below representing the order, in which the study has been executed as well as how the chapters have been arranged.



Source: Author

Figure 2. The Structure of the Master's Thesis

Moreover, the figure 1 above as well illustrates major inputs, which have been initially considered, as well as the key results obtained from getting the parts of the study accomplished. The initial information illustrated in blue, while the findings are shown in green.

2. LITERATURE REVIEW

The aim of the literature review is to provide a relevant description of the scientific advancements related to the scope of the study, reveal modern theories and methods which are connected to the research and may be viewed as instruments for achieving research objectives.

According to the formulated research questions and objectives, literature review should deal with several major areas related to the scope of the study. All of them may be separated into several groups: sustainability and including its principles techniques, concept of critical raw materials and related studies, and approaches and methods for modelling of material flow. These groups are sequentially described in the literature review below. Besides, to provide information in a clearer way, some of the parts are further distinguished into sub-chapters when it is suitable.

2.1. *Sustainability*

According to the formulated research questions, one of the major areas which should be studied in the literature review is sustainability. These days, sustainable approaches are considered in a huge variety of modern practices. Therefore, this part of the literature review describes the concept of sustainability, approaches including principles of sustainability related to the study such as circular economy, reverse logistics, closed-loop supply chain, and recycling, which may be viewed as one of the fundamental high-level instruments for establishing sustainable systems.

2.1.1. Concept of Sustainability

History of sustainable approaches in a variety of fields may be traced back to ancient times. However, only in the middle of the twentieth century, the concern about possible resource depletion and its consequences on the environment gained power on a wide scene. It was a starting point when the term sustainable development globally emerged. According to (Pisani 2006), the adoption of a National Environmental Policy Act of the United States Government in 1969 has happened to become a final trigger with other less famous prior events in a row.

The considerable interest in sustainable development may have been caused by the severity of the consequences which can appear in case the global problems stay unsettled. According to (Su 2013), there is a growing need for a development of approaches, which will allow to maintain environment and ensure opportunities for further development of humanity.

Thus far, one may find huge variety of sustainable development definitions. In (Brundtland 1987, p.12) was stated that "sustainable development is a development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

Although the needs may as well rightly refer to the world's poor, in the context of the research, under the needs should be seen global needs for resources and materials as well as for the global environmental conditions.

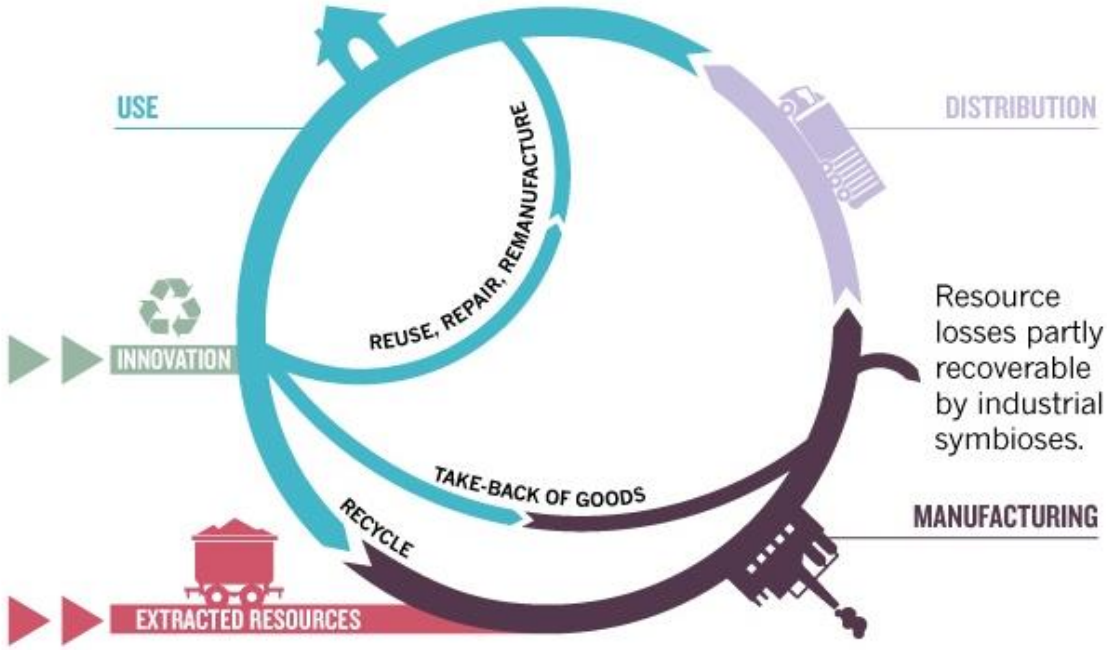
2.1.2. Circular Economy

The transition to a sustainable society is a complex challenge which cannot be achieved in a moment and without new fundamental approaches. In order to allow a successful shift, research activities related to sustainability issues have greatly raised and penetrated different areas of studies. (Stahel et al., 1981)

The first idea of economy in loops and its opportunities was offered in 1976. (Stahel et al., 1981) However, it was only the starting point of the circular economy (CE) development. As it was stated in (Su, 2013), the concept of CE was for the first time introduced by environmental economists Pearce, D.W. & Turner, R.K. (1990), while the study of Reike et al. (2017) claims that the first article related to the CE has been published only in 2007. Moreover, the article related to the history of CE states "there is no clear evidence of a single origin or originator of the CE concept." (Winans et al., 2017)

Although the precise evaluation of the CE creation date may not be gained and is obviously out of the main scope of the research, it is an indisputable fact that CE is currently on the research front of the scientific activity. (e.g. Reike et al., 2017) In addition, CE has widely gained importance among policymakers as well. (European Commission 2015; Lieder et al., 2016)

In contrast to the traditional linear approach, which describes a flow of resources from cradle to grave, from initial stage of mining raw materials to its disposal, the CE introduces a regenerative system with a set of loops. The fundamental idea of CE is to develop a system in a way to reduce its input of resources, waste, energy usage, and emissions.



Source: Stahel, 2017

Figure 3. Illustration of a CE Concept

The figure 3 above provides a basic illustration of the CE ideas and its structure. In a first place, resources come into the system and start the cycle. However, after the usage stage in contrast with a traditional approach, instead of disposal, products should be reused, repaired or remanufactured. Besides, products which cannot fulfill the requirements for the previously mentioned procedures should be recycled and start the cycle again. These actions will allow to minimize waste and resource depletion. Besides, CE practice implies to utilize during all the stages technologies which would as well allow to minimize energy usage and emissions.

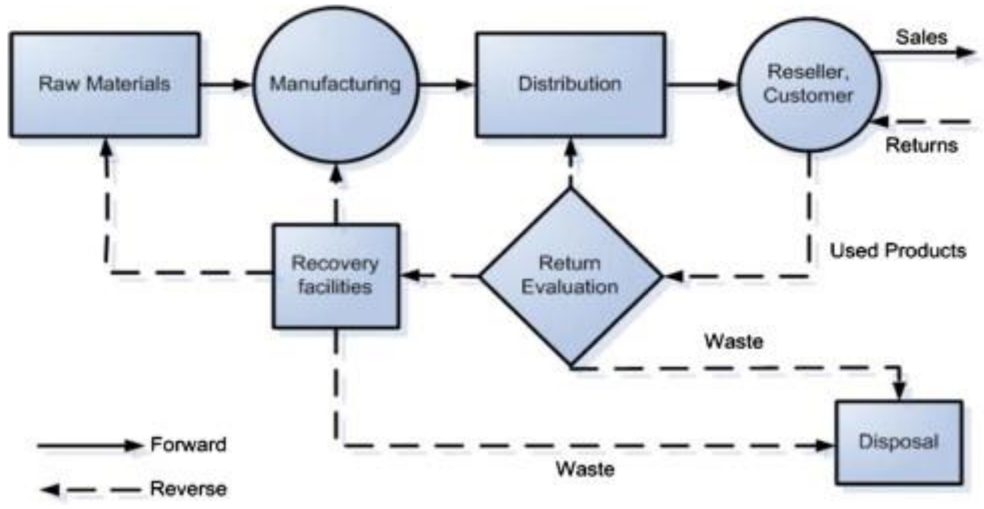
Although the main focus of CE described above remains the same, the history of CE may be divided into three main periods: dealing with waste in 1970-1990, eco-efficiency related to establishment of beneficial relations between business and environment in 1990-2010, and value retention period started approximately in 2010. The detailed description of the CE phases may be found in (Reike et al., 2017).

Thus, during the creation and its development, CE has integrated ideas of different concepts and approaches such as: concept of 3R (reduce, reuse and recycle), environmental design, industrial ecology, efficient energy use, industrial symbiosis, biomimicry, systems thinking, etc.

2.1.3. *Reverse Logistics and Closed-Loop Supply Chain*

In addition to CE, recycling as well recognized by the other practices as well. Among them there are well-established Reverse Logistics (RL) and Closed-Loop Supply Chain. (CLSC)

Instead of a traditional forward supply chain, RL is connected to the opposite flow direction of resources, from customer to initial point, where value may be captured again. According to (Rogers et al., 1999), RL defined as "the process of planning, implementing, and controlling the efficient, cost effective flow of raw materials, in-process inventory, finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal."



Source: Tonanont et al., 2008

Figure 4. Conceptual Representation of a Product Life Cycle

Figure 4 above provides a general representation of a product lifecycle. Besides, the diagram distinguishes flows related to forward and reverse supply chains: solid and dashed lines respectively. Moreover, in case of considering simultaneously forward and reverse supply chains, in order to properly describe the gained network, should be applied the concept of CLSC. The detailed discussion on RL and CLSH as well as the history of both concepts may be found in (e.g. Govindan et al., 2015; Souza, 2012).

2.1.4. Life Cycle Assessment

According to (Yan et al., 2015), the concept of Life Cycle Assessment (LCA) has emerged and become a valuable tool for decision-making purposes because of several key factors. First of all, the increased attention to environmental issues over the last decades has resulted into the shift towards sustainable systems and life cycle accountability. Instead of direct impacts related to production processes, manufacturers became responsible for the whole lifecycle of the products including stages of usage, transportation, and disposal. Secondly, environmental concerns have penetrated consumer markets and governmental procurement as an important product selection criterion. Finally, companies tend to voluntary participate in life cycle initiatives in order to continuously improve efficiency.

The study of Finkbeiner et al. (2006) claims that creation and development of international standards for LCA became a crucial step which allowed to define and consolidate its procedures and methods. Moreover, clear standardized representation was another factor which made LCA internationally recognized and well-established practice for environmental impact analysis.

The standards have been issued by International Organization for Standardization (ISO). The modern version consists of two standards (International Organization for Standardization 2006a, 2006b), which together describe LCA in detail. The first of them includes its principles and framework, while the second provides information for practioners on conducting the LCA.

Table 2. Phases of LCA

Phases of LCA	Description
Phase 1. *Goal and scope definition*	Defining goal, system boundaries and level of detail
Phase 2. *Inventory analysis*	Collection of data and description of inventory in terms of inputs / outputs
Phase 3. *Impact assessment*	Provide additional information to better understand environmental impacts
Phase 4. *Interpretation*	Analysis of results, conclusion and discussion

Adopted from (ISO 2006a)

The process of LCA study consists of four main phases, described in the table 2 above. The detailed review of the different versions of ISO standards related to LCA and differences between them may be found in (Finkbeiner et al., 2006; Pryshlakivsky et al., 2013).

These days, one may find a variety of LCA applications in different areas. For instance, (Buyle et al., 2013) provides a review for construction sector, while the study of Vileches et al. (2017) includes literature review of LCA studies related to building refurbishment. (Güereca et al., 2015 describes advancements made over the last decades in the use of LCA in Mexico. (Nealer et al., 2015) review recent LCA studies related to energy and greenhouse gas emissions for sector of electric vehicles.

Besides, it is important to mention, that LCA method may be used to study not only product lifecycles and its impacts, but also lifecycles of materials and resources. For instance, (WorldSteel Association, 2017) represents a LCA study for steel conducted by the WorldSteel Association, while for copper LCA has been conducted by European Copper Institute. (2017)

To sum up, LCA is a convenient modern approach for comprehensive assessment of a product or material impacts during all the stages of its life cycle. Besides, LCA allows to evaluate actual situation as well as to explore opportunities for further development.

2.1.5. Recycling

Taking into account all mentioned above, recycling may be viewed as an essential part of CE, RL, CLSC, and LCA as one of utilized approaches to redirect flows of end-of-life products from disposal to a beginning of a lifecycle and to recapture its value. In addition, recycling as well participates in other practices, such as Waste Management, Environmental Management, Cleaner Production, and other. (Reike et al., 2017)

Recycling of materials has started long ago, and for now has become a well establish industry. Although the modern achievements of the world recycling industry have reached significant progress, recycling rates vary dramatically according to different materials, industries, and regions. (e.g. Graedel, 2011; DSM Environmental Services, Inc., 2015)

For instance, the recycling rate of structural steel, which was claimed by the Institute of Scrap Recycling Industries to be the most recycled material in the world, in 2013 has reached remarkable 97.5%. (Institute of Scrap Recycling Industries, Inc., 2016) However, not many materials may share the same or even close recycling values.

The issue of limited recycling is especially pressing for rare or narrow-applied materials. For example, as it was shown in (European Commission, 2010), total recycling rate of niobium which is applied in several industries accounts only for approximately 20% from its annual consumption. In addition, (Graedel et al., 2011) reports that for more than 30 metals, from in a total 60 included into analysis, functional end-of-life recycling rate does not exceed 1%.

There are many barriers and limitations towards a global and comprehensive material recycling. First of all, recycling deals with different materials and products and, in some cases, ways of material recovery are not as obvious as for metals and alloys. Moreover, recycling may be limited by other factors not connected to the process of material recovery. Thus, establishment of an effective recycling system is a complex endeavor which should tackle a variety of issues. Exemplary recycling limitations are long unavailability of materials due to long periods of products' usage, inevitable losses of material along each step of supply chain, quality discrepancy between available recyclables and industrial needs, and complicated material's recovery due to complex products. (Schneider et al., 2014; Grosso et al., 2017)

The principal factor which may affect a global recycling system of materials and, therefore, manipulate overall recycling rate of a material is a level of technological advancement. Gap between "as it is" and "as to be" states may be eliminated with a proposition of innovative technologies related to different stages of a material recycling process: product design and development, manufacturing and packaging, separation and classification, and recycling with material recovery itself. Thus, innovations and new technologies may be seen as a regulator, influencing the system and its efficiency.

However, due to the steadily growing demand for materials (e.g. Giljum et al., 2009), even in a theoretical case of materials' full recycling and recovery, the need for extraction of raw materials cannot be eliminated but may be significantly reduced.

Thus far, one may find a multiplicity of studies related to assessment of recycling feasibility and its particular benefits. In order to provide a clear representation of modern findings concerning advantages of recycling, the description below will be arranged in several steps.

First of all, recycling is profitable from an economic point of view, which may be seemed as a main condition allowed recycling industry to become a widely well-established practice. This fact may be indirectly confirmed by the abundance of private companies connected to recycling of materials or products. (e.g. OmniSource Corporation, 2018; Lally Pipe &Tube, 2018; The Eagle Metal Group, 2018)

Moreover, different reports and studies continue to evaluate new options for recycling. For instance, in (Choi et al., 2010) the authors have performed feasibility analysis of establishing photovoltaics recycling system. The study has identified several crucial to photovoltaics recycling factors, such as: incoming module cost, shipping cost, landfill tipping fee, and others. Taking different levels for each factor, the pull of scenarios has been aggregated. Finally, feasibility of recycling has been evaluated with regards to each combination of included in the model factors. The results show that recycling is feasible only for a limited set of scenarios representing part with positive projections. In addition, another study of photovoltaics recycling feasibility has revealed unprofitability for all 16 scenarios analyzed. (D'Adamo et al., 2017)

While some of the products and industries continue to stay unprofitable for recycling taking into account modern technological opportunities, for other different researches offer new ways to implement innovative recycling methods. For instance, in (Emel'yanova et al., 2011) was offered a new approach to recycle steelmaking zinc-bearing dust. Study has revealed its economic feasibility considering modern market conditions and installed equipment. Another example can be found in (Georgi-Maschler et al., 2012), where authors have proposed a new process for lithium-ion batteries recycling which included different modern recycling technologies.

Besides the economic benefits, recycling may be as well be considered sustainable from an environmental viewpoint. The common practice to describe environmental benefits of recycling is to evaluate possible energy savings and reduction of carbon dioxide (CO2) emissions.

As an illustrative example for a described above approach of determining environmental recycling advantages may be seen in a study of Colling et al. (2016), which describes a potential energy savings and reduction of CO2 emission as a result of a National Solid Waste Policy adoption in Brazil. According to the conducted analysis, in case of fulfilling recycling goals set in the Policy, total energy savings and CO2 emissions reduction in comparison to annual values will constitute 4,56% and 45,16% respectively. Another example can be obtained from (Li et al., 2017), which contains a discussion on modelling of aluminum industry in China and its environmental impact in terms of CO2 emissions.

Furthermore, another benefit of recycling may be found in a social area. First of all, as the majority of other industries, recycling activities lead to creation of jobs and employment. In addition, recycling firms can generate more profit than landfills and waste incinerators, which, in turn, positively affects local economy. According to the study (Warringa et al., 2013), the both facts have been admitted for a region under the assessment. Thus, recycling may as well be considered sustainable from a social perspective.

To sum up, recycling activities have an interdisciplinary nature: the approach is an essential part of different concepts and practices. Besides, modern recycling industry is a well-established international network. The main source for development of existing recycling systems and its efficiency is a technological advancement which is as well the only way to overcome variety of limiting conditions and barriers typical for recycling. The benefits of recycling explain the significance of recycling, which shall be considered sustainable from economic, environmental, and social viewpoints.

2.2. ***Critical Raw Materials***

Another major part which is covered in literature review is the concept of critical raw materials and studies related to them conducted for economies of different regions and countries. Besides, this part briefly considers the most important ideas related to the methodologies utilized in the studies of critical raw materials.

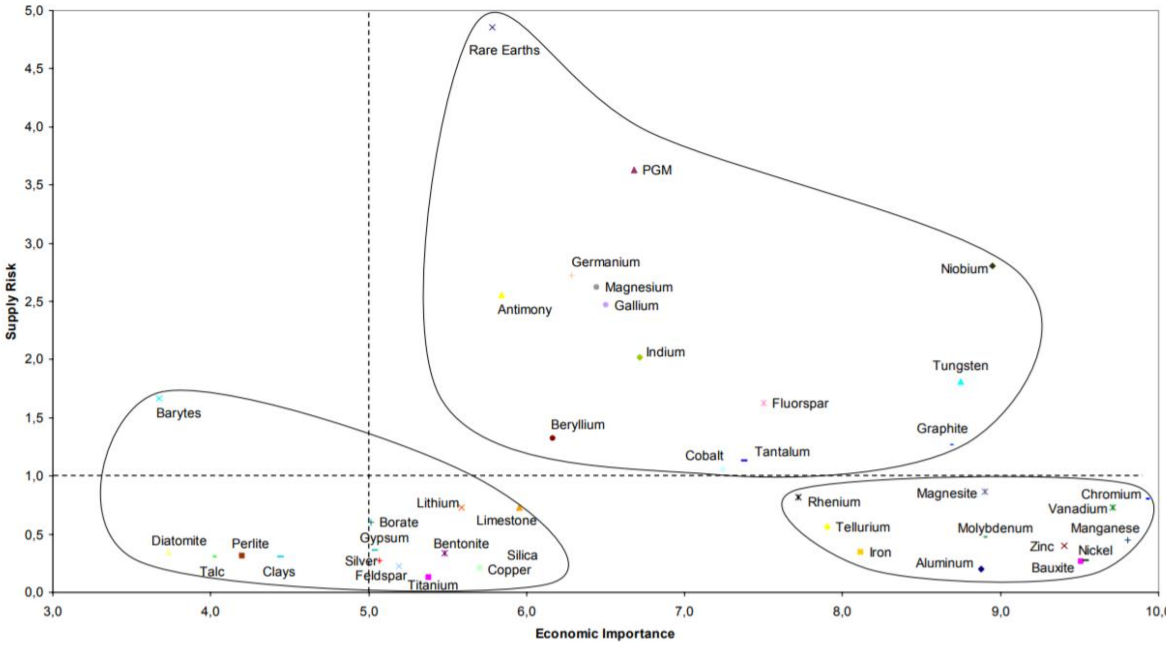
Modern economy strongly depends on access to raw materials which allow its functioning and opportunities for further development. (e.g. European Commission, 2018) In order to defend national economy from possible shortages and supply disruptions, different countries started assessments of materials' criticality which led to creation of the concept Critical Raw Material. (CRM)

Definition of CRM may be found in one of the reports. For instance, one of the studies determines CRM as follows: "to qualify as critical, a raw material must face high risks with regard to access to it, i.e. high supply risks or high environmental risks, and be of high economic importance." (European Commission, 2010) In other words, among all materials under evaluation, critical should demonstrate more probable possibility of shortage, which, in turn, will negatively affect national economy due to their high economic importance.

The importance of CRM has greatly raised in recent years evidenced through a large number of studies relevant to materials' criticality which have been conducted in different regions and countries, such as European Union (European Commission 2010, 2014a; Deloitte Sustainability et al., 2017), United States (U.S. Government Accountability Office 2010; U.S. Department of Defense 2001, 2008, 2009a, 2009b, 2009c, 2011; Commission on Engineering and Technical Systems 1999; Committee on Assessing the Need for a Defense Stockpile 2008; Humphries 2011; Grasso 2012; Bauer et al., 2010; McGroarty et al., 2012), Japan (Hatayama et al., 2015), and others. The broader and more detailed review of materials' criticality assessments can be found in the study of Erdmann et al. (2011).

Thus far, three CRM studies have been conducted for the European Union (EU) region. The first report has been issued by European Commission in 2010. (European Commission, 2010) According to the developed methodology, criticality of a raw materials should be evaluated with regards to several key factors, such as:

1. Economic importance of the material
2. Supply risk
    2.1. Level of concentration of worldwide production
    2.2. Political stability of producing country
    2.3. Economic stability of producing country
    2.4. Potential for material substitution
    2.5. Recycling rate
3. Environmental country risk

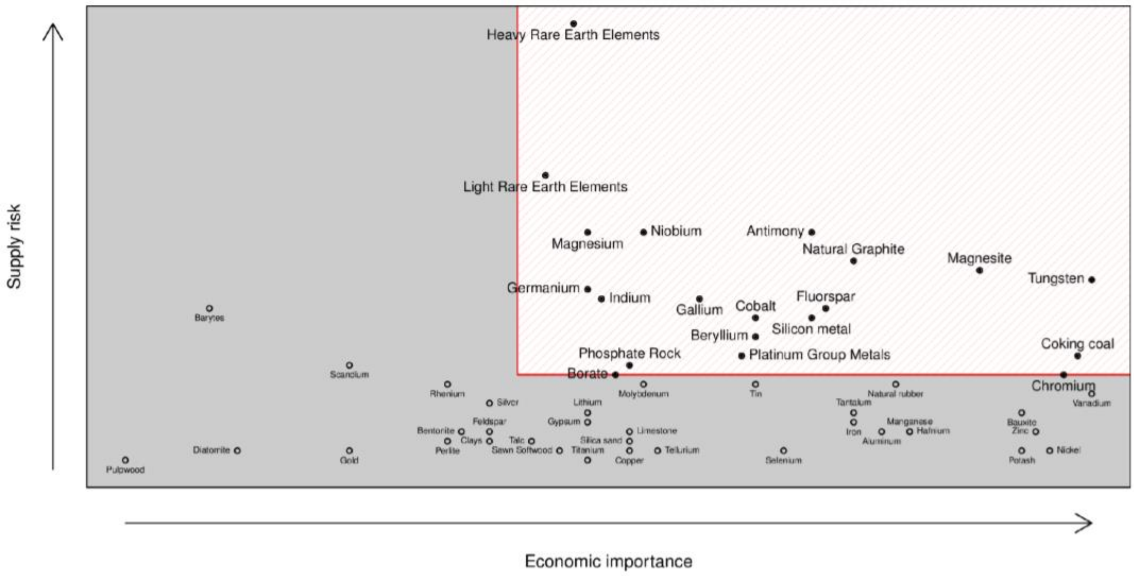


Source: European Commission, 2010

Figure 5. Results of the 1st CRM Study for the EU

As it may be seen in the figure 5 above, all raw materials have been organized into three main clusters. The top right cluster includes materials assessed critical for European Union. Although the figure represents calculation for supply risk and economic importance, the evaluation of environmental country risks has not changed the results of the study. Thus, fourteen of forty-one raw materials have become CRM.

The second assessment has been carried out in 2014 and included a broader scope of materials. Instead of forty-one materials, it considered fifty-four: new abiotic materials as well as biotic materials, which have not been previously included. The results, of the study are presented in the figure 6 below.



Source: European Commission, 2014a

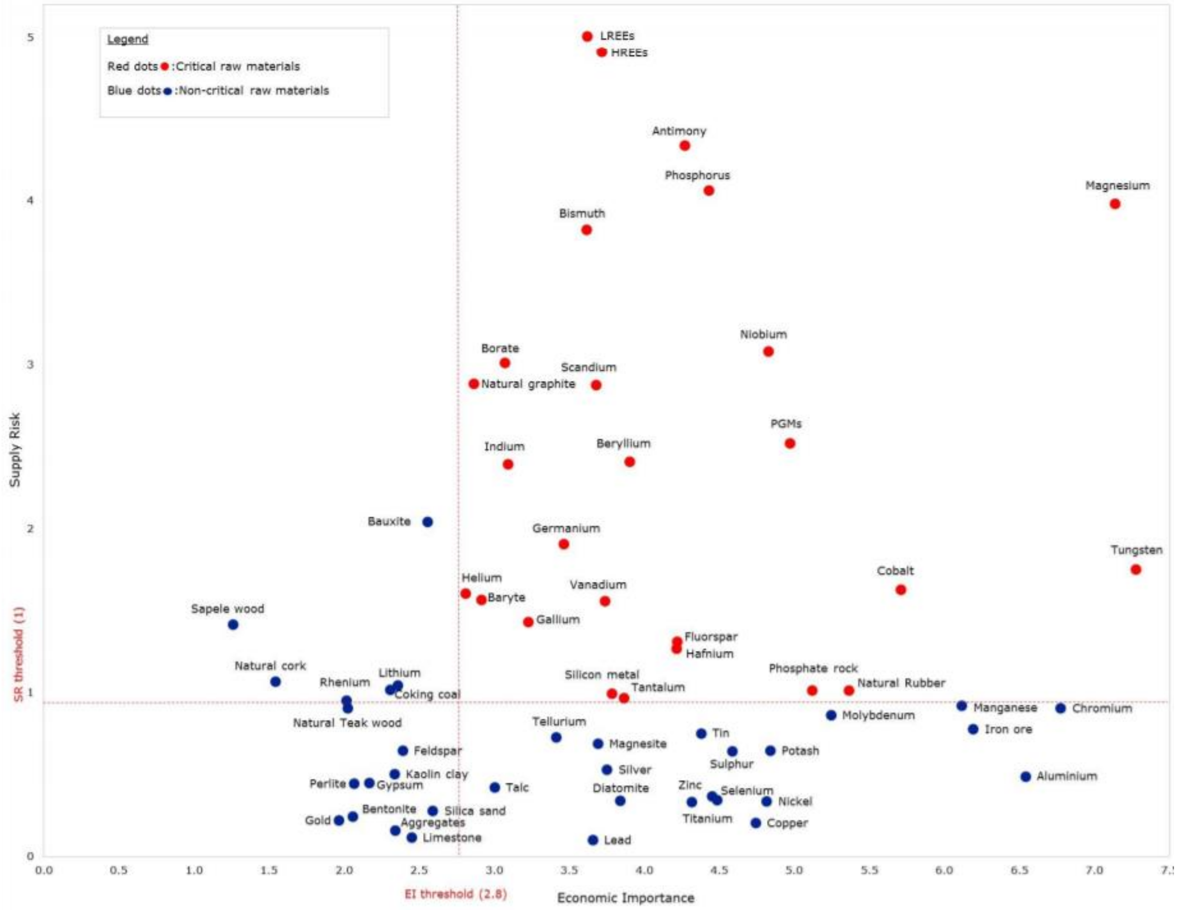
Figure 6. Results of the 2nd CRM Study for the EU

Twenty materials included in the top right cluster of the diagram, illustrated in the figure 6 above, have been assessed critical, which has increased list of CRM of the EU for six new materials, while tantalum, previously assessed critical, has not entered the criticality list.

In addition to list of materials considered and results, methodology has been changed as well. In comparison to the previous approach, the new one implies to evaluate criticality only on two dimensions, such as:

1. <u>Supply risk due to poor governance</u>
   1.1. Substitutability
   1.2. End-of-life recycling rate
   1.3. Country concentration of production
   1.4. Level of governance
2. <u>Economic importance</u>
   2.1. Applications
   2.2. EU megasector value

The third CRM report for the EU has been issued in 2017. (Deloitte Sustainability et al., 2017) The number of candidate materials have continued to be increased and this time included seventy-eight individual materials. Besides, the methodology utilized in two previous reports also has been adjusted with a series of small developments, while the fundamental idea of approach did not face any crucial changes. The results of the third CRM study for the EU are presented in the figure 7 below.



Source: Deloitte Sustainability et al., 2017

Figure 7. Results of the 3rd CRM Study for the EU

In comparison to the results of the previous study of 2014, the list of CRM has been extended by three materials previously not included into analysis (bismuth, helium, phosphorus); six materials previously not assessed as critical entered the list (baryte, hafnium, natural rubber, scandium, tantalum, vanadium); while three materials have been excluded from the list (chromium, coking coal, magnesite). The full list of CRM may be found in the table 3 below.

Table 3. Materials Assessed Critical for the EU in 2017

Antimony	Natural Graphite	Bismuth
Beryllium	Niobium	Hafnium
Borates	Phosphate Rock	Helium
Cobalt	Silicon Metal	Natural Rubber
Fluorspar	Tungsten	Phosphorus
Gallium	Platinum Group Metals	Scandium
Germanium	Light Rare Earths	Tantalum
Indium	Heavy Rare Earths	Vanadium
Magnesium	Baryte	

Adopted from: Deloitte Sustainability et al., 2017

The detailed discussion on EU methodologies for CRM assessment may be found in the study of Blengini et al. (2017).

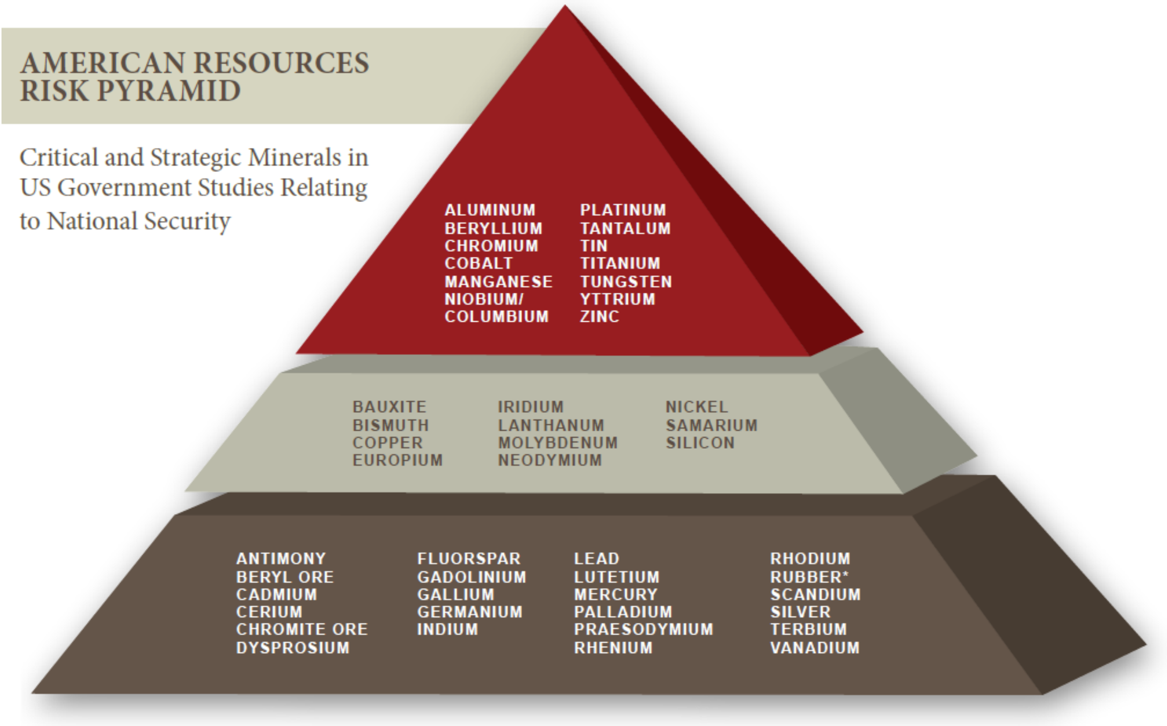
Furthermore, similar studies of materials criticality for national economy have been conducted in United Stated as well. Although the assessments may seem similar to the CRM studies for the EU, some of them tend to focus on strategic importance of materials instead of its criticality.

According to (European Commission, 2010 p.23), strategic materials are used for military uses, while critical materials may harm national economy in case of supply shortages. The problem of unified system of definitions concerning the criticality and strategic importance of materials have been raised in many reports even among studies conducted inside one country.

One may find a variety of studies related to materials criticality and strategic importance conducted for USA: U.S. Government Accountability Office 2010; U.S. Department of Defense 2001, 2008, 2009a, 2009b, 2009c, 2011; Commission on Engineering and Technical Systems 1999; Committee on Assessing the Need for a Defense Stockpile 2008; Humphries 2011; Grasso 2012; Bauer et al., 2010; McGroarty et al., 2012.

Besides, the report of McGroarty et al. (2012) provides a clear and comprehensive review and analysis of other American studies. Besides, authors created an American Resources

Risk Pyramid, which represents several levels of materials' criticality for USA. The Pyramid is illustrated in the figure 8 below.



Source: McGroarty et al., 2012

Figure 8. American Resources Risk Pyramid

The top priority level includes fourteen materials, the second consists of eleven, while the third priority level combines another twenty-three materials. The total amount of materials which are represented in the Pyramid is forty-eight.

In case of combining results of the American study (McGroarty et al., 2012) with results obtained in the last CRM study for the EU (Deloitte Sustainability et al., 2017), it is possible to find that twenty-nine materials have been assessed critical in both studies.

Thus, notwithstanding the differences between the methodologies utilized for evaluation of materials' criticality in different countries and diversity of unique conditions related to country's political, economic, industrial, environmental, geographic, and logistical situation, several materials have been assessed critical in different independent studies.

2.3. *Material Flow Modelling*

In order to answer the main RQ of the study, the material flow of niobium should be modelled. Modeling of material flow may be conducted in several principal ways using different approaches. Therefore, this part of the study provides literature review of several relevant techniques that may be utilized for this purpose. First of all, it covers the concept of a model, then the major relevant modelling techniques and its fundamental ideas are discussed.

2.3.1. Concept of Model

To begin with, before starting the description of modelling techniques and methods, it is vital to define what is a model. In addition, according to the requirements of this study, it is important to clarify what type of a model should be utilized. Classification of models is a broad area as one may find a huge variety of classification parameters and for each of those the unique classification may be organized.

Any model is a simplified representation of reality focused on the most essential part. According to the definition provided in (Oxford Dictionaries, 2018), model is "a simplified description, especially mathematical one, of a system or a process, to assist calculations or predictions."

Exemplary high-level classification of models may be found in (Singh, 2009). According to the source, all models may be distinguished into three groups: physical models, mathematical models, and computer models. In additions, on the next level, all of them may be divided into static and dynamic models. In this study, model of material flow should represent the class of dynamic computer models.

2.3.2. Modelling Approaches

These days, technological advancement has led to creation of a variety of different approaches that may be utilized in order to model a material flow. Among them there are Material Flow Networks, Material Flow Analysis, Probabilistic Material Flow Analysis, System Dynamics Modelling and Simulation, Life Cycle Assessment, Discrete-Event Modelling and Simulation, Agent-Based Modelling and Simulation, Input-Output Models, Regression Analysis.

Each of the techniques has been developed for a specific purpose, while the additional development and further consolidation have made them general concepts for a broad use in specific application sphere. For instance, System Dynamics has been developed by widely-known Professor of Massachusetts Institute of Technology (MIT) Jay W. Forrester for corporate and managerial area. (e.g. Forrester, 1968) However these days, System Dynamics become a widely-applied practice for modelling complex systems from completely different fields. (e.g. Milling, 2007; Radzicki et al., 2008)

The mentioned above methods possible to be applied for modelling of material flow will be discussed below in order to provide a short overview of principle ideas forming their basis. The methods are discussed in the same order as they have been mentioned.

2.3.3. Material Flow Network

According to (Bornhöft et al., 2013), Material Flow Network (MFN) has been developed by Moller (Möller, 2000). The MFN is based on Petri Nets (or place/transition nets). Although the approach is widely used to increase efficiency of operational processes (e.g. Herrmann et al., 1995), there can be found its applications for modelling material flow on a national economy level. For instance, Chen et al. (2016) present a methodology which allows to build material flow networks for US economy. In the study MFN was implemented for modelling the manufacturing stage of material flow.

In particular, the process of MFN is supported by software product Umberto, which allows to simultaneously assess production process from economic and environmental points of view and achieve holistic transparency of production system. The official web site of the software company may be found in (Umberto, 2017).

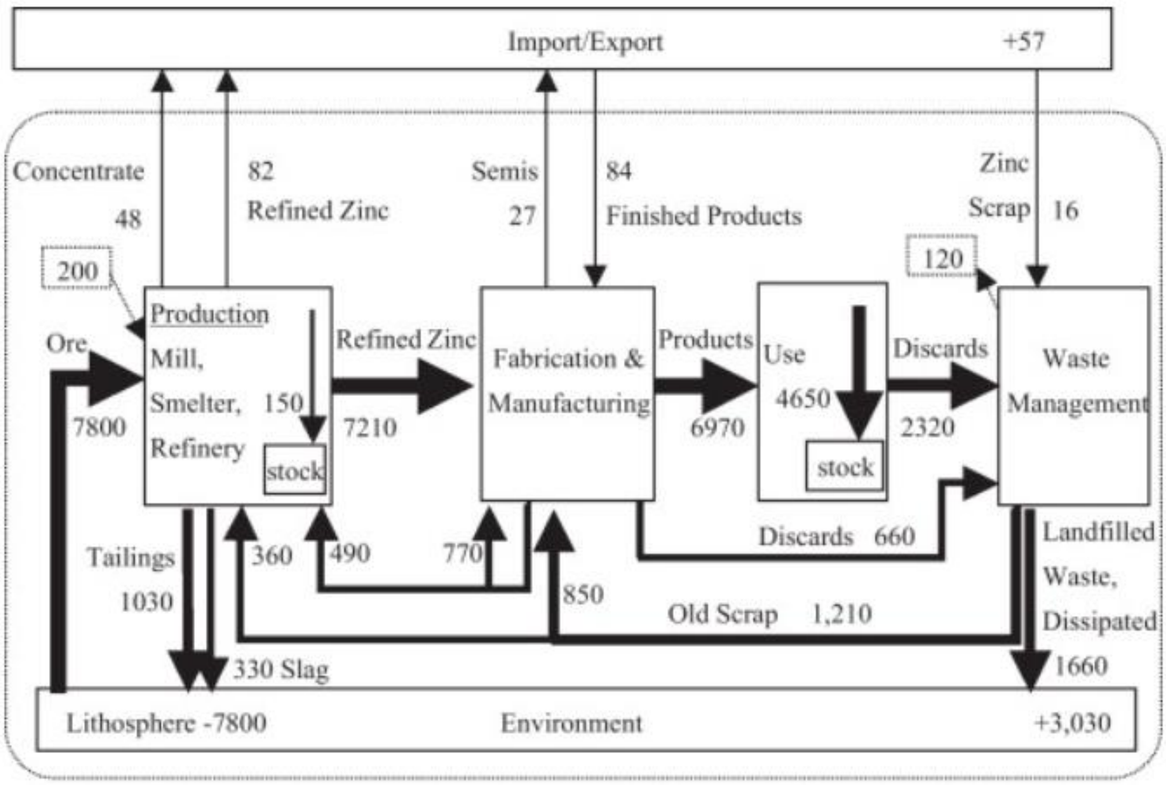
2.3.4. Material Flow Analysis

The key principle Material Flow Analysis (MFA) lies in fundamental law of conservation of material and mass balancing. In the book of Brunner & Rechberger (2004, p.3), MFA is described as “a systematic assessment of the flows and stocks of materials within a system defined in space and time. It connects the sources, the pathways, and the intermediate and final sinks of a material.”

According to the description of the MFA given in the book, the term ‘material’ stands for material as well as for substances, while substance may consist of one substance or mixture of those with positive or negative economic value. In case of modelling only substances by

MFA, the name may be changed for Substance Flow Analysis. However, this study concerns modelling material flow of one material.

As it was discussed in (Huang, 2012), modern MFA includes indicators from social, economic, and environmental scopes. For instance, resource consumption relates to social aspect, material input – to economic, while recovery efficiency may be an example of environmental indicator.



Source: Graedal et al., 2005

Figure 9. Graphical Representation of the MFA.

To illustrate the idea of MFA, graphical representation of the MFA of Zinc conducted on a global level has been provided above. The boxes represent major stages of material flow, arrows represent flows of material, while elongated rectangles illustrate environmental sector and zinc import and export channels.

Moreover, approaches of MFA may be classified into three categories concerning the time factor: static approach, dynamic approach, and mixed approach. Due to the inclining of this study to establish dynamic model, the detailed review of dynamic MFA may be found in the study of Müller et al. (2014).

2.3.5. *Probabilistic Material Flow Analysis*

The Probabilistic Material Flow Analysis (PMFA) is a newly developed method which was based on traditional MFA. The PMFA was developed by Gottschalk et al. (2010) to estimate environmental concentrations of new pollutants which is necessary to evaluate risks caused by them. The main aim of the method is to allow calculations with the significant lack of information on material flow.

The developed PMFA has connected traditional approach for MFA with Monte Carlo simulation, sensitivity analysis, uncertainty analysis, and Bayesian and Markov Chain modelling.

The application of the PMFA may be found in Gottschalk et al. (2009), while in Gottschalk et al. (2010b) have been discussed further possibilities of PMFA and its limitations. In addition, there are other reports conducting MFA with probabilistic approach but in different ways, such as Laner et al. (2015)

2.3.6. *System Dynamics Modelling and Simulation*

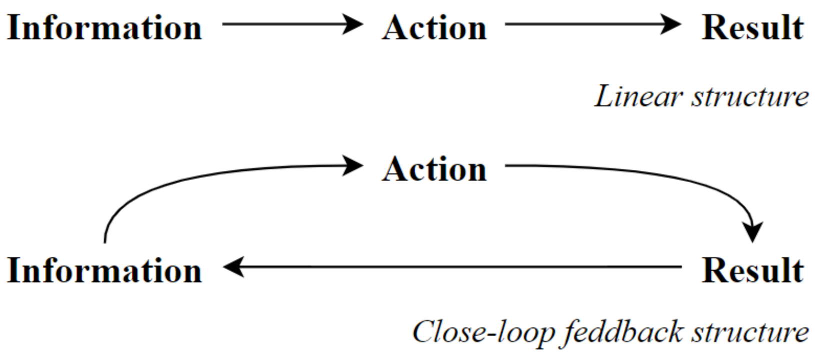
As it was already stated above, System Dynamics has been developed by MIT professor Jay W. Forrester. (Forrester, 1961) These days, System Dynamics represents one of the three main paradigms of Simulation Modelling. (e.g. Moon, 2016) Therefore, the full term of the approach may be viewed as System Dynamics Modelling and Simulation. (SDSM)

The major purpose of SDMS, for which it was initially created, is to model behavior of complex systems. One may find a huge amount of definitions for complex systems. For instance, Xepapadeas (2010) describes complex systems as ‘systems consisting of many interacting components, with macroscopic systems properties emerging from the interactions among these components.’

Actually, any real system may be viewed as complex, however, in a majority of cases, such representation would include redundant details which may be removed without any serious decrease in meaning. The very same situation may be seen in different fields. For instance, in economics it is described by the marginal utility.

Although such approach may be vastly utilized, it is important to understand the real nature of systems around. The key principle is feedback loops. Instead of an open-loop impression, it is essential to consider close-loop character of the systems. (Forrester, 2009)

The figure 10 below illustrated open-loop and close-loop approaches for considering systems: the linear structure considering open-loop is represented on the top of the figure, while the real close-loop feedback structured is represented below.



Adopted from Forrester (2009, pp.6,7)

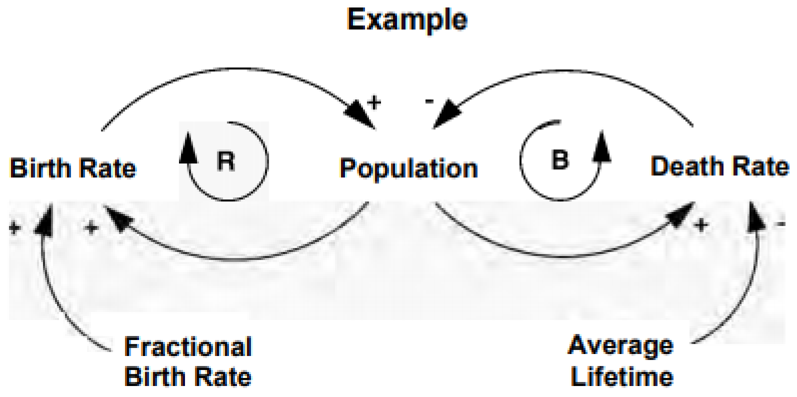
Figure 10. Exemplary Feedback Structures for a Considered System

Moreover, another problem which seriously affects understanding of a system behavior is a high order of complex systems. While considering a system of a first or second level, one may predict its dynamics, the systems of third order or higher cannot be analyzed without further investigations. For this issue SDMS has been developed. (Forrester, 2009 p. 403)

The information provided in this part above briefly described the history of SDMS and its fundamental principles, while the explanation of SDMS notations is covered below.

SDMS includes two main concepts which should be described: casual loop diagram (CLD) and stock and flow diagram.

CLD may quickly represent structure of interactions between the variables of the model and show those polarity. Besides, CLD includes information on important delays and may be viewed and may be viewed as one of the essential instruments for developing models. Exemplary representation of CLD may be found in the figure 11 below.



Source: Sterman, 2000 p.138

Figure 11. Exemplary Casual Loop Diagram

In the figure 11 above the named variables are connected with arrows which represent interaction between them. Symbols of pluses and minuses state for positive and negative polarities of connections respectively, while polarities of loops may be as well be determined with ‘R’ for reinforcing loops and ‘B’ for balancing ones. In addition, arrows of connections including important delays may be marked additionally.

While CLD perfectly suitable for representation of interconnections, it lacks opportunity to explicitly describe structure of stocks and flows. Therefore, stock and flow diagram may be considered the second crucial concept of SDMS. The exemplary representation of stock and flow diagram may be found in the figure 12 below.

Source: Sterman, 2000 p.193

Figure 12. Exemplary Stock and Flow Diagram

In the figure 12 above stock is represented with rectangular. While stocks may have initial values, they can be changed only by flows which are illustrated by the arrows. In turn, flows are determined by the valves. Moreover, clouds (in the beginning and at the end of the flow represented in the figure) state for sources of the flows (or sinks) which are infinite. Besides, the diagram may include other variables which would be connected by arrows, but the precise representation modes depend on the particular modelling software.

2.3.7. *Life Cycle Assessment*

Material flow may be modeled in accordance with a set of practices related to LCA. Although the LCA perfectly suitable to be included into the list of approaches and, therefore, should be mentioned in this part of the study, the detailed description of LCA has been already provided in the section 2.1.4 Life Cycle Assessment above. Moreover, the way of modelling material flow in accordance with LCA may result in necessity to partly utilize other approaches.

2.3.1. *Other approaches*

In addition to the described above approaches, several other techniques may be utilized, such as Discrete-Event Modelling and Simulation (DEMS), Agent-Based Modelling and Simulation (ABMS), Input-Output Models, Regression Analysis.

These days, Simulation Modelling includes three major paradigms of modelling: SDMS, DEMS, and ABMS. SDMS has been already discussed in the section 2.3.6 of this study above.

DEMS has been created on a basis of Queueing Theory and represent considering system via entities, flowcharts and resources conducting operations on entities. The method is well-established in modelling of operational processes and resource efficiency. DEMS may be applied for modelling of material flow. However, in case of significant lack of information and for the purposes of modelling high-level systems, this method may not be seen as the most suitable. The detailed description of DEMS may be found in the study of Zeigler et al. (2010).

ABMS has been developed much later than SDMS and DEMS. While the initiatives to develop a unified solution, which would allow modelling of individual agents and interactions of those, the first commercial product has been developed relatively recent. The detailed discussion on ABMS method may be found in (Borshchev, 2013).

To sum up, it is essential to underline that each method has its own modelling focus. SDMS is focused on modelling interconnected variables and stocks to elicit system behavior. DEMS method mainly considers sequences of operations to analyze process efficiency and flow of entities. ABMS aimed at implementing into model individual properties of agents to model interactions between the agents.

All methods are supported by software. One of the products which allow DEMS is Arena. (Arena, 2017) For SDMS may be used software as VenSim (Vensim, 2017) or Stella iThink. (Stella, 2017) The biggest commercial product for ABMS is AnyLogic. (AnyLogic, 2017) Moreover, in addition to ABMS method, the product includes SDMS and DEMS. Furthermore, all methods may be used separately or simultaneously. Models integrating more than one modelling method are called integrated, hybrid or multi-method models. Examples of such models may be found in (Shafiei et al., 2013; Wand et al., 2014).

Another approach that may be considered for modelling material flow is input-output model. The technique is a quantitative econometric method which has been developed by Wassily Leontief to represent connections between different parts or branches of national economy. Moreover, for the development of this model Wassily Leontief has been awarded with a Nobel Prize in Economics in 1973. (The Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel, 2017)

The utilization of the method is based on a description in a matrix form a set of variables for each branch of economy. The resulting matrix is also known as a 'Leontief's Matrix.' The method has gained huge importance during the second half of the twentieth century and has been widely used on a governmental level, for example in national economies of United States of Soviet Republics and France. The further description of the input-output models may be found in the work of Leontief (1986).

Another econometric approach that may be utilized to perform modelling of material flow is Regression Analysis. (RA) This is a quantitative method, which allows to analyze interdependences between variables according to the statistical data on previous periods. After the calculations of regressions, the values of variables for further periods of time may be projected with an accordance to a particular level of trust. Besides, the results of regression analysis may be calculated for different trust levels: the higher level of determination leads to broader value intervals and on contrary.

However, this method represents a black-box strategy which takes into account only the input and output data and does not consider the structure of dependence between the variables included into the model. Moreover, the quality of the developed model can be evaluated with several estimators, such as statistical significance, goodness of fit, and others. The detailed description of the method may be found in Freedman (2009). The application of RA method for modelling of material flows may be represented, for instance, by the study of Tanning et al. (2014).

2.4. ***Summary***

The conducted study of the up-to-date academic literature has shown modern state of the scientific advancements in several major areas relevant to the study. The first part of the review has been devoted to the sustainability and practices which have been based on it or have been adjusted through including of sustainable principles. According to the conducted study of the literature, the impact of sustainable approaches may be viewed in fundamental ideas of RL and connected to it CLSC. Besides, the concept of CE itself clearly represents a vision for a new economy through an implementation of sustainable principles on high-level, while the other approaches are devoted to help in establishment of it on lower levels of system decomposition for particular branches of economy, industries or business. Moreover, the attention gained by LCA may be as well explained by the international development of sustainable ideas and penetration of those in governmental, business, and social areas. Finally, recycling is widely considered in the described practices as sustainable from economic, environmental, and social points of view.

Furthermore, literature review elicited concerns of different countries for sustaining a supply of raw materials, which has led to creation of a new concept CRM. While the first reports may be seen as introductory studies which had been mainly devoted to providing a glimpse on an issue related to criticality of raw materials, the modern studies have further developed initial methodologies and represent resumptive sources describing in details actual conditions. In addition to studies of criticality conducted by governmental offices and international organizations, one may find CRM studies analyzing particular materials assessed critical or utilization of CRM in precise industry or region.

Moreover, the third part described approaches which may be utilized in order to model material flow. Although some of the studies related to the material flow modelling are not connected to sustainability, in a majority of cases, the key aim of modelling is to evaluate situation in economic or environmental terms and to offer conclusion which may be of help for establishing new systems or developing the existing ones.

Finally, the reviewed scientific literature allows to additionally clarify the importance of the study and ways to achieve established objectives and, therefore, answer formulated research questions.

3. METHODOLOGY

Methodology is an important part of a research, which allows to ensure quality of the study and its credibility. On order to provide a clear description of the methodology, this chapter has been divided into several sub chapter. The first describes methods for achieving research objectives and explains how the formulated objectives should be achieved. Besides, this sub-chapter includes the description of the modelling approach choice. The second illustrates the refined framework of the study and its focus. The next provides explanation of the constructed research design including two main stages. Finally, the data collection is discussed.

3.1. *Methods for Achieving Research Objectives*

First of all, after the study of different approaches which may be used for modelling of material flows, it is necessary to decide which of them should be utilized in this study. This subsection deals with a short explanation considering the matter.

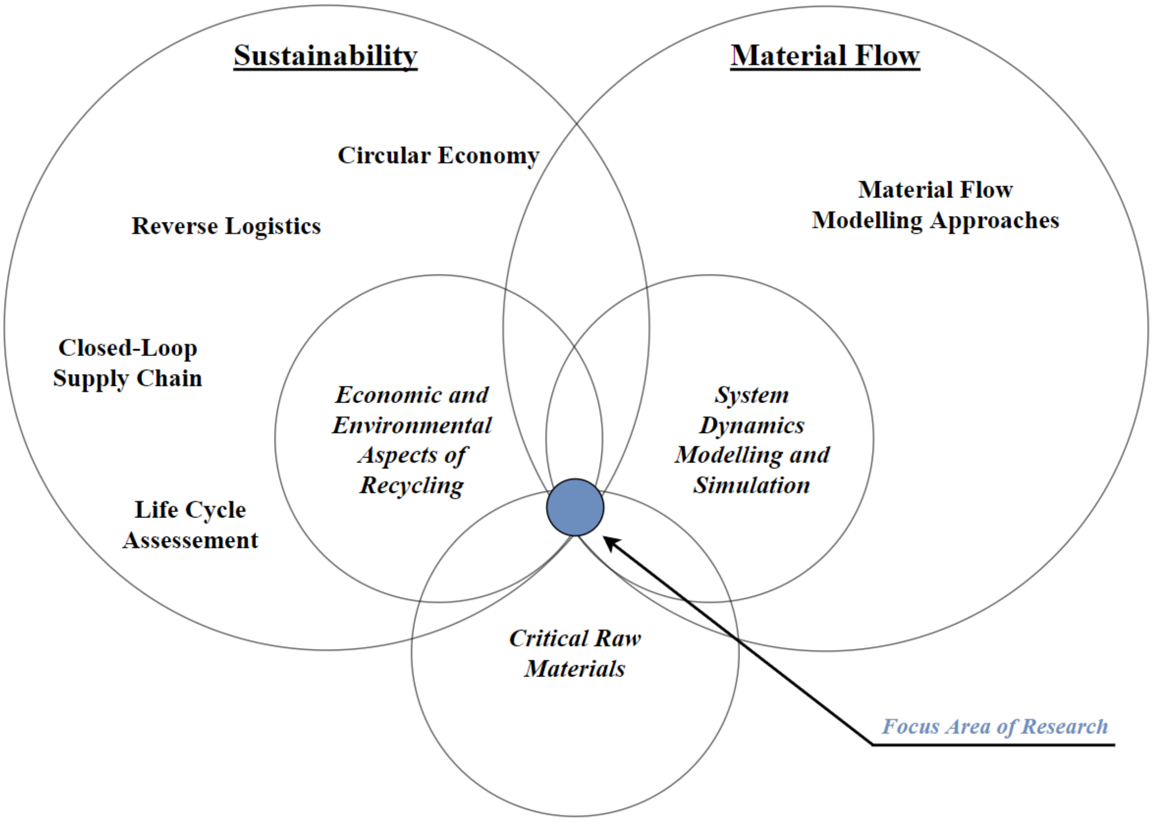
In accordance with the results of the analysis conducted by the Author of the study performed to decide which modelling approach should be utilized to model material flow of niobium, the choice has fell on System Dynamics Modelling and Simulation, due to its suitability and convenience to model high-level systems.

In addition, it should be mentioned that, while the Author has an experience in SDMS, it was concluded as the most suitable approach for this study and, therefore, the choice has not been influenced by Author’s preferences related to a personal experience.

However, although the decision on modelling approach has been made, the SDMS approach will be particularly utilized to provide answers not for all research questions. Actually, SDMS should deal with RQs from three to five, while for the first two questions mainly considering the study of the structure of niobium material flow and its traits will be utilized in-depth study. The full list of decomposed RQs may be seen in the table 1.

3.2. *Refined Theoretical Framework*

According to the gained results from the analysis of the up-to-date scientific literature and decision of which modelling approach should be utilized, the refined theoretical framework of the study and its focus area may be illustrated by the figure 13 below.



Source: The Author

Figure 13. Refined Theoretical Framework of the Study

The determination of economic and environmental conditions for implementation of innovative recycling methods of niobium may be viewed connected to establishment and development of sustainable systems for material production and consumption, and more broadly to sustainability area. However, in order to achieve it, the material flow of niobium should be modelled, which will allow to perform further analysis of the modern situation and, according to it, to evaluate possibilities for implementation of innovation recycling technologies.

For the modelling purposes, the SDMS will be utilized, considered as the most suitable method. Moreover, as the material of this case study niobium has been assessed critical raw material for different countries and regions multiple times, the research is connected to area of CRM.

Thus, the blue circle in the intersection of the areas covered in the literature review represents focus area of the research.

3.3. ***Research Design***

The fundamental goal of the research is to determine what economic and environmental benefits can be achieved in case of implementation innovative niobium recycling technologies.

The main RQ: "*What are the economic and environmental benefits possible to achieve from the implementation of innovative recycling technologies for niobium*?"

Besides, in order to answer the main RQ in a clear and resumptive way, it can be divided into several RQs. The list of the RQs of the study has been already presented in the table 1.

However, research design should describe in addition to formulated RQs and objectives, other information on research which would be sufficient to understand the process of answering every RQ. Therefore, the study has been divided into two main stages.

The first stage implies to conduct an in-depth study of the niobium material flow and covers RQ 1 and RQ 2. The result of the first stage is a conceptual model of niobium material flow During this stage should be studied niobium specifics, structure of the material flow, and information on niobium recycling, which should be used to refine the initial conceptual model of niobium material flow.

The second stage is connected to creation and further development of a SDMS model of Niobium material flow. The final version of the model should provide numerical results which would be sufficient to answer RQ 3, RQ 4, RQ 5, and RQ 6. The model should allow to simulate the dynamics of niobium material flow and include its economic and environmental specifics.

Thus, the description of the developed research design may be illustrated in the table 4 below.

Table 4. Research Design

#	Research Question	Research Objective	Research Method	Stages	Results
RQ 1	What is the structure of niobium material flow?	Reveal the structure of the niobium material flow	Multi-method study	First stage: in-depth study	Conceptual model of niobium material flow
RQ 2	What niobium recycling technologies are available?	Investigate niobium recycling technologies			
RQ 3	What amount of niobium scrap is (theoretically) available?	Evaluate the amount of niobium scrap (theoretically) available	Multi-method quantitative study	Second stage: SDMS with in-depth study	System Dynamics model including economic and environmental aspects of niobium recycling
RQ 4	What are the possible economic benefits of an implementation of innovative recycling technologies for niobium?	Determine economic benefits possible to obtain from an implementation of innovative niobium recycling technologies			
RQ 5	What are the possible environmental benefits of an implementation of innovative recycling technologies for niobium?	Determine environmental benefits possible to obtain from an implementation of innovative niobium recycling technologies			

3.4. *Data Collection*

Taking into account that the study aims to model niobium material flow on a global level, for data collection should be reasonable to mainly focus on open-access sources. The crucial information on niobium material flow and its specifics may be found in reports, reviews and web pages of companies related to niobium on any stage of its life cycle. In addition, report and studies of non-profit organizations may be as well viewed as valuable sources of information. Moreover, the reports of governmental agencies and departments should be seriously considered. Finally, scientific papers related to studies of recycling technologies, environmental and economic aspects of recycling and other stages of material life cycle, and niobium and its specifics in different areas should be included in the study.

Thus, in addition to primary data, secondary data will be used as well, which is connected to the fact, that in the majority of cases reviews and reports are based on primary data and represent them in more complex ways including calculations and various analyses. Such strategy may be viewed as a multiple case study.

4. CONCEPTUAL MODEL OF NIOBIUM MATERIAL FLOW

This chapter is devoted to development of a conceptual model of niobium material flow, which should represent the structure of material flow as well as the specifics on niobium recycling. Moreover, the information provided in this chapter should answer two research questions, formulated as follows:

- RQ 1: *What is the structure of niobium material flow?*
- RQ 2: *What niobium recycling technologies are available?*

In order to answer these RQs, the in-depth analysis of several aspects has been conducted, the results of which allowed to construct initial and refined conceptual model of niobium material flow, and, therefore, achieve the objective of the first stage of this study.

Furthermore, the chapter describes the analysis results and development of the conceptual model process distinguishing them in several subchapters. First of all, the specifics of niobium have been studied. This subchapter was further split into topical areas which included material overview and description of material properties and applications, niobium-containing minerals, mining, processing, product forms and application, and disposal.

The second subchapter introduced the specifics of metal recycling as well as provided explanation on modern recycling indicators. The next subchapters provided details related to niobium recycling and its technologies respectively. Finally, the initial and refined conceptual models of niobium material flow have been developed. The last subchapter summarizes the obtained results and allows to hold the focus during a gradual transition to the next chapter of this study.

4.1. *Niobium Specifics*

4.1.1. General Overview

Niobium is a chemical element with atomic number 41 and element symbol Nb. The material was previously known as Columbium, while, nowadays, the old name is widely used only in Americas. It is gray and lustrous paramagnetic ductile metal highly resistant to abrasion and heat.

Niobium can be found in the major CRM lists of different countries. Niobium has been included in the list of CRM for the EU within the studies of the years 2010, 2014, and 2017.

(European Commission 2010, 2014; Deloitte Sustainability et al., 2017) In addition, according to the summarizing review of American studies of criticality, niobium has been included in the top-level criticality level of American Resources Risk Pyramid. (McGroarty et al., 2012) Besides, other countries as Japan assess niobium critical and closely monitor global situation with niobium and its flows. (e.g. Hatayama and Tahara, 2015) Thus, it is possible to consider niobium as a globally critical raw material, which additionally pushes towards finding new ways of sustaining global material flow of niobium.

4.1.2. Properties and Applications

Prominent properties of niobium have caused its wide application in different industries. First of all, niobium is used as an additive in alloys in order to increase its strength, particularly at low temperatures, and durability as well as to reduce weight. Secondly, niobium is used for high temperature applications, which allows to increase material's high temperature resistance and corrosion and reduce its erosion. Thirdly, superconducting properties of niobium, which occur under -264ºC, has led to its usage in superconducting magnets for magnetic resonance imaging (MRI) scanners, particle accelerators, and nuclear magnetic resonance (NMR) equipment. Fourthly, the material is applied in electroceramics in optical modulators, surface acoustic wave filters, lenses, and glasses. Finally, other minor applications of niobium can be found in a variety of fields.

The description of the niobium properties and areas was based on the information obtained from (Shaw et al., 2011; Tantalum-Niobium International Study Center, 2017a; Royal Society of Chemistry, 2017).

4.1.3. Minerals

Niobium does not occur in nature in a form of a free metal but can be found as a component of different minerals, such as columbite, tantalite, pyrochlore, loparite, and others. Besides, niobium containing minerals quiet often include tantalum as well. (Schulz et al., 2014) Therefore, while the extraction of tantalum usually may be considered economically more efficient, especially due to its higher market price, such minerals are not processed for purposes of niobium extraction.

The primary mineral from which niobium is mined is Pyrochlore. Its known largest reserves are located in Araxa, Brazil and can suffice the world Niobium demand at the current level for approximately 500 years. (Tantalum-Niobium International Study Center, 2017b)

The detailed description of niobium mineral profile may be found in (Shaw et al., 2011; Papp, 2015).

4.1.4. Mining

The mentioned above Araxa deposits are owned by the world's biggest niobium producer CBMM (CBMM, 2017a), which covers around 90% of the world niobium production. Besides, there are two other niobium mining companies which correspond to remaining 10% of its world production. The first mine is located in Brazil. However, niobium business, which included this mine and three processing facilities as well as the other assets, has been recently sold by the Anglo American company (Ellichipuram, 2016) to China Molybdenum Company (CMC). (China Molybdenum Co., Ltd., 2017) The second mine situated in Canada belongs to Magris Resources Inc. (Magris Resources Inc., 2017) Moreover, artisanal mining activities have been registered (mainly in Africa), but its overall contribution is equal to 1% of total world output. (Niobay Metals, 2017)

Furthermore, the world production of niobium may be increased due to the emergence of new niobium producers which are going to start mining operations in different countries. Technoinvest Alliance has planned to build a tantalum-niobium mining complex in Irkutsk region located in Siberia, Russia. Cradle Resources has explored for mining opportunities in Tanzania at Panda Hill. In addition, explorations related to opportunities of niobium mining have been performed in Kenya and Malawi. The further overview and detailed information may be found in (Papp, 2015).

World mine production of niobium in 2015 was 64,300 tons of niobium content. (Papp, 2017) Here and after under the term 'tons' metric tons are considered, unless otherwise noted. The additional data and information on niobium mining and production may be found in (Cunningham, 2017).

4.1.5. Processing

Processing of niobium may be divided into two major schemes: processing of pyrochlore and processing of columbite and other tantalum-bearing ores. Due to the fact that all major active niobium mining companies extract and process pyrochlore, only pyrochlore processing scheme will be discussed in detail. Besides, the Panda Hill mine in Tanzania, which should start operating in the second half of 2018, will process mineral Pyrochlore as well.

The process starts with primary physical processing which allows to obtain instead of extracted pyrochlore homogenized ore. The next step is concentration, which may include different sets of operations depending upon the precise properties of extracted pyrochlore. CBMM concentration yard includes operations of wet grinding, magnetic separation, desliming, and floatation. The result of the concentration stage is enriched pyrochlore. After refining stage aimed to remove impurities as sulfur, phosphorus and lead, for which CBMM uses pyrometallurgical process, pyrochlore finally becomes a concentrate containing around 60% of niobium pentoxide. (Nb_2O_5)

Generally, niobium in a form of pentoxide is the initial chemical for production of other niobium products. For further production, different technological processes may be utilized in accordance with the desired product type, such as aluminothermic reduction, electron beam furnace, and other chemical processes.

The detailed description of niobium manufacturing processes may be found in (CBMM, 2017b; Tantalum-Niobium International Study Center, 2017c; Niobec, 2017a).

4.1.6. Products and Usage

Niobium products manufactured in different forms for different applications. Due to the material's prominent properties, niobium is applied in a variety of industries. According to the information provided in (Niobec, 2017b), niobium products may be generally separated into four main groups including Standard-Grade Ferroniobium (SG FeNb), Vacuum-Grade Alloys (VG FeNb and VG NiNb), Niobium Metals and Alloys, and Niobium Chemicals.

Besides, the source includes information distribution of market shares for groups of niobium products. As it can be seen from the table 5 below, SG FeNb has a dominant position with more than 90% of the market, while the other forms are used in the residuary market with almost the same values of about 3%. In addition to market shares, the table provides information on major application areas and principal markets for presented niobium product groups.

Furthermore, niobium products are manufactured by the mining companies as well as by the other companies, which obtain niobium in intermediate forms. Three major active companies (CBMM, CMC, and Magris Resources Inc.) produce niobium in a form of SG FeNb, while only CBMM among other mining companies manufacture more complex products including VG Alloys represented by the VG FeNb and VG Nickel Niobium (VG NiNb) which are, according to (Cunnigham, 2004) widely added to cobalt- and nickel-based alloys for jet engine applications; Niobium Metals and Alloys such as Niobium Metal Reactor Grades, Niobium Metal Commercial Grades, Niobium Zirconium; and Niobium Chemicals including High Purity (98.5% Nb content) and Optical Grade Niobium Pentoxides. The detailed list of niobium products manufactured by the CBMM may be obtained from (CBMM, 2017c).

Although one may find a variety of companies manufacturing niobium products, for the purposes of the study to model material flow on a global scale, it is essential to mainly consider initial flow of raw material from three mining companies, as the technologies of niobium manufacturing do not vary significantly.

Table 5. Niobium Major Products, Applications, Markets and Market Shares

Product	% of Nb Market	Major Applications	Principal Markets
Standard-Grade Ferroniobium (SG FeNb) about 60% of Nb content	90,2 %	❖ High strength low alloy steel (HSLA) ❖ Stainless steel ❖ Heat-resistant steels	❖ Automotive industry ❖ Heavy engineering and infrastructure ❖ Power plants ❖ Oil and gas pipelines ❖ Petrochemical sector
Vacuum-Grade Alloys VG FeNb and VG NiNb	3,0 %	❖ Superalloys	❖ Aircraft engines ❖ Power generation ❖ Petrochemical sector
Niobium Metals and Alloys e.g. Nb metal, Niobium-Tin alloy, Niobium-Titanium alloy, etc.	3,4 %	❖ Superconductors	❖ Particle accelerators ❖ Magnetic resonance imaging ❖ Various small-tonnage uses
Niobium Chemicals e.g. Nb oxides, Nb carbides, etc.	3,4 %	❖ Functional ceramics ❖ Catalysts	❖ Optical appliances ❖ Electronics

Adopted from Niobec, 2017b & Tantalum-Niobium International Study Center, 2017d

4.1.7. *Disposal and Recycling*

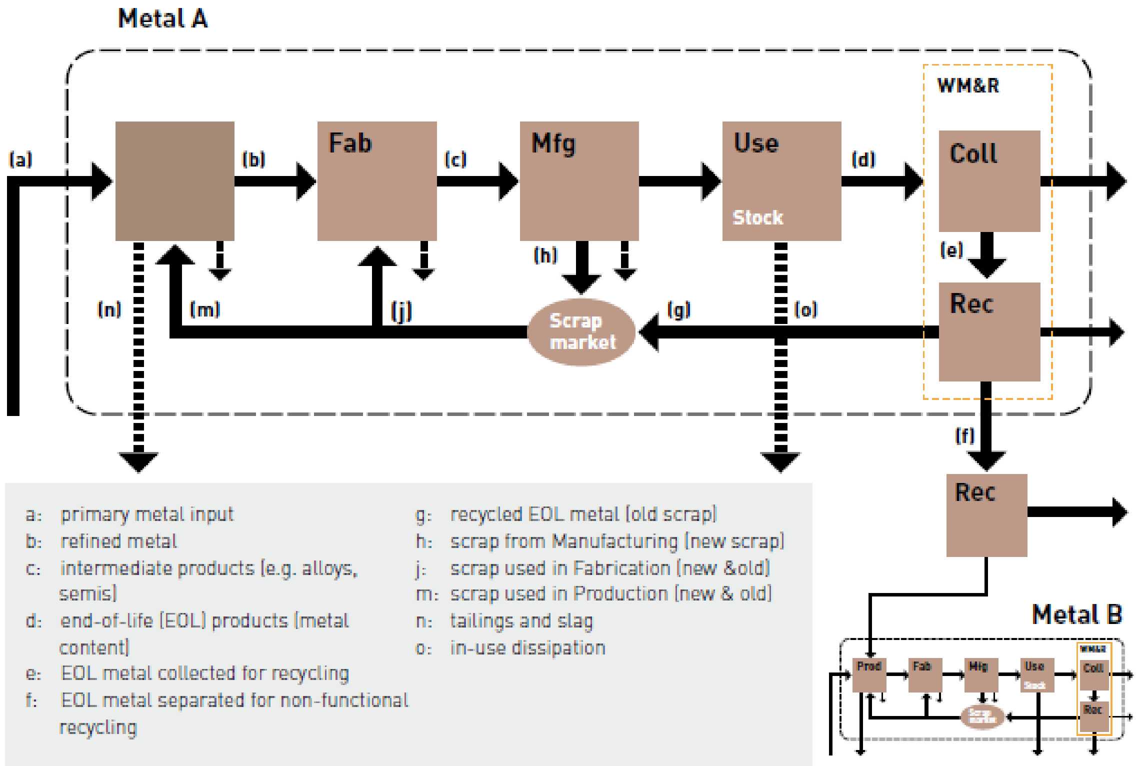
After the usage of niobium products, they have several utilization options. Generally, all of them may be distinguished into two main ways: recycling or landfilling. In comparison to other end-of-life products, niobium may be mainly found in a variety of steels with different quality for different applications, and, therefore, the further usage of niobium-containing end-of-life products is significantly limited to the same area of initial applications.

The detailed discussion on niobium recycling may be found in the subchapter 4.3 Niobium Recycling provided below.

4.2. ***Metal Recycling Specifics***

While the utilization for landfilling and other ways which are not connected with recovery of material is clear, for the second option related to recycling it is essential to elaborate specifics further.

To begin with, it is essential to define the process of recycling and related to it terms. Recycling rates may be defined and calculated in a variety of ways. However, in order to model material flow considering its recycling specifics, the recycling process should be studied and well-defined. This study offers to use terms related to scrap and recycling rates presented in the comprehensive report on modern metal recycling. (Graedel et al., 2011)



Source: Graedel et al., 2011 p.16

Figure 14. Metal Life Cycle

As it can be seen from the figure 14 above, the metal life cycle is separated into several major stages: production, fabrication, manufacturing, usage, and waste management and recycling including collection and recycling stages. In addition, the figure illustrates interconnections between different metal life cycles: metal A and metal B.

Besides, the metal end-of-life recycling may be separated into functional recycling and non-functional recycling. Basically, functional recycling leads to a return of material for its further production or situation when material continues to intentionally exist in a recycled product allowing specific beneficial properties, while non-functional recycling takes material away from its own life cycle in a form of impurity or 'tramp' element.

Moreover, the study distinguishes home scrap, new scrap (pre-consumer), and old scrap (post-consumer). Home scrap represents the scrap originated during fabrication and manufacturing processes, which may be used for them again. New scrap or pre-consumer-scrap originates from the same stages but it cannot be simply used again in the processes and should be recycled. The last type is old scrap or post-consumer, which represents the traditional scarp emerged in a form of end-of-life products.

In addition, there are several major indicators, which should be considered. End-of-life recycling rate (EOL-RR) indicating the fraction of the material returned into the life cycle after recycling from the old scrap originated after the usage stage.

Recycled content (RC) indicates the fraction of secondary material in the total input of material or, in other words, how much of recycled material is used in a production process.

Old scrap ratio (OSR) describes the fraction of old scrap in the total recycling flow including the flow of old scrap as well as the flow of new scrap generated from the production processes.

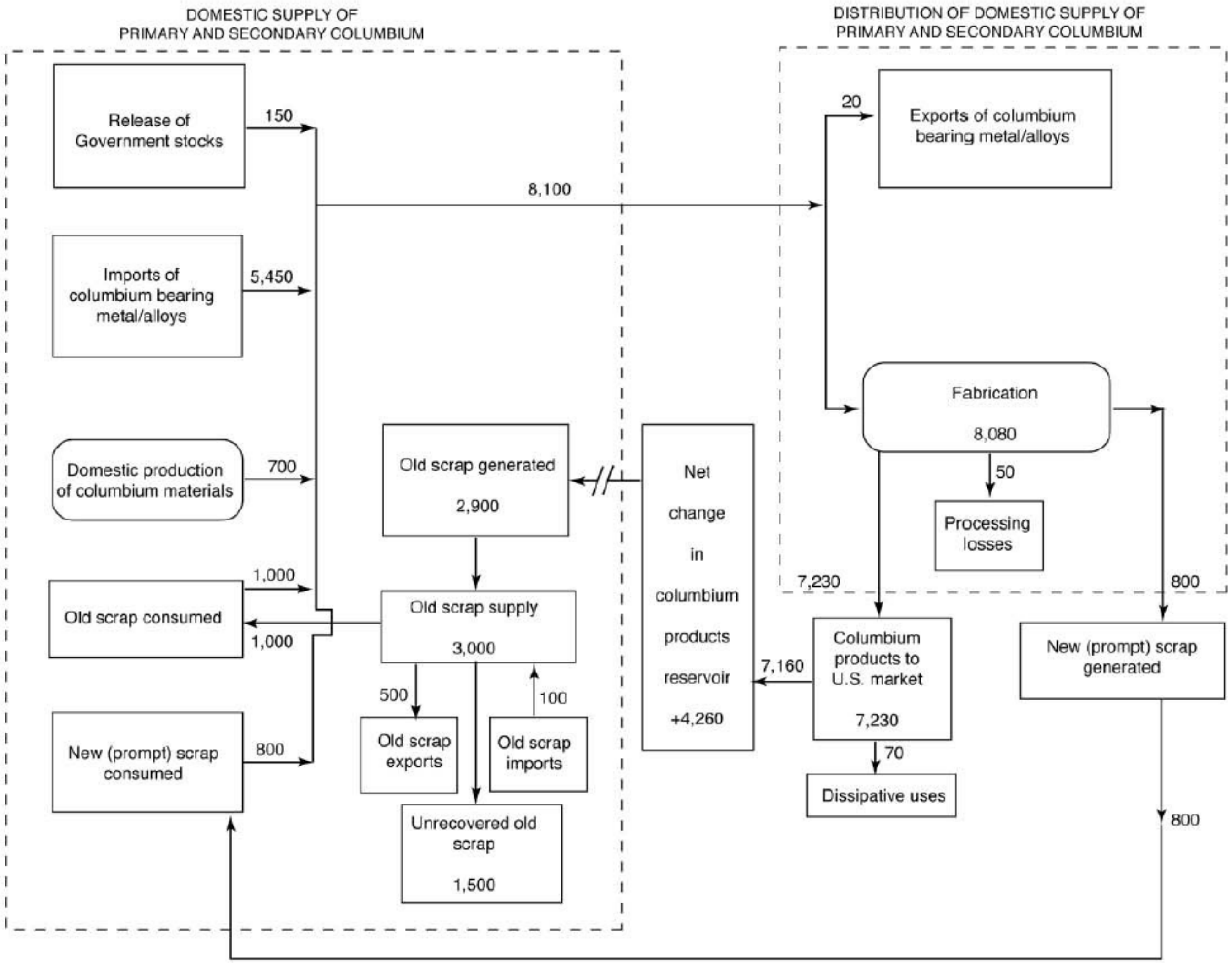
Recovery rate (RR) may be describes as recycling or recovery efficiency and defined by the current state of technological development related to recycling of particular material or group of them.

Due to fact that this study is focused on niobium recycling technologies and, therefore, functional recycling of niobium from old scrap, the home and new scrap as well as non-functional recycling are not studied in a great detail.

4.3. ***Niobium Recycling***

In accordance with (European Commission, 2010 p.37), the estimated recycled share of the total niobium consumption is about 20%. However, the source does not further specify the provided value, for instance, whether the value represents functional recycling or overall recovery of material. European Commission (2014b p.118) claims that while the functional recycling of niobium is negligible, the recovery of niobium-containing superalloys may reduce demand for material for as much as 20% of apparent niobium consumption. The same information may be found in Cunningham (2017).

Moreover, it is essential to explain that the majority of the reports indicating recycling of niobium at the 20% level and not specifying it in a greater detail, usually base calculations on the study of Cunningham (2004) or other studies, which had included statistics from there. The study (Cunningham, 2004) has conducted analysis of niobium material flow and its recycling in the United States in 1998. In addition, it determines several valuable indicators for recycling of niobium, such as OSR, CR, and EOL-RR which have been evaluated as follows 56%, 22%, and 50% respectively.



Source: Cunningham, 2004

Figure 15. Niobium Material Flow in United States in 1998

The figure 15 above represents a model developed to assess material flow of niobium in United States in 1998. All the values are in tons. Although this report refers to almost twenty years back situation, this is one of the most detailed and resumptive studies devoted to analysis of niobium material flow. The full description of the model may be found in (Cunningham, 2004).

According to the assessments provided in the (Deloitte Sustainability et al., 2017 p.34), the end-of-life recycling input rate (EOL RIR) for niobium is 0%, while the EOL RIR is described as ‘production of secondary material in EU from post-consumer functional recycling (old scrap) sent to processing and manufacturing and replacing primary material input. Moreover, the source specifies that in the previous reports (European Commission 2010, 2014a), recycling rates and EOL-RIR refer only to functional recycling. Furthermore, the EOL RIR at some point may be seen similar to the recycled content, which represents the fraction of recycled material in flow of material during its production. (Graedel et al., 2011)

Thus, the results of the comprehensive analysis may be unified and presented in the table below, which contains several indicators on niobium recycling. Cells of the table with the NA indicate that the information on a particular recycling indicator is not presented.

Table 6. Niobium Recycling Indicators

Source	**Study Moment**	**RR**	**OSR**	**RC**	**EOL-RR**	**RIR**
Cunningham, 2004	1998	**50%**	**56%**	**22%**	*NA*	*NA*
European Commission, 2010	2010	*NA*	*NA*	**20%**	*NA*	*NA*
Graedel et al., 2011	2011	*NA*	**44%**	*NA*	**56%**	*NA*
European Commission, 2014a	2014	*NA*	*NA*	**20%**	*NA*	*NA*
Deloitte Sustainability et al., 2017	2017	*NA*	*NA*	*NA*	*NA*	**0%**

In addition, the end-of-life recycling is strongly influenced by the least efficient stage of a recycling chain, which is typically the collection stage and related activities. (Cunningham, 2004) Therefore, low level of collection of niobium-containing products may be seen as one of the crucial factors influencing poor recycling of niobium. However, the study of collection activities and related to them specifics of niobium recycling is not the main object of this research, which is focused on niobium recycling technologies and possible to achieve by implementation of those economic and environmental benefits.

Thus, the modern situation with recycling of niobium may be describes as follows: recycling of niobium-containing steels and superalloys on a global level may contribute to the inflow of material with as much as 20% of its apparent consumption, while the other functional recycling of niobium is negligible and may be not considered at all. Besides, the actual niobium RR considered to be 50%.

4.4. ***Niobium Recycling Technologies***

Although the RR has been considered for further studies at 50%, one of the important aspects that should be studied is the advancement of modern recycling technologies of niobium. However, due to the poor functional recycling of niobium, the detailed information on specifics of niobium recycling and its technologies has not been found in a recent and modern literature. Therefore, the study aims to generally consider niobium recycling process discussed in the study of Cunnigham (2004) as well as metal recycling processes, since niobium is a ferrous metal, and the basic metal recycling processes and related technologies may be seen applicable to it as well.

Recycling of iron and steel scrap containing niobium starts with scrap collection and its primary processing. Scrap dealers purchase scrap and process it mechanically and chemically till it can be consumed in furnaces of steel mills. Usually, this process includes shredding, which allows to achieve fist-sized fragments, followed by baling to compact the scrap into bundles. Besides, there is sorting which allows to classify scrap according to different metal composition. On the next stage, steel mills carefully purchase scrap of specific composition to melt it in basic oxygen or electric arc furnaces.

However, the process of recycling superalloys is much more complicated. To begin with, these alloys are usually produced for high-temperature application and extreme conditions. Moreover, another issue is that they have a very complex composition. While the majority of superalloys includes more than twenty elements, each of them should be carefully considered in the recycling process containing separation and further recovery stages. All superalloys should be certified. Turnings of superalloys are degreased, fragmented and compressed by balers for remelting. Shredders are not utilized, while the remelting is conducted via air or vacuum remelting. The major source for superalloys recycling comes as home or new scrap. The recycled products are often accepted only for downgraded application to limit the impurities and ensure the quality of VG alloys.

The modern recycling companies utilize almost the same process. For instance, one of the niobium scrap recycling companies H.C.Stark (2017a) offers three-step process consisting of mechanical separation, thermal treatment, and chemical processing. Separation allows to achieve higher concentration of material in scrap and avoid unrequested elements. Thermal treatment utilized by electron beam melting, while chemical processing leads to further purification of the final product. According to the provided in the company's report on recycling technologies information, the recycling process allows to obtain in the end almost virgin material.

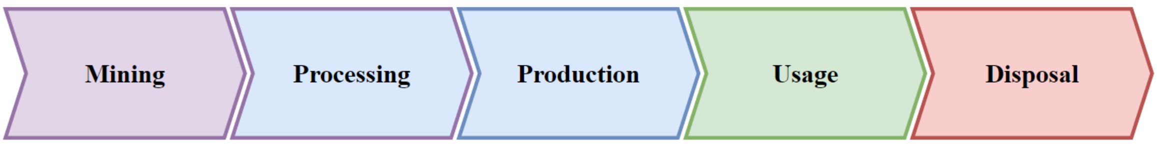
The description of the traditional and modern recycling technologies has been done in accordance with the information provided in (Cunnigham, 2004; H.C.Starck, 2017b). Besides, there many companies recycling niobium. For example, the Minor Metal Trade Association claims themselves to be the leaders in recycling of niobium from sputtering targets. (Minor Metal Trade Association, 2017)

4.5. ***Niobium Material Flow***

According to the conducted study on niobium and its specifics related to different stages of niobium life cycle, the development of a conceptual model of niobium material flow becomes possible.

To begin with, it is necessary to include major stages of niobium material flow into conceptual model. It was decided to add five major stages, such as mining, processing, production, usage, and utilization. This separation on major stages allows to represent material flow in a holistic way as well as to clearly represent its structure.

The illustrative representation of an actual conceptual model of material flow may be found in the figure 16 below.

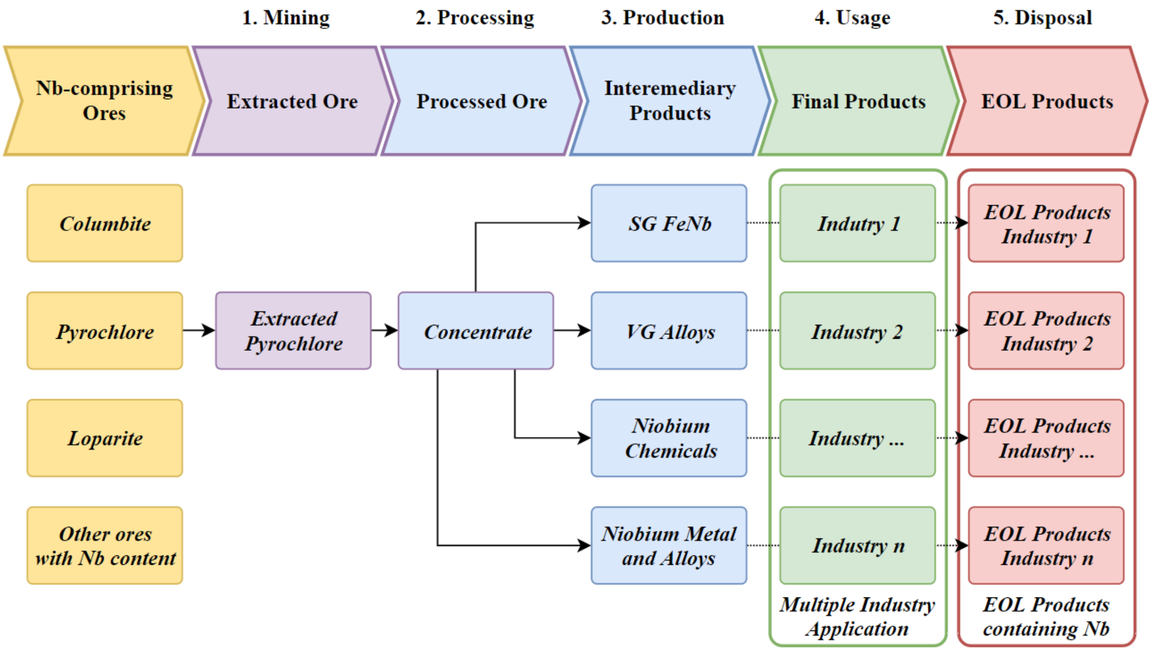


Source: Author

Figure 16. Stages of Nb Material Flow

However, current version of conceptual model obviously represents only stages of material flow and its sequence. In order to include information on niobium specifics, it is necessary to further develop it by the way of describing the forms of the material during different stages. The result of the development may be seen in the figure 17 below, which represents the conceptual model of niobium material flow.

First of all, one may find niobium in different ores, such as Pyrochlore, Columbite, Tantalite, etc. For this purpose, one extra stage was added to the conceptual model to show that niobium may be obtained from different ores. This stage is represented by yellow-colored elements,



Source: Author

Figure 17. Conceptual Model of Nb Material Flow

However, as it was discussed above, pyrochlore may be seen as the main source of niobium, due to the fact that all major niobium extracting mining companies mine pyrochlore. Therefore, the material flow starts with extraction of pyrochlore during the mining stage and its further processing to achieve niobium concentrate.

Till now, the flow of material follows the same route for all product types, and its distribution starts during the production of intermediary products. In accordance with the studies on niobium specifics and market situation described in the table 5, four groups of intermediary products have been considered: SG FeNb, VG alloys, chemicals, and metal and other alloys.

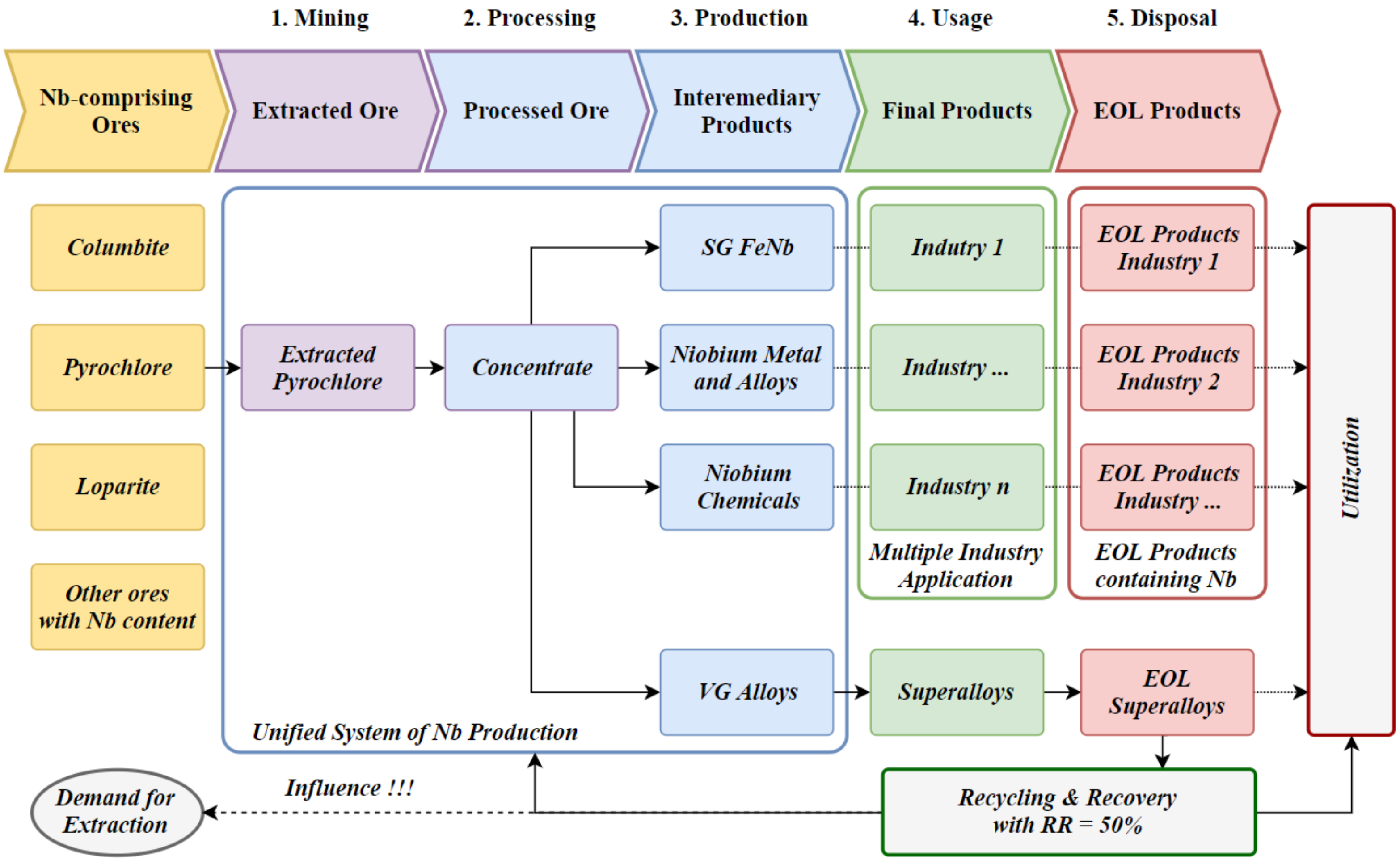
These four types of products are used in a variety of industries, which are additionally grouped into multiple industry application of niobium. After the usage stage, containing the material products become end-of-life (EOL) products, which may be utilized for landfilling or recycled.

However, as only the recovery of niobium from superalloys has been viewed significant enough to be considered in this study, the further decomposition of the conceptual model of niobium material flow may be seen not necessarily. The important modelling objective for the next stages related to the quantitative description of material flow is to take into account the recycling of superalloys during the assessments. Therefore, the refined conceptual model of material flow may be illustrated in the figure 18 below.

In comparison to the initial version, the refined version of the conceptual model provides information on niobium recycling specifics. Flow of material related to superalloy applications has been excluded from the generic material flow and shown as a separate flow in the lower part of the figure. When the superalloys are being disposed after its usage, some part of them is being recycled. Therefore, the material comes from EOL Superalloys into recycling chain where it will be recovered with 50% efficiency. Recycling and recovery is shown in the lower part of the figure with a grey-colored rectangular.

Besides, the dashed lines represent flows of material which have not been precisely determined. Although the functional recycling of niobium from other than superalloys uses has been considered negligible, there is still some fraction of material which enters the recycling chain and being recycled. In addition, the information on collection of niobium contained in superalloys is also cannot be seen resumptive, as the study knows only that the result of the superalloy recycling may constitute as much as 20% from the total consumption of Niobium. Thus, as long as the credible data for some of the flows has not been found, several of them has been intentionally presented as dashed.

Finally, due to the fact that recycling of niobium reduces the demand for material, and, therefore, the need for extraction of niobium-comprising ores, the refined conceptual model represents this interconnection between recycling and extraction with a named dashed line in the bottom of the diagram.



Source: Author

Figure 18. Refined Conceptual Model of Niobium Material Flow

Furthermore, the refined version has as well included a representation of boundaries of the global niobium production system, including processes related to Mining, Processing, and Production stages of material flow. In the figure 18 above, the system is called 'Unified System of Nb Production' and its boundaries are shown with a blue box. Therefore, according to the developed conceptual model, this theoretically unified system gains recycled material and, therefore, adjusts its production volumes in accordance with the level of demand for the material.

4.6. ***Summary***

This final subchapter summarizes the gained results described in this chapter and formulate the residuary objectives of the study, which should be covered further.

The main objective of this part was to develop a conceptual model of niobium material flow as a result of comprehensive study of the structure of material flow as well as of its recycling specifics. The detailed description of niobium specifics may be found in the beginning (subchapter 4.1), while the middle parts are devoted to recycling: specifics, actual situation and technologies. (subchapters 4.2, 4.3, 4.4) The process of development of the conceptual model and niobium material flow itself in its current state have been described at the end.

While this chapter provides information, which may be seen substantially sufficient to answer RQ 1 and RQ 2, the residuary RQs mainly related to quantitative description of material flow and contributing the second major part of this study will be covered in the next part devoted to system dynamics model of niobium material flow.

5. SYSTEM DYNAMICS MODEL OF NIOBIUM MATERIAL FLOW

This chapter of the study is aimed to describe the developed system dynamics model of niobium material flow including three following main parts:

- primary system dynamics model of niobium material flow;
- economic extension of the system dynamics model;
- environmental extension of the system dynamics model.

Each part starts with a detailed explanation of a modelling objective and discussion of the taken into consideration details and specifics. Therefore, the development process of each part is presented step-by-step, which should provide a clear and explicit illustration of the gained results. Moreover, after each of the parts has been discussed, the simulation results obtained from it are presented, that may be seen sufficient to answer the related research questions.

Thus, this chapter provides a clear discussion of the gained results related to the developed system dynamics model and its extensions allowing to perform a quantitative assessment of niobium material flow from specific viewpoints and answers the following research questions:

- RQ 3: *What amount of niobium scrap is (theoretically) available?*
- RQ 4: *What are the possible economic benefits of an implementation of innovative recycling technologies for niobium?*
- RQ 5: *What are the possible environmental benefits of an implementation of innovative recycling technologies for niobium?*

Furthermore, the VenSim software (Vensim, 2017) discussed in the literature review has been chosen to be utilized for the purpose of this research to conduct a system dynamics simulation and modelling of niobium material flow. Therefore, all the following figures representing the developed system dynamics model and its extensions or the fragments of those have been obtained from the VenSim modelling software.

5.1. ***Primary System Dynamics Model***

This part is devoted to a description of the primary system dynamics model of niobium material flow and its development process.

5.1.1. Modelling Objective

The main objective of the model is to answer RQ 3: *What amount of niobium scrap is (theoretically) available?*

In order to achieve this goal, niobium material flow should be translated into system dynamics model, which would allow to evaluate the flow of material during its main stages quantitatively and consider various recycling scenarios. The structure of the model has been developed in accordance with the conceptual model of niobium material flow described in the previous chapter of this study.

Besides, the development process has included several aspects which should be further clarified before describing the developed model itself as well as the gained simulation results.

5.1.2. Assumptions and Limitations

To begin with, lack of the data and scarcity of precise information have led to necessity to limit the system dynamics model in order to ensure its credibility and reliability of the gained simulation results.

The considered time period has been limited to forty years starting in the last decade of the twentieth century: the initial time – 1994, simulation end – 2034. There are two main reasons for such modelling time limitation.

First of all, in order to evaluate the current state of the system, the past situation should be considered and included in the model, due to the abundance of long-term delays in the material flow. In addition, in case the present state of the material could be fully determined, the past state could be not considered in the model. However, the existing data may describe only several parts of the flow: material extraction, structure of material flow, and application areas. Therefore, the past state should be modelled to describe the actual situation.

The second reason relates to modelling horizon. Due to the uncertainty of long-term projections, it was decided to consider 2034 as the end year. In case the market of niobium products and its development could be forecasted in a greater detail, the model could extend its time horizon.

Moreover, due to the time boundaries, it was as well assumed that the market of niobium has not seen structural changes from 1994 till now and distribution of niobium product among its end-uses may be seen similar.

Finally, due to the intention to simulate different niobium recycling scenarios, and as long the precise data on collection fraction of niobium products in forms of superalloys for recycling as well as the other data has not been collected, it was decided to include superalloys in the analysis as well as other niobium products.

5.1.3. Material Flow Decomposition

First of all, in order to describe the material flow from system dynamics perspective, the structure of material flow should be further revised. The main issue, which led to emergence of an additional attention to the structure of material flow, clearly discussed and represented in the developed conceptual model, was the uncertainty whether the decomposition level of the obtained data would suite the decomposition of the flow.

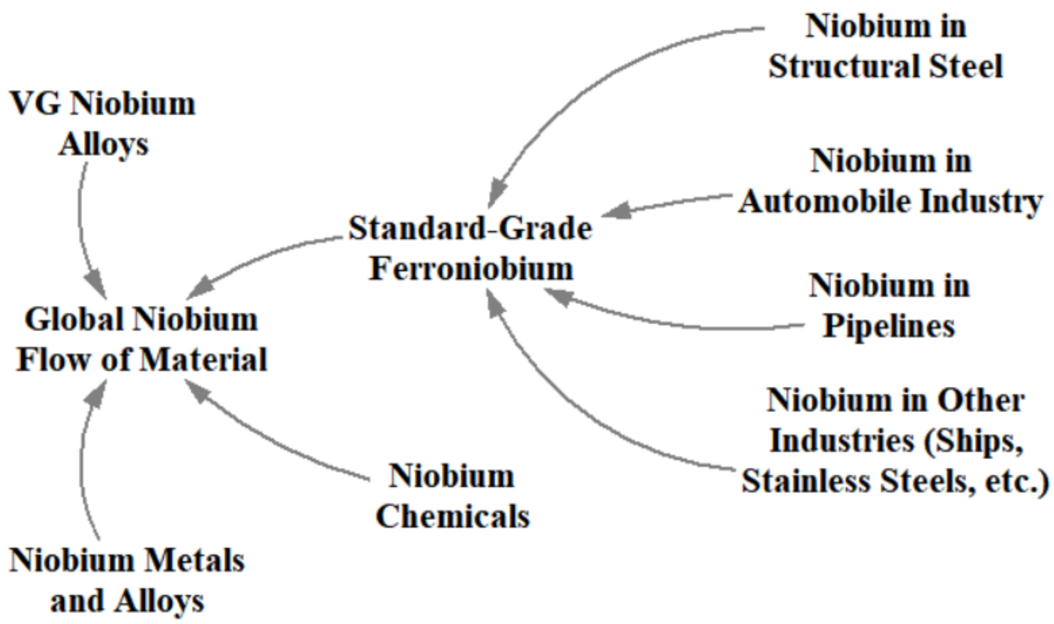
In other words, the study has accumulated the sufficient amount of information on niobium material flow and could represent the flow in system dynamics model in a great detail. However, in that case, the data for the description of precise flows would not be available. Therefore, the decomposition of the material flow should be done carefully to match the depth of the data collected.

The developed conceptual model clearly represents the actual situation of niobium material flow and its four main products which may be considered in the dynamic model. After the additional study on the options and analysis of the obtained data concerning the material flow, it was finally decided how to represent niobium material flow in the model.

The system dynamics model has considered decomposition of material flow in accordance with a view presented below:

1. Material flow of standard-grade ferroniobium:
   1.1. Niobium in structural steels
   1.2. Niobium in automobile steels
   1.3. Niobium in pipeline steels
   1.4. Niobium in other steels (e.g. Ships and stainless steels)
2. Material flow of vacuum-grade alloys
3. Material flow of niobium metals and alloys
4. Material flow of niobium chemicals.

The described decomposition of niobium material flow may be additionally illustrated by the figure 19 below.



Source: Author

Figure 19. Decomposition of Material Flow

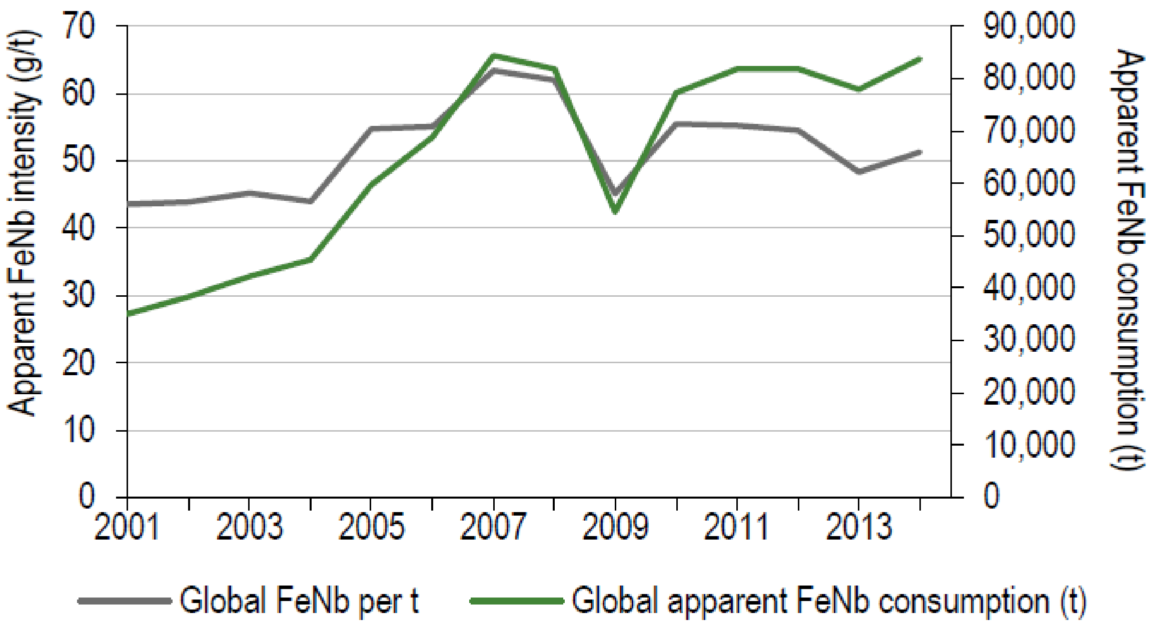
5.1.4. Modelling Inflow of Material

After the adoption of material flow structure, the rate of material production should be considered in the model. The objective of this part of the model is to represent the inflow of material into the system. However, as long as the time intervals involve past periods as well as the future ones, the process of modelling may be separated into two steps.

During the past periods, the model should access data on mine production of niobium, while for the future, the material demand should be projected. The determination of periods as related to past or present is not simply connected to the actual time. The threshold value is determined with the most modern estimation of world niobium mine production.

5.1.5. Niobium Mine Production: Statistics

While the data on demand for niobium and its consumption may be found in a variety of reports, the mining rates are kept not described. For instance, data on niobium consumption during the recent years may be found in the following reports (PROMETIA, 2018), which state that the global apparent consumption of niobium in 2014 reached 85000 tons. The figure below illustrates the dynamics of the apparent niobium consumption (right grade) as well as its alloying intensity in steels (left grade) during the beginning of the present century.



Source: Gibson, 2016 p.10

Figure 20. Global Niobium Consumption (in tons)

However, the evaluation of consumption should not be viewed suitable. Besides, the data should cover the period starting from 1994. Therefore, the detailed data on global niobium extraction has been obtained from the reports of United States Geological Survey covering the needed period of time starting from 1994 till 2015. The table 7 below represents considered in the model niobium extraction rate.

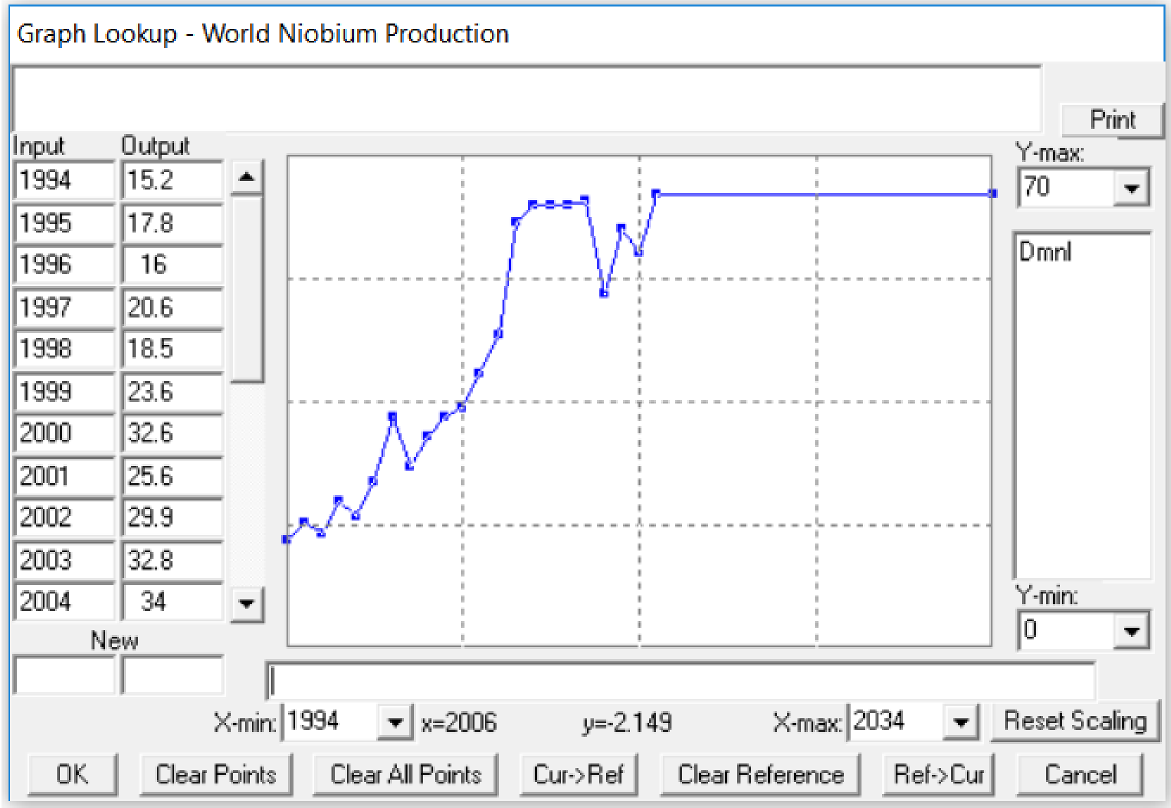
Table 7. World Mine Production of Niobium from 1994 till 2015 (in tons)

Year	Mine Production	Year	Mine Production
1994	15200	**2005**	38700
1995	17800	**2006**	44500
1996	16000	**2007**	60400
1997	20600	**2008**	62900
1998	18500	**2009**	62900
1999	23600	**2010**	62900
2000	32600	**2011**	63400
2001	25600	**2012**	50100
2002	29900	**2013**	59400
2003	32800	**2014**	55900
2004	34000	**2015**	64300

Source: Cunningham, 2018

Therefore, the 2015 has been considered as the last determined year, while from the 2016 the mining rate should be projected.

In order to consider statistics on global niobium mine production, the data has been included in the form of variable 'World Niobium Production', which affects the flow of material production.



Source: Author

Figure 21. Fragment of the Model 'World Niobium Production'

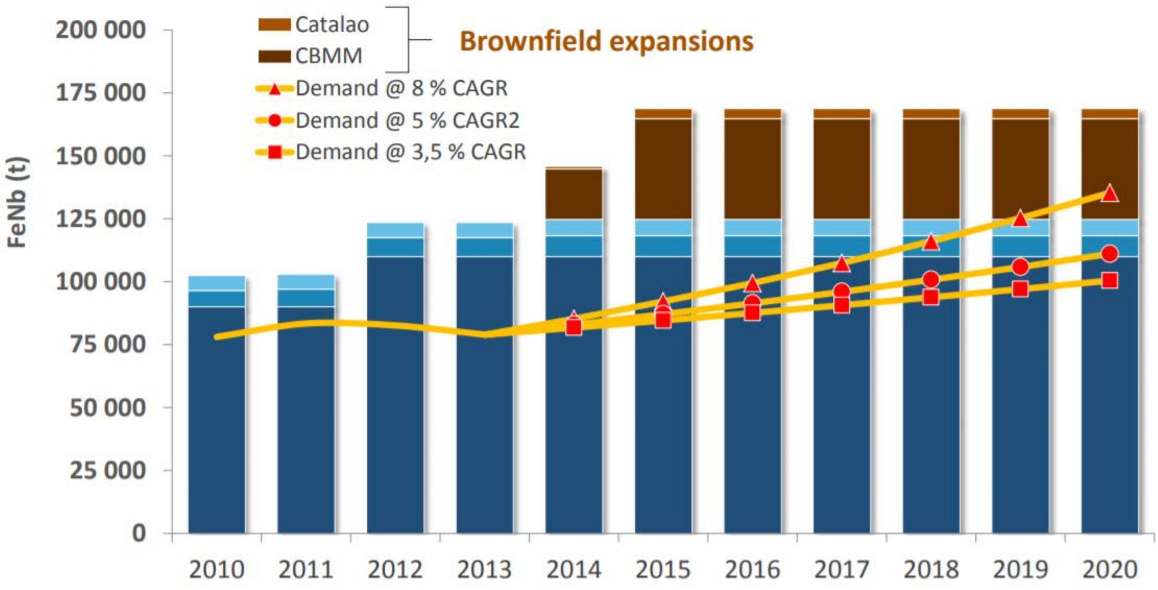
Figure 21 above represents how the variable has been determined in the model in accordance with statistical information obtained from United States Geological Survey.

5.1.6. Niobium Mine Production: Projection

While the inflow of material for the past periods has been modelled in accordance with statistical information, the world mine production from 2016 and further on should be projected. However, due to the absence of any forecasts for mine production, another indicator should be considered.

Due to the fact that the production of niobium is strongly connected to the material consumption, forecasts for the second may be viewed worth-considering. However, before considering the world niobium mine production projection via the demand forecasts, one restriction should be removed. In order to do it, the ability of world niobium production capacity to meet the requirements of the demand should be confirmed.

According to the information provided in (Niobay Metals, 2018), the actual world niobium production capacity surpasses the demand and its situation will not be changed, due actual surplus as well as to the capacity extension of the major niobium producers. The figure 22 below represents a bar chart describing the capacity of SG FeNb production, which dominates the markets, with the height of bars, while the yellow line illustrates the demand for material. The brown parts of the bars describe the planned production capacity extensions.



Source: Niobay Metals, 2018

Figure 22. World Niobium Production Capacity and its Extension

Therefore, knowing that the capacity exceeds the demand, the material production may be assumed sufficient to cover the demand for niobium during the future periods of time considered in the model. Thus, the additional modelling assumption has been introduced.

Furthermore, the adoption of the assumption has allowed to remove the restriction, and the projection of the material production may be modelled in accordance with niobium demand forecasts.

5.1.7. Modelling Demand for Niobium

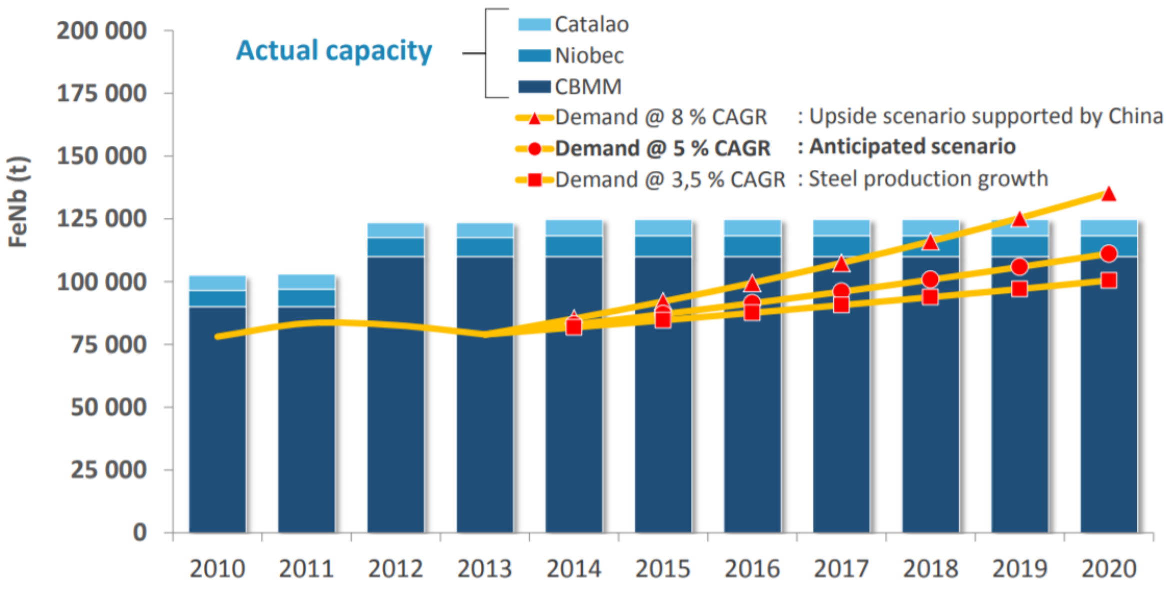
Taking into account that the several flows of material for different end-use areas have been considered, there are two major options of modelling demand for material.

First of all, for each of the considered in the model end-uses of niobium its own trends and projections may be considered. This option may be seen as the most determined and clear, however the substantial amount of data should be available. The initial demand value may be calculated in accordance with distribution shares, while for the next periods the demand will be affected with specific factors defining its change. However, in that case, the data on every end-use and its specifics should be available.

Another option relates to modelling of future niobium demand in total, taking into account estimations of niobium products forms distribution among the considered end-use areas in the future. However, due to the absence of forecasts related to niobium markets shares among various product forms and end-use areas, the choice of this modelling option may lead to adoption of another assumptions.

To decide which of the ways should be followed, it is necessary to elicit niobium market and demand trends, which will be presented below.

While the figure 22 provided in addition to production capacity the demand projections, the more detailed description of the demand forecast and its various scenarios may be found in the other place of the same source.

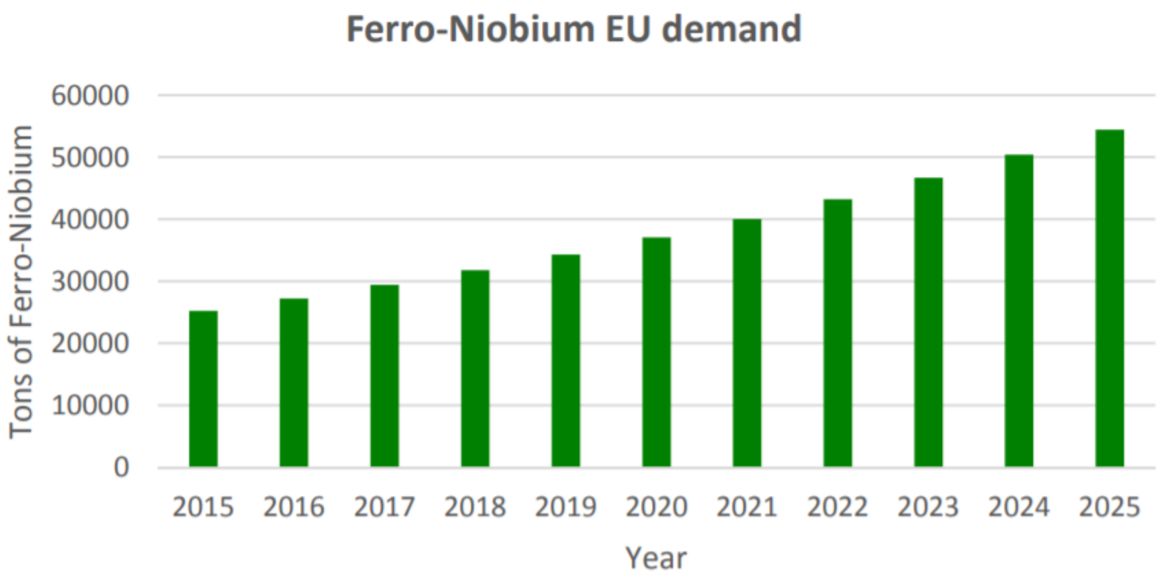


Source: Niobay Metals, 2018

Figure 23. Scenarios of Niobium Demand Projection and Production Capacity

The figure 23 above represents the projected scenarios for niobium demand starting from 2013. Three different demand growth levels have been considered for various Compound Annual Growth Rates (CAGR) including 3,5%, 5%, and 8%. According to (Staff, 2018), CAGR does not represent the true growth rate, but shows the growth in case it would a steady constant over time. While the demand at 5% CAGR has been indicated as anticipated scenario, China has considered the upside scenario with 8% CAGR.

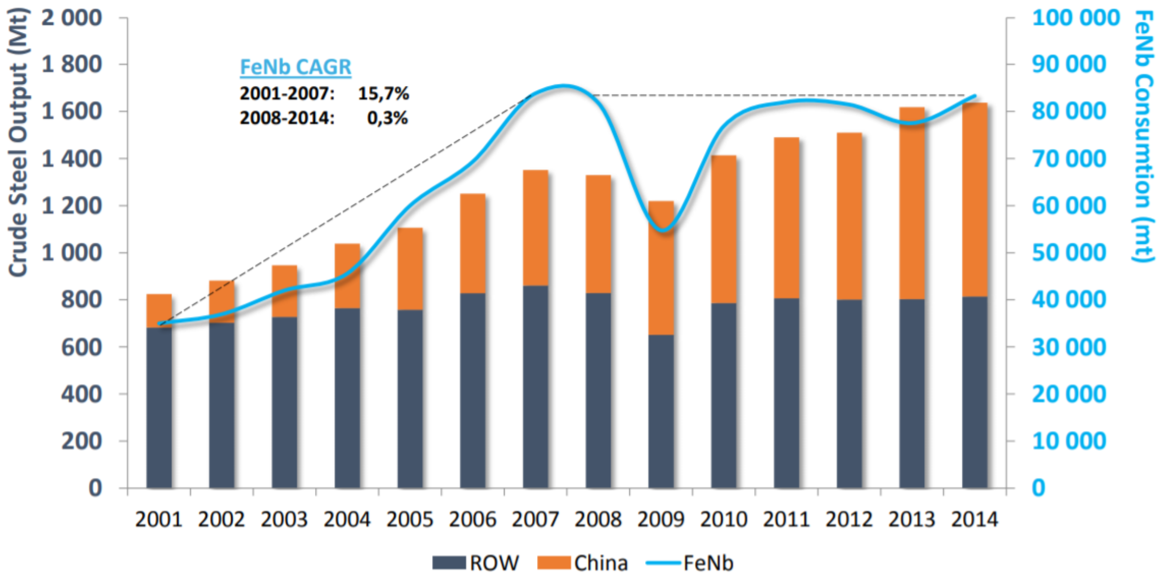
Moreover, the report (MSP REFRAM, 2016) evaluated the demand for SG FeNb in EU region in accordance with 8% CAGR. The evaluation may be seen in the figure 24 below, representing the demand with a bar chart for period from 2015 till 2025.



Source: MSP REFRAM., 2016

Figure 24. SG FeNb EU Demand Projection for 2015 - 2025

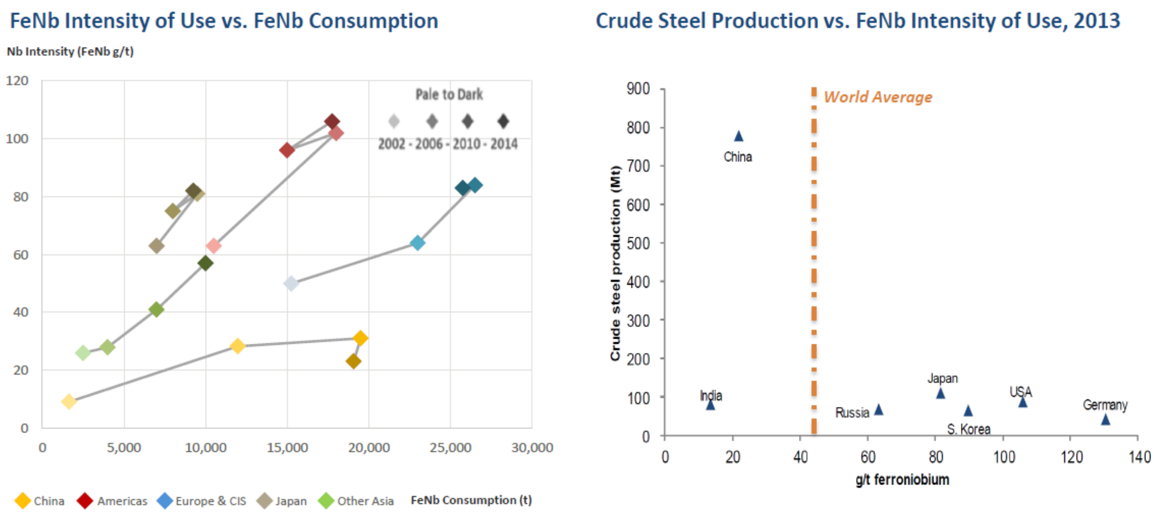
The fast-growing demand may be explained by two factors. First of all, taking into account that SG FeNb is mainly used in steel production, the demand follows the crude steel output. However, in addition to growth connected to the increase in amount of crude steel output, the content of Nb in such steels as well rises.



Source: Niobay Metals, 2018

Figure 25. Crude Steel Output and SG FeNb Consumption

The connection between crude steel output and consumption of SG FeNb clearly represented in the figure 25 above. Besides, the production of crude steel additionally separated into Chinese production (in orange) and rest of the world (ROW) production (grey), which allows to see that in 2014 Chinese production may be considered almost equal to ROW production.



Source: Cradle Resources Limited, 2015

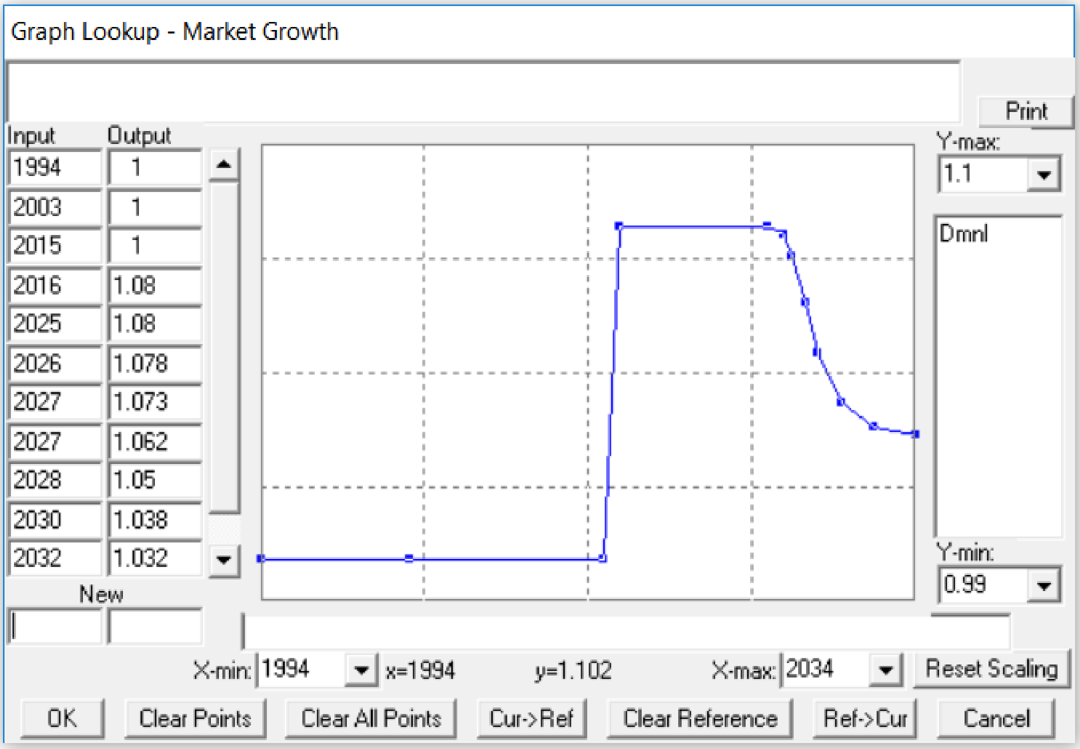
Figure 26. SG FeNb Consumption (left) and Crude Steel Production (right) vs. SG FeNb Intensity of Use

Although the volumes of Chinese crude steel production are very high, the Chinese SG FeNb consumption does not match, due to the low content of Nb in Chinese steels in comparison, for instance, to American and European steels: approximately 30 grams per ton (g/t) in contrast to American 100 g/t and European 85 g/t. Therefore, the increase of Nb content in Chinese steels as well may be seen as one of the factors for SG FeNb demand growth. The global average content of Nb in steel has constituted around 45 g/t. The additional data may be seen in the figure 26 above.

While the projections for demand of SG FeNb and its growth as well as the description of the major affecting it factors may be found in several sources, the discussion on the other forms of niobium products does not include any precise values. For instance, the report (MSP REFRAM, 2016) just claims that other than SG FeNb products may face rapidly increasing demand. The detailed description of niobium product forms and further opportunities for their applications may be found in (Bilewska, 2016).

To sum up, since the exact data has been found only for the future demand for SG FeNb, the study has decided to follow the second option for modelling material demand. Thus, it was decided to consider demand forecast for SG FeNb at 8% and assume that the other niobium products related to high-technology applications will face not lower increase in demand than SG FeNb. Therefore, the same 8% GR was considered for other Nb products.

Moreover, the model will distinguish niobium market growth rates among mid-term and long-term projection time periods. The obtained 8% CAGR will be used for period of 2016 - 2025, while during the 2026 – 2035 period the CAGR of niobium market decreases and aims at 3% annually. The way of modelling niobium market growth is illustrated in the figure 27 below.



Source: Author

Figure 27. Fragment of the Model 'Market Growth'

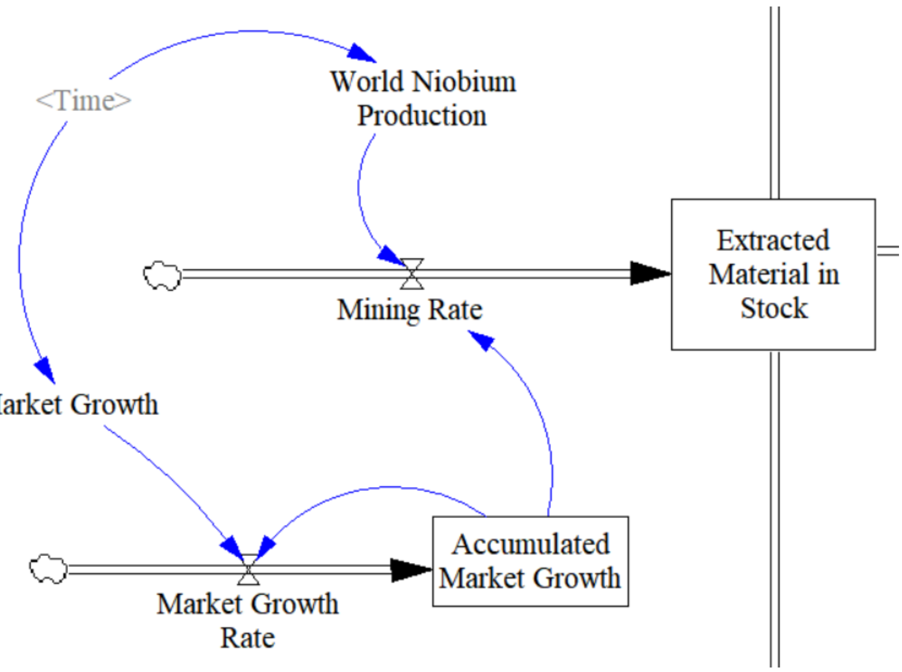
The figure 27 above represents the fragment of the model related to determination of variable 'Market Growth', which is used as a multiplier in the equation of total production rate. As it may be seen from the figure, from the initial modelling time (1994 year) till the beginning of 2016 year the market growth is not considered (variable 'Market Growth' = 1), as the production rate is modelled only in accordance with statistical information. However, since the moment when the year 2015 ends, the variable has been set at 8% GR (variable 'Market Growth' = 1.08). Furthermore, from the beginning of 2026 the growth of the market starts to decrease aiming to set up at an annual 3% GR in 2034. Instead of linear decrease, S-shaped behavior has been considered. The detailed description of the S-shaped behavior in System Dynamics may be found in Sterman (2000, p.295).

To sum up, in order to consider future trends of niobium production in the model for 2016-2034 period, since the projections on the mine production are not available, the forecasts on demand for niobium has been considered. Besides, the study has confirmed that the production capacity is substantially sufficient, as there is a surplus that will continue to exist. Finally, the considered growth rate has been discussed.

5.1.8. Consolidation of Production and Demand

This part describes how the data on global niobium mine production from the past periods has been connected with niobium demand projection determining the same production rate during the future periods. The objective of this part is to model the production volumes in past 1994 – 2015 years as well as in the future 2016-2034 years in a coherent manner.

The production of material in the model is represented with a variable ‘Mining Rate’, which determines the inflow of material into system in tons of niobium content. The part of the model related to material production is presented in the figure 28 below.



Source: Author

Figure 28. Fragment of the Model ‘Mining Rate’

As it may be seen from the figure, the ‘Mining Rate’ is connected with two other variables: ‘World Niobium Production’ and ‘Accumulated Market Growth’. The calculation of the rate has been done as it is shown below.

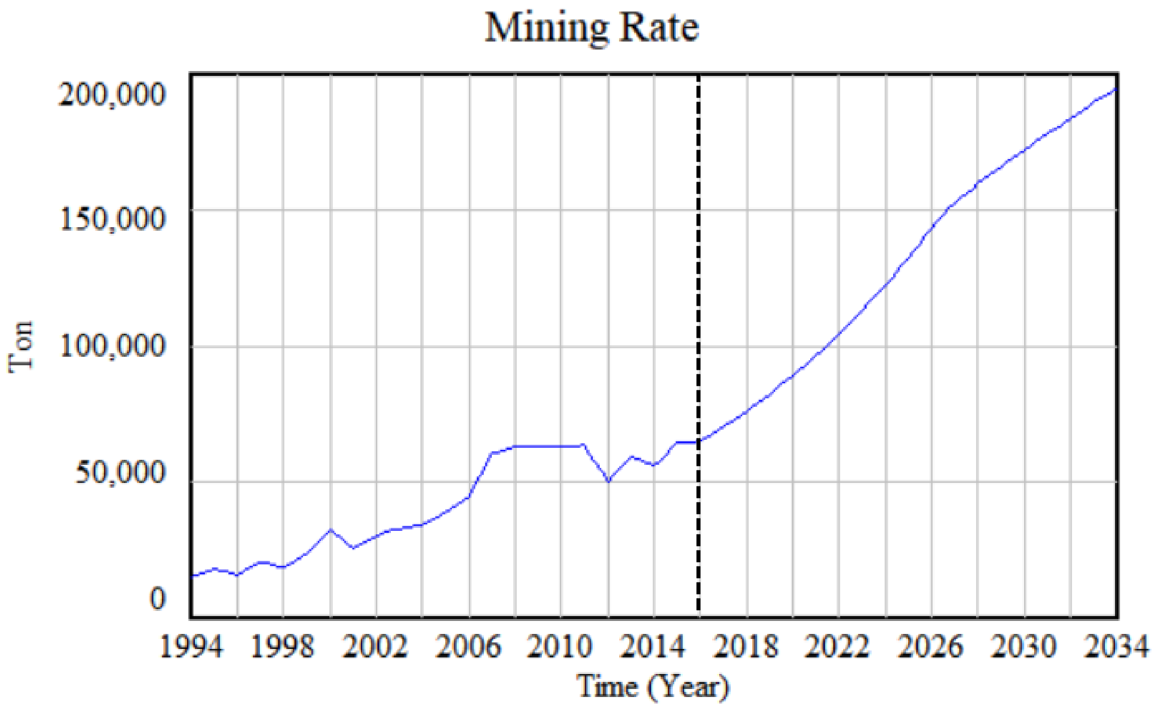
*‘Mining Rate’ = ‘World Niobium Production’ * ‘Accumulated Market Growth’*

While the variable containing statistical information on niobium production is directly connected to the rate, the way which allowed to considered market growth should be explained further. First of all, due to the absence of specific function which could allow to calculate the growth of variable at a certain growth rate in percentage, the additional flow and stock had to be included in the model.

The idea of the developed fragment implies that the stock accumulates the flow which is equal to market growth multiplied on actual level of stock (initial level = 1). The stock 'Accumulated Market Growth' include at a certain moment of time necessary coefficient which is used to project the material production starting from the beginning of 2016 year.

Therefore, the constructed fragment may be viewed as an additional structure working in a way as a specific formula. For instance, the software iThink developed by a company Stella includes a necessary in this case built-in function CGrowth, which would allow construct model without additional extensions. (e.g. Stella, 2018)

The exemplary results of the modelled mining rate are shown in the figure 29 below.



Source: Author

Figure 29. Modelled Mining Rate

The dashed black lone represents a threshold. The data on the left match statistical information, while the righter part illustrates the gained projection. Besides, it may be additionally seen that the inclination of the graph changes around 2027, which shows that the market growth speed has started to decrease, in accordance to the considered scenario.

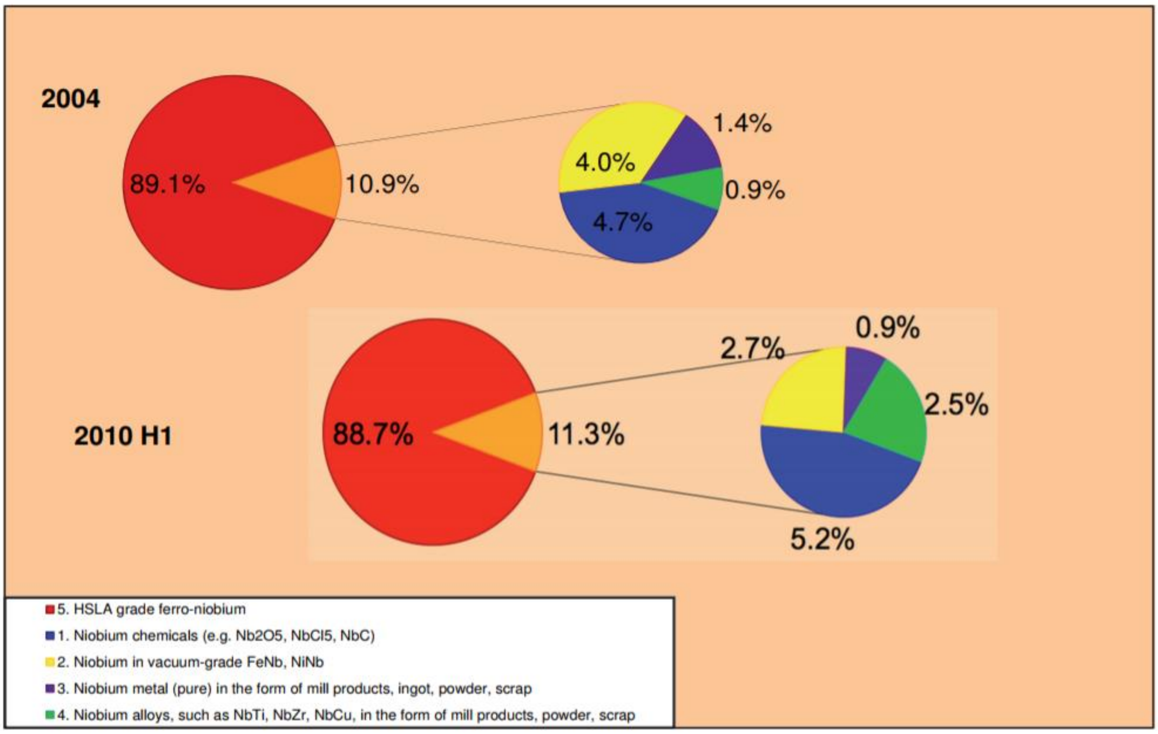
5.1.9. Distribution of End-Uses

The data on distribution of end-uses of niobium products by application areas and industries may be found in different sources, which provide not always the same information. Besides, the in-depth study has revealed that the majority of them cite each other, while the initial information is provided in several key sources.

In addition to the distribution of Magris Resources provided in the section 4.1.6. Products and Usage, the valuable information may be as well found in (Tantalum-Niobium International Study Center, 2011; Niobay Metals, 2018).

The first source represents one of newsletters quarterly being issued by Tantalum-Niobium International Study Center (TIC) containing relevant news and features on niobium and tantalum and available on the TIC's official web page. (Tantalum-Niobium International Study Center, 2018)

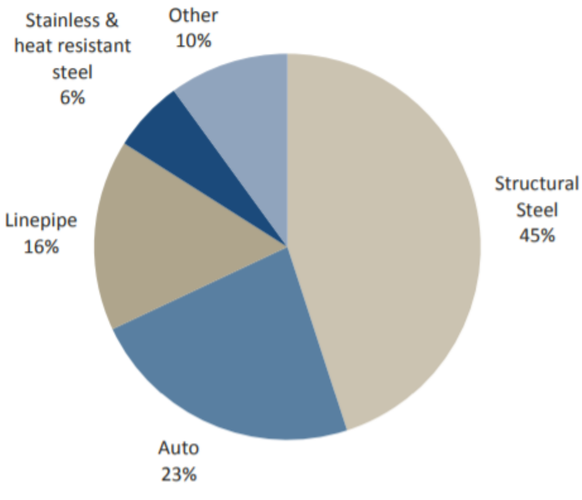
According to (Tantalum-Niobium International Study Center, 2011), in 2010 almost 90% of niobium was produced in a form of HSLA grade FeNb. The abbreviation HSLA stands for High-Strength Low-Alloy, which may be seen as another name of SG FeNb. The residuary part (more than 11%) included niobium application in other forms, such as chemicals, VG alloys, pure Nb metal and various Nb alloys. Moreover, this distribution has been included in the niobium-tantalum profile of British Geological Survey (Schulz et al., 2014), which may be seen as an additional factor for its credibility. The illustration of the discussed distributed may be found in the figure 30 below.



Source: Tantalum-Niobium International Study Center, 2011 p.8

Figure 30. Distribution of Niobium Products in 2004 and 2010

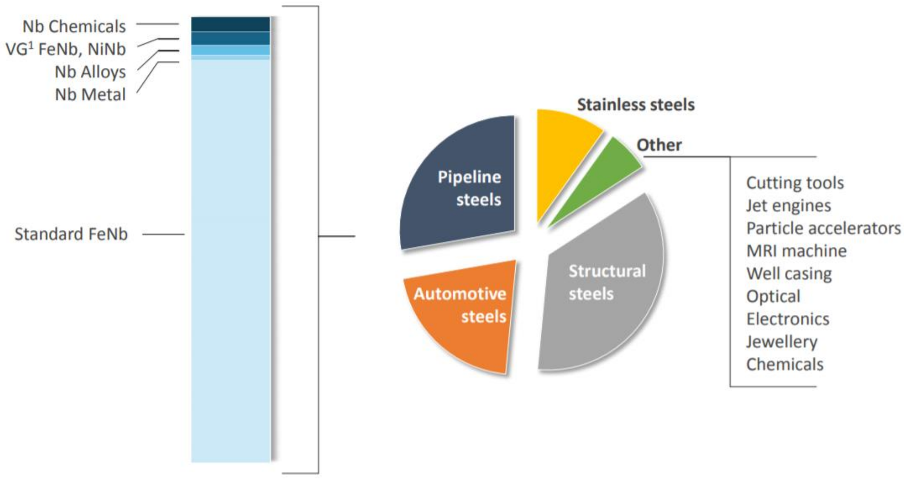
The figure 31 below, represents a distribution of end-uses of SG FeNb in 2012. The sector diagram represents the further distribution of SG FeNb among different industries. As it is seen from the figure, SG FeNb is mainly used in production of structural steel (45%), automobile industry (23%), and pipelines (16%). The minor applications represent 6% and relate to stainless and heat resistant steels, while the 10% used for other not specified areas.



Source: Cradle Resources Limited, 2015

Figure 31. Distribution SG FeNb End-Uses in 2012

The very same data may be found in the presentation of the MDN Inc. (Niobay Metals, 2018), represented in the figure 32 below.



Source: Niobay Metals, 2018

Figure 32. Distribution of Niobium and SG FeNb End-Uses

Although the year has not been specified, it may be considered as an assessment of the distribution of SG FeNb for the early 2010s. Besides, the bar chart on the left of the figure 32 above additionally describes the distribution of niobium product forms which are also may be seen similar to the data obtained from (Tantalum-Niobium International Study Center, 2011).

Thus, taking into account mentioned above, the study has considered niobium end-uses distribution as it is presented in the table 8 below.

Table 8. Distribution of Niobium End-Uses

Considered End-Uses		Distribution Shares *	
SG FeNb	Structural Steel	88.7 %	45 %
	Automobile		23 %
	Pipeline		16 %
	Other (e.g. stainless, ships)		16 %
VG Alloys		2.7 %	
Nb Metals and Alloys		3.4 %	
Nb Chemicals		5.2 %	

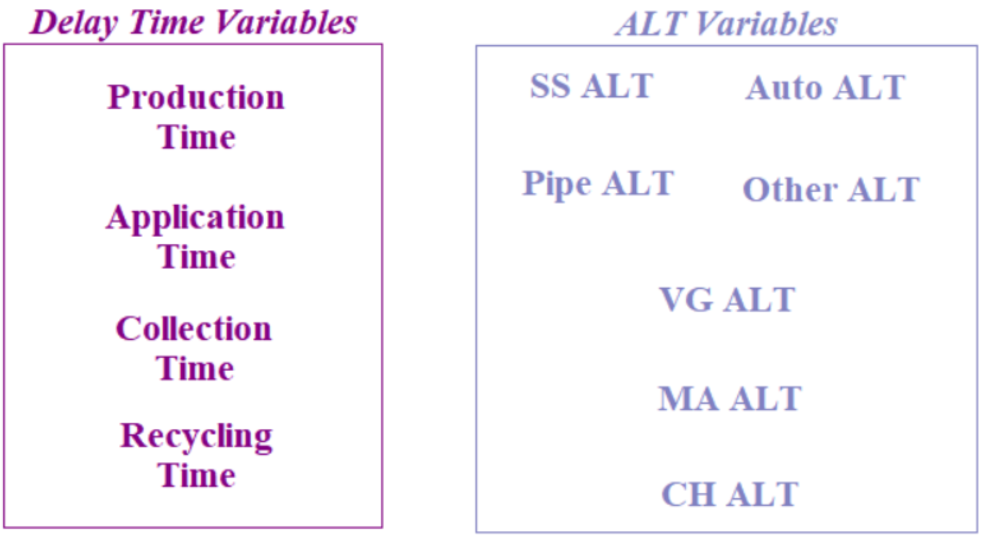
* It is important to clarify that, while the first-level distribution share of SG FeNb is 88.7%, the sum of the second-level distribution shares represent the fraction not among all end-uses but only among related to SG FeNb end-uses. Due to the fact that the model includes only one stock for SG FeNb and four end-uses, the shares have been calculated from the scratch and altogether account for 100%.

5.1.10. Modelling Delays

There is one another important point, which should be covered before the description of the main fragments of the developed model could be introduced. This part provides explanation on the considered in the system delays. In order to develop a dynamic model representing the realistic behaviour of the material flow, a set of delays has been included.

Besides, to clarify the importance of delays, one may consider situation without delays. In case the model had not included delays, it would have become a basic distribution model of the considered inflow. The materail inflow to the system, simultaneously separeted after the first-level distribution and the second one. The moments when material come into and disposed would become the same, as the delays between different stages are not considered. Moreover, in that case, the stocks would not accumulate any material and may not be viewed at all. The description above in a basic way describes the situation what if the delays had not been included in the model and clarify their importance for the developed model.

Thus, to model the flow of material in accordance with system dynamics principles, a variety of dealys has been considered. Every stock represented in the develop model has included its own delay. Moreover, for every branch of the flow, the input material will come through six various delays before it can reach the point of being recycled. Therefore, all ocnsidered in the model dealys may be separeted in several groups. Besides, the figure 33 below illustrates all considered groupd of delays in the model.



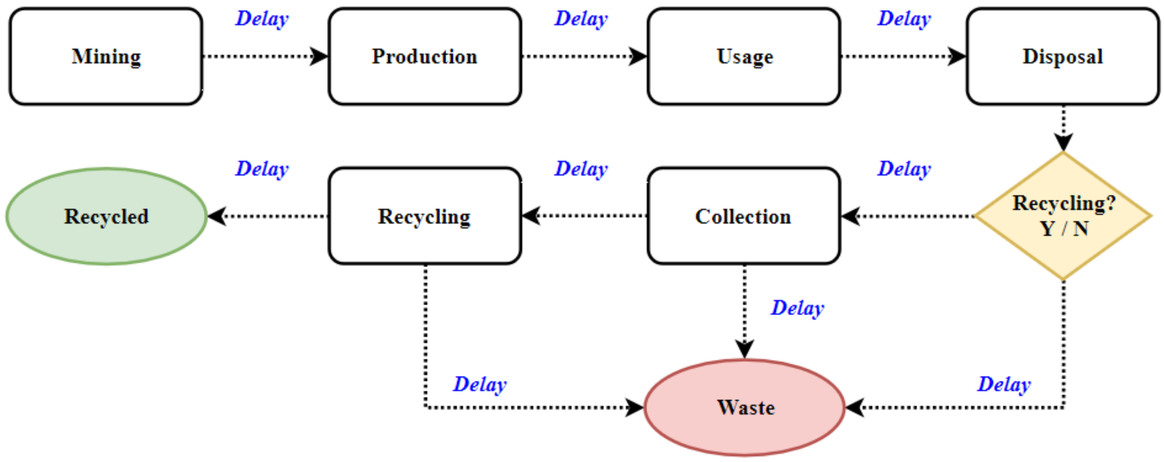
Source: Author

Figure 33. Considered Delays

As it may be seen from the figure 33 above, all delays may be distinguished into two groups: delay time variables and average lifetime variables. The first group of variables determines duration of delays related to every considered flow of material in the model except to the materail usage, for which the second group is responsible.

To explain meaning of every delay and reason for its implementation in the system, the exemplary flow including the same stages may be considered. The figure 34 below represents the considered in the model sequense of processes (rectangulars), while every has its own duration.

Therefore, in order to represent the real system, delays have been included. For instance, mining of material takes a certain time. Besides, the extracted material is not simultaneously used in manufacturing. Thus, the total time bay be viewed as a process time (functional time) and other delays (non-functional time) related to transpartation of material, downtimes, safe inventory stocks, etc.



Source: Author

Figure 34. Considered Delays and its Structure

One may see from the presented structure of the flow, how many delays affect in the model the materail flow. However, due to absence of precise estimations of time duration for every stage and process, as well as due to the considered decoposition level of the flow, the delays have been calculated approximately. While for mining and production the interval of 6 months has been considered, the duration of collection and recycling has been set to three months.

However, the second group of delays describing average life times (ALT) of material for different end-uses considered in the model, may be viewed as the most the most unflencing the system and its behaviour. Due to the fact that this variables determines the behaviour, the specific data should have been found. Therefore the study of ALTs for every considered end-use has been conducted.

In accordance with results of the study, the delays have been set with certain deurations in accordance with specifics of each end-use area. The table 9 below illustrates the delay variables and considered durations.

Table 9. Description of Delays

Variable	Value	Delay Group	Delay Type	Quantity
Production Time	6 months	Overall Delays	Fixed Delay	4
Application Delay	6 months			7
Collection Time	3 months		First Order Delay	
Recycling Time	3 months			
Structural Steel	30 years	Specific Delays (ALTs)	Fixed Delay	1
Automobile Sector	10 years			
Pipeline Sector	35 years			
Other Steels (e.g. Ships, Stainless)	20 years			
VG Alloys	20 years			
Niobium Metals and Alloys	10 years			
Niobium Chemicals	10 years			

While the duration values of overall delays have been considered approximately in accordance with overall information obtained during the in-depth study of material and its life cycle, the ALTs are based on the data from various sources described below.

The sources with information on ALTs:

- Constructions from structural steel: Donnelly, 2015; AskEngineers, 2018;
- Automobile : European Automobile Manufacturers Association, 2018;
- Gas and oil pepiline: Pipeline & Gas Journal, 2018;
- Ship – Shippedia, 2018;
- MRI scanners – Rentz, 2017;
- Superalloys – Cunnigham, 2004.

Furthermore, the developed model does not include certain values inside the equation, but uses specific variables for dealys, which allows to easily adjust from one place of the model all of them in case the further more detailed information on lifecycle and related time periods will be obtained.

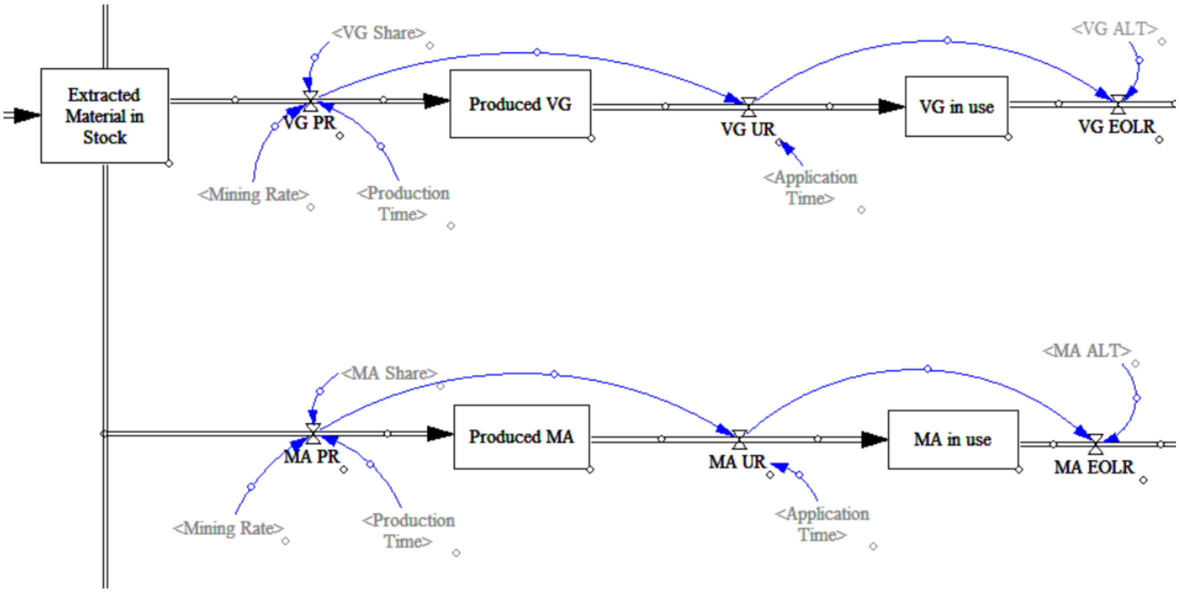
Besides, the last two columns of the table 9 above describe the considered delay type and the quantity of uses of a variable in the delays during the material flow modelling. Two delay types has been utilized: fixed delay and first-order delay. The detailed description of the both may be found in (Sterman, 2000 p.409), while the brief description of the main idea of dealy type may be found in (Osgood, 2000).

To sum up, this section has described the considered in the model delays: importance of delays for the developed model and the basic description of the fundamental idea of those from system dynamics viewpoint, related to delays variables and its place in the structure of the model, considered values of delay durations, utilized delay types and related aspects.

5.1.11. Modelling Material Flow

This section describes how the material flow of niobium has been modelled. The developed model implies that the overall flow of material (variable 'Mining Rate') is distributed into several flows in accordance with considered structure of flows and related distribution shares.

The stock 'Extracted Material in Stock' may be seen as an initial source for all other branches. In order to illustrate the utilized principle of material flow modelling, the fragment of the model related to the distribution of the main flow into branches and further modelling of those is presented in the figure 35 below.

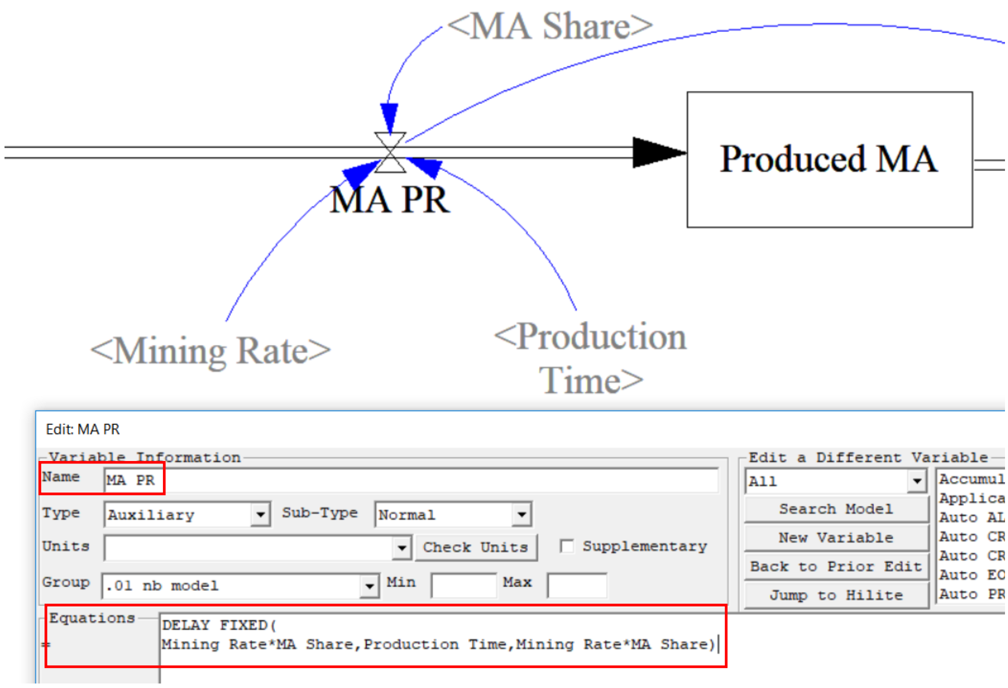


Source: Author

Figure 35. Fragment of the Model

As it may be seen from the figure 35 above, the fragment illustrates modelling of material flow for two flows: flow related to VG alloys (the higher branch) and to Metal and Alloys (the lower branch). Besides, all the branches are modelled in accordance with the same principle. Below the modelling principle will be explained for the case of Metal and Alloy branch.

The first step, when the material comes into the branch, is the flow 'MA PR', which represents the production of material in various forms for considered end-use area Niobium Metal and Alloys. The abbreviation 'MA PR' stand for metal and alloys production rate.

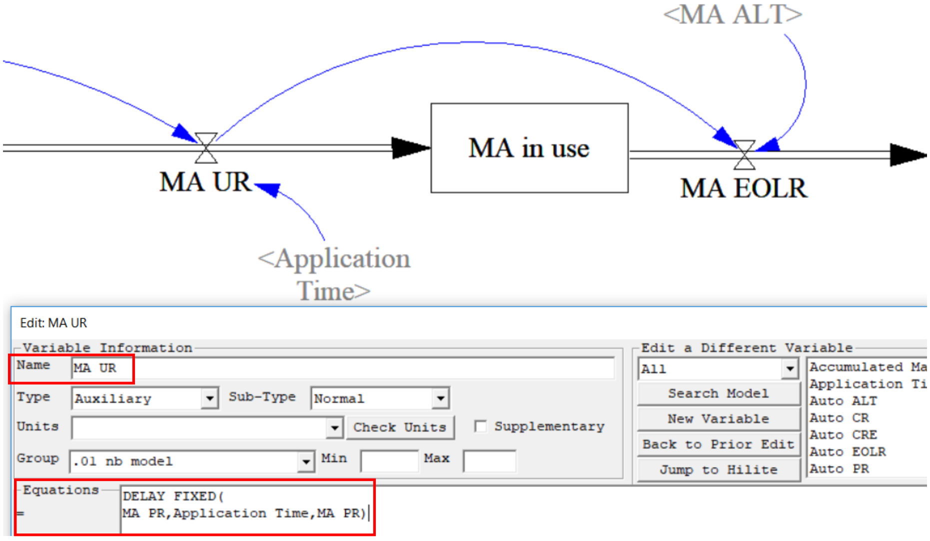


Source: Author

Figure 36. Modelling Production of Metals and Alloys

The description of the equation determining the flow ‘MA PR’, may be seen in the figure 36 above as well as the other variables afecting it, such as ‘Mining Rate’, ‘MA Share’, and ‘Production Time’. The function ‘Delay Fixed’ allows to model the delay of a certain duration. The variable ‘MA Share’ represents the fraction of the material which comes into the branch. In this case variable ‘Production Time’ represents the delay. The equation field as well as the variable name are additionally marked with a red-colored boxes in the figure.

Almost in the same way two next flows of material are modeled. The main difference between the previously described flow and ‘MA UR’ and ‘MA EOLR’ is in that the first includes the multiplier (‘MA Share’), while the second two delay the full flow situated before it. The figure 37 below represents the residuary fragment inlcuding two flows as well as the equation field of the varialbe ‘MA UR’.



Source: Author

Figure 37. Modelling Rate of Material Disposal

The abbreviation 'UR' stands for usage rate, while the 'EOLR' stands for end-of-life rate. Between the flows ther is a stock named 'MA in use', which shows how much material is in use. Besides, the delay used in the equation of 'MA EOLR' represents the scpecific delay, the duration of which is equal to estimated for this particular end-use average life time. The other delays connected utilized in this fragment are overall delays ('Production Time' and 'Application Time'), which have the same values for all flows. Equations of the both variables utilize previously mentioned function 'Delay Fixed'.

Finally the flow 'EOLR' comes to the next stock, which will be described in the next section describing the part of the model related to recycling of material. The same approach is utilized for all the branches of material flow. In addition to approach, the values of overall variables are the same, while ony the variables including ALTs and shares are specific.

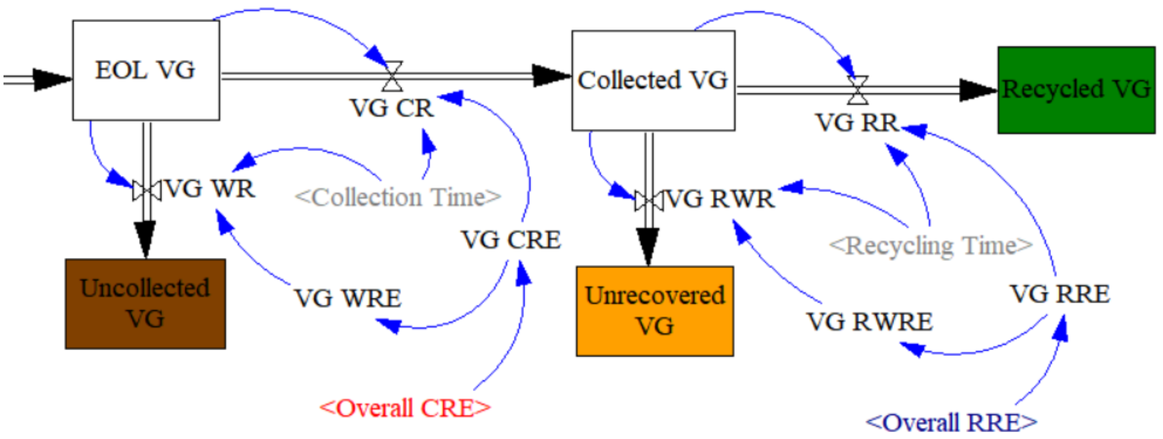
To sum up, this section describes how the material flow has been modelled and how the distribution of the flow has been implemented in the model. Besides, the detailed description of the considered modelling approach has been explained as well as the other related to it aspets for an exemplary case of the branch metals and alloys.

5.1.12. Modelling Recycling

Since the description of introductory information about the model has been provided as well as the explanation of the other parts and fragments of the developed model, only the recycling stage and the manner of its implementation have not been introduced yet. This section provides a detailed explanation of the part of the model related to recycling of material as well as its collection and utilization.

The previous section discussed modelling of material flow and its distribution. Although the discussion mentioned that the flow ‘EOLR’ is the input of a certain stock, the further details have not been provided, due to the fact that this stock ‘EOL VG’ may be viewed as a more connected to the part of the model related to recycling instead of the distribution of material among the flow branches. Besides, it is important to underline that the discussed separation of model into parts has being done only for purpose of a clear explanation, while the model is a single holistic object.

First of all, the recycling parts of the different considered in the model flows have been constructed in a similar way from a structural point of view. Therefore, the detailed explanation will be provided only for one exemplary case. The figure 38 below illustrates a fragment of the model related to a recycling stage of the branch of material flow VG alloys.



Source: Author

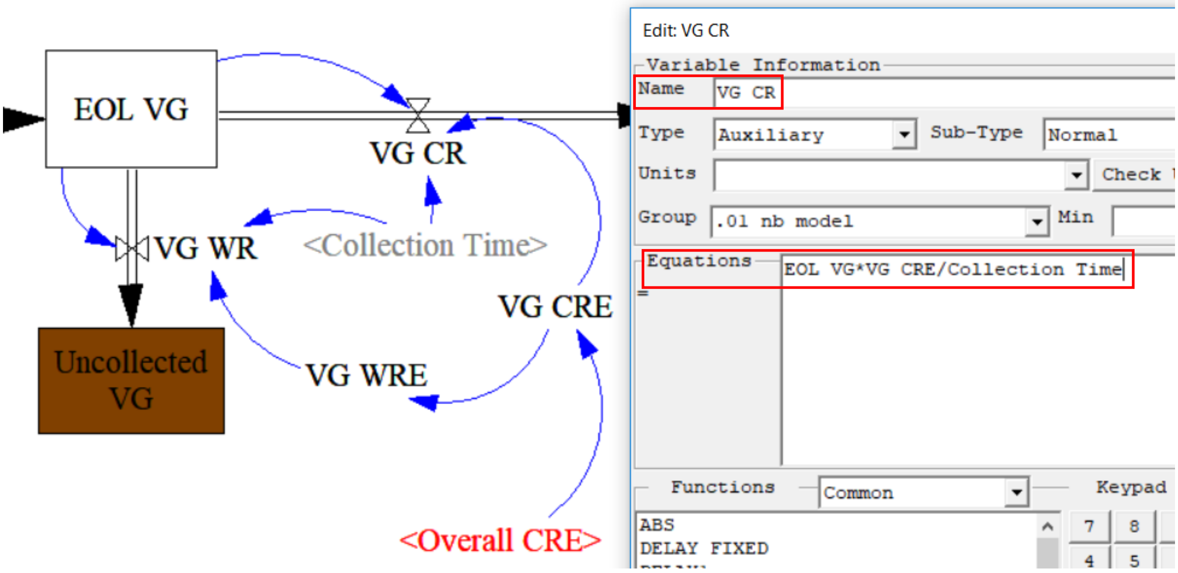
Figure 38. Disposal and Recycling Fragment of the Model

As it may be seen from the figure, the fragment related to recycling starts with a stock of ‘EOL VG’, which includes disposed after usage VG alloys. After that, the material can be collected for recycling purposes or can be utilized for landfilling or other not related with recovery options. This is the first considered in this part crossroad, where the material is diverted from being recycling, which may be described with an efficiency of material collection for recycling purposes.

The variable ‘VG CRE’ represents the fraction of material which is going to be collected, while the variable ‘VG WRE’ illustrates the residuary fraction. Abbreviations ‘CRE’ and ‘WRE’ stand for Collection Rate Efficiency and Waste Rate Efficiency respectively. In addition, due to the fact that the whole flow should be distributed into two ways, the variable ‘VG WRE’ is determined as follows: *‘VG WRE’ = 1 – ‘VG CRE’*

These variables are affecting two outflows: ‘VG CR’ represents the flow of collected material and flow ‘VG WR’ – not collected. The utilized abbreviation ‘CR’ stands for Collection Rate, while ‘WR’ for Waste Rate.

The figure 39 below represents the discussed fragment as well as the equation utilized for ‘VG CR’, which is affected by the three other variables. The fields of the equation modifier with the variable’s name and equation have been additionally market with a red rectangular.



Source: Author

Figure 39. Modelling Collection Rate

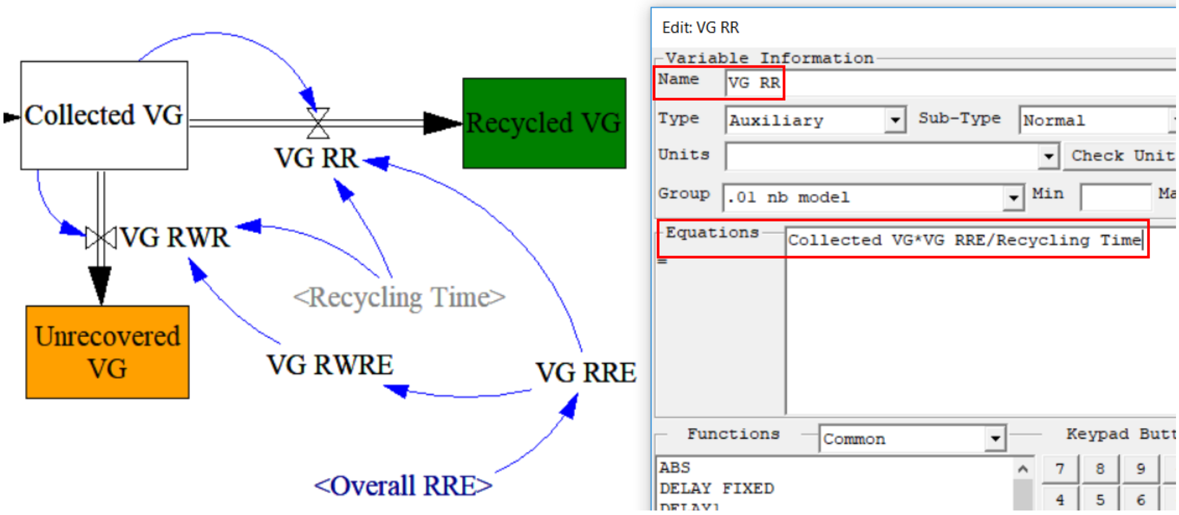
As it may be seen from the figure above, the rate has been determined as a fraction with a first order delay. The delay variable ‘Collection Time’ illustrates the considered value of delay. The same equation has been used for ‘VG WR’, only the fraction was determined by the other variable ‘VG WRE’.

The flow ‘VG WR’ illustrating the fraction of not collected material goes into a final stock ‘Uncollected VG’, which accumulates a wasted material. The stock is shown in a brown color, as well as the other considered in the model stocks with a wasted material. On the other hand, the flow of collected material ‘VG CR’ goes further into the next stock, which is called ‘Collected VG’.

The stock accumulates collected for recycling material. The efficiency of recycling determines how much material is going to be recovered from the collected scrap. Therefore, the material outflow from the stock ‘Collected VG’ is being separated again into two flows: ‘VG RWR’ and ‘VG RR’, which stand for VG Recycling Waste Rate and VG Recycling Rate respectively.

The distribution is completed by the use of two variables describing the rates: ‘VG RRE’ and ‘VG RWRE’, which stand for VG Recycling Rate Efficiency and VG Recycling Waste Rate Efficiency. Moreover, the second variable determined as *‘VG RWRE’ = 1 – ‘VG RRE’.*

The figure 40 below illustrates the discussed fragment of the model as well the equation used to determine the ‘VG RR’. The fields of the equation modifier with the variable’s name and equation have been additionally market with a red rectangular.



Source: Author

Figure 40. Modelling Recycling Rate

Each of the flows takes material to the final stock: the obtained from recycling material is accumulated in the stock ‘Recycled VG’, while the wasted, due to the technological efficiency of material recovery during the recycling process, part goes into the stock with a name ‘Unrecovered VG’.

The stocks are represented in a green and an orange colors respectively. Furthermore, the rates have been defined as a fractioned flow with a first order delay. The variable ‘Recycling Time’ has been utilized in the related equation as the duration of delays.

Thus, the description of the exemplary case has explained structure of the model in relation to recycling stages of material flow, its variables, equations, logic and general approach applied during the development of all the branches of material flow. Besides, the model considers three main stocks, which accumulate the material in the end of material life cycle.

Due to the fact that the information on the collection rate of material (for further recycling) related to end-uses of VG alloys has not been collected as well as to the other considered end-use areas, it was decided to determine all ‘ – CRE’ variables equal to a variable ‘Overall CRE’, through which all of them may be set to a certain level. Besides, due to the very same situation concerning the recovery rates, all ‘ – RRE’ variables have been set equal to ‘Overall RRE’, describing the considered 50% recovery rate for niobium recycling.

The variables ‘Overall CCE’ and ‘Overall RRE’ and the way of their connection to the variables local to the material flow of VG Alloys may be seen in the figures 38, 39 & 40 above. Shadow variables of those have been included for all considered branches, which allows to avoid excessive difficulties of a graphical representation of multiple connections in various parts of the model. The figure 41 below represents the fragment of the model with the actual variables.

Source: Author

Figure 41. Master Collection and Recycling Efficiency Variables

To sum up, this section has discussed the part of the developed system dynamics model devoted to modelling of material recycling and of the other related to it activities and specifics. The discussed exemplary case of VG alloys illlustrates the recycling in the other branches of material flow and, therefore, the way how the recycling has been considered in the whole model.

5.1.13. Additional Structures

Since the modelling of material flow in the developed primary system dynamics model has been discussed, the additional structures included in the model to obtain certain simulation results in the proper form has not been introduced.

Due to the fact that the model allows to simulate the material flow, in order to answer the formulated research questions of the study, the additional structures have been included in the model. This section describes the developed parts of the model, which were necessary to obtain data from the model and avoid additional calculation out of the utilized software.

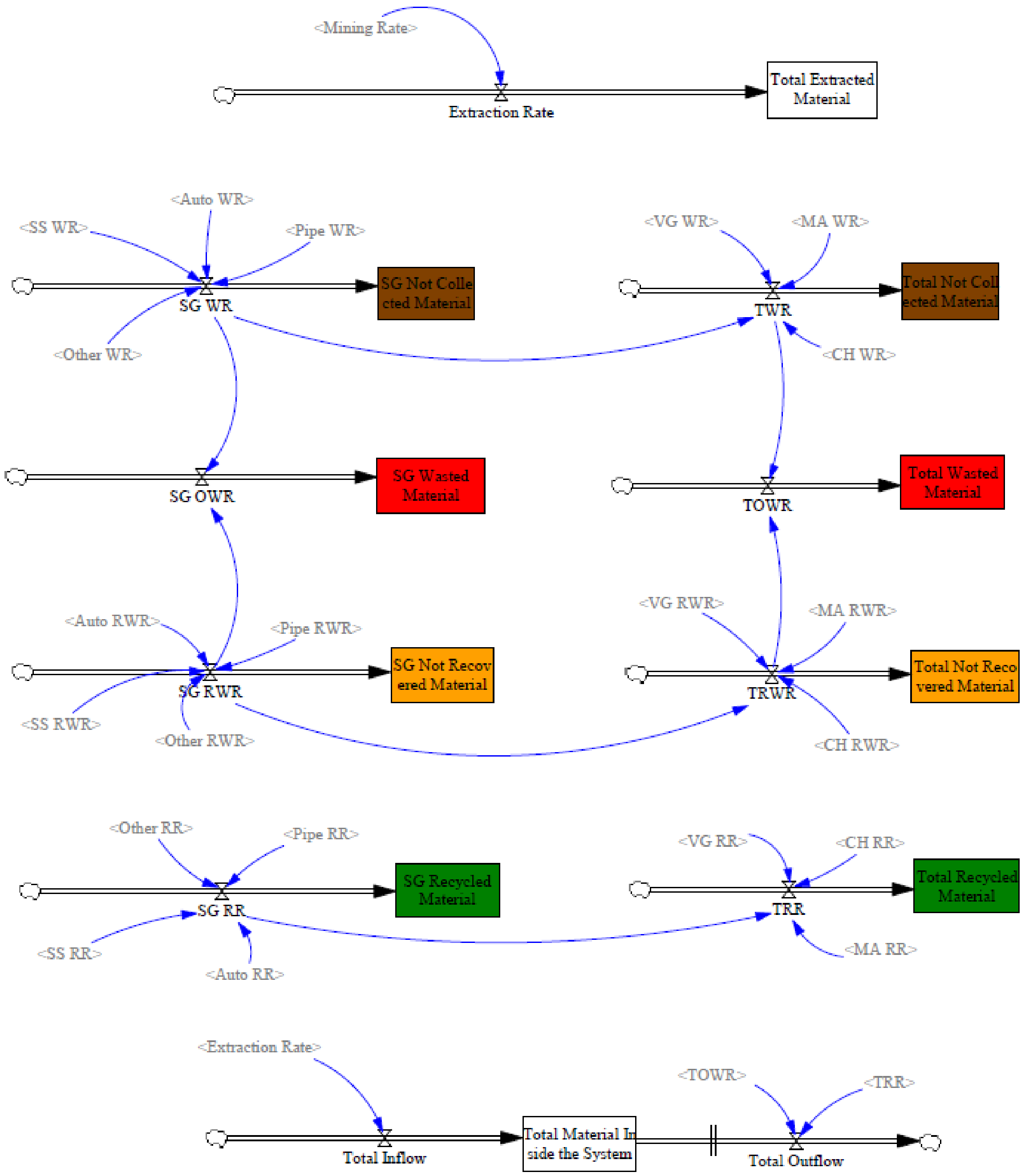
The model has included various secondary variables which may be seen relevant for the aim of the study. The figure 42 below illustrates several secondary variables as well as the constructed structure of their interconnections.

First of all, the secondary variable ‘Total Extracted Material’ has been added to the model as a stock, which accumulates the amounts of mined material.

Besides, the variables for evaluation of the total amounts of recycled material (in green), not collected material (in brown), and not recovered material (in orange) have been added to the model. Besides, the variable illustrating the amount of wasted material (in red) due to the poor collection fraction as well as to low level of material’s recovery has been included as well.

Due to the fact that the materail flow has been separated into smaller branches twice, some the described varables have been constrcuted to estimate the same amounts but only for the material flow of SG FeNb. The same color sclassification have been used. The variables have been calculated through creation of various sets of shadow variables mainly representing the flows in the model.

Furthermore, the estimation of the material inside the system has been included in the model as well. The obtained value represents how much material has come into the considered system and has not reached any of the final points. The variable is called ‘Total Material Inside the System’.



Source: Author

Figure 42. Additional Structures

The more detailed description of other secondary variables as well as of the precise caluclations is not provided in this section, due to the additionality of the developed secondary variables and their specific constructions, while the brief description may be seen sufficient to introduce the concepts.

5.1.14. *Summary*

In conclusion, this section of the study has described the developed primary system dynamics model of niobium material flow aimed to allow simulation of the material flow including recycling stages and its specifics.

First of all, the objective of the model as well as the initial assumptions and limitations have been introduced. The major aim was to evaluate the theoretically available for recycling amount of scrap.

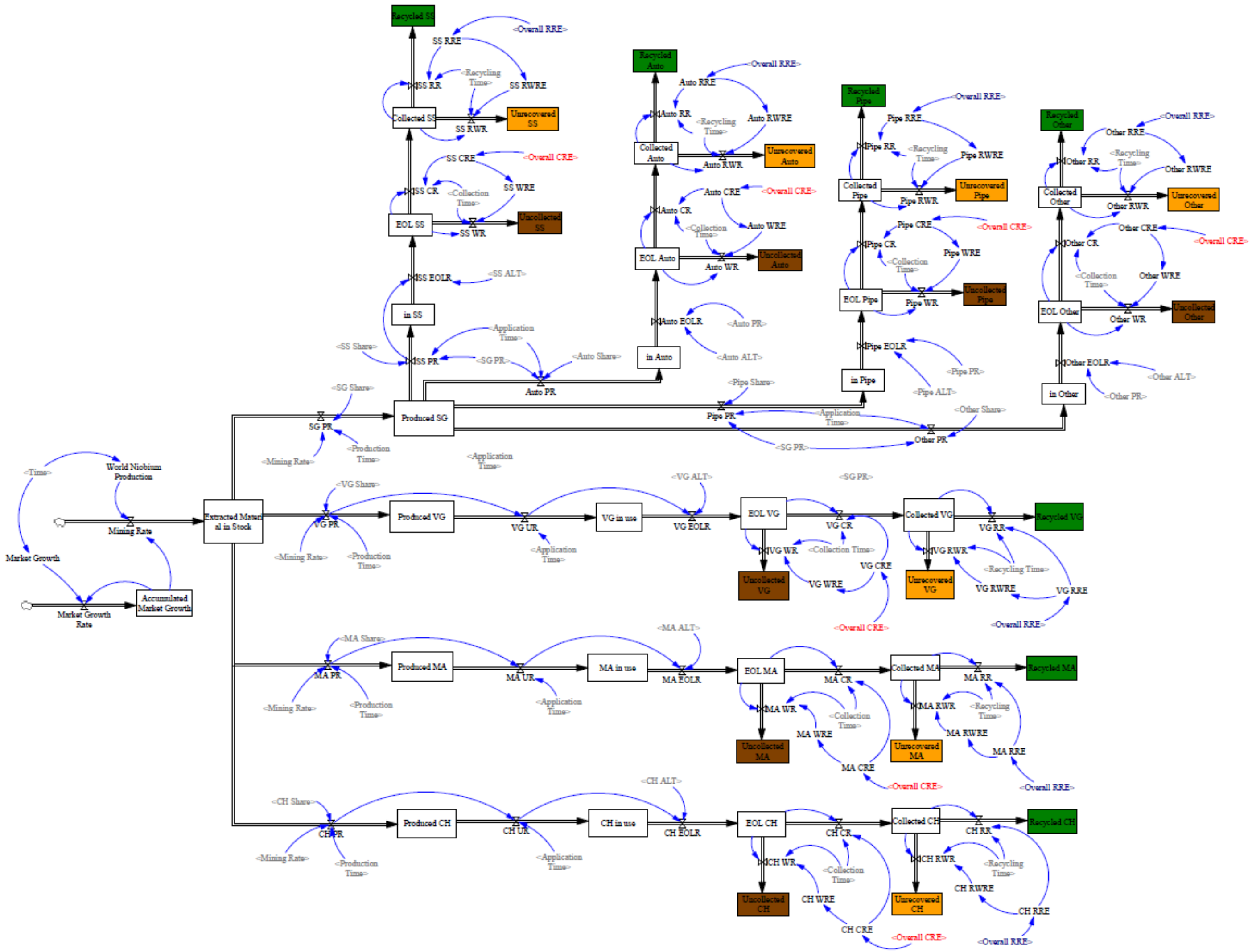
Moreover, the fundamental principles which has been utilized during the development of the model has been discussed. The approach to model production of material has included the statistical data for the past periods of time, while for the future demand has been projected in accordance with an in-depth study. In addition, their consolidation in the model has been introduced as well as the mode of implementation.

Then the modelling of the material flow in accordance with the considered distribution structure has been presented. The set of conceptual ideas utilized during the process has included approach allowed to rightly separate the generic material flow into branches taking into account its specifics and the specifics of the major stages of material flow. Besides, the considered delays and related to them specifics have been discussed.

Finally, the study has introduced the developed parts of the model related to recycling, the considered method of its implementation for all the branches of material flow. Two major variables affecting the stage include material collection efficiency and material recovery efficiency of recycling technology. Furthermore, the additional structures included in the developed system dynamics model to elicit simulation results has been briefly covered.

In addition, it is essential to clarify that the model was developed not cycled, due to the objective to evaluate theoretically available amount of scrap while the actual recycling was considered negligible, and, therefore, not affecting the production of raw material.

Thus, the description provided previously has illustrated different parts of the developed system dynamics model. Therefore, in order to illustrate the developed model and its main part related to material flow in a holistic way, the representation is shown in the figure 43 below.



Source: Author

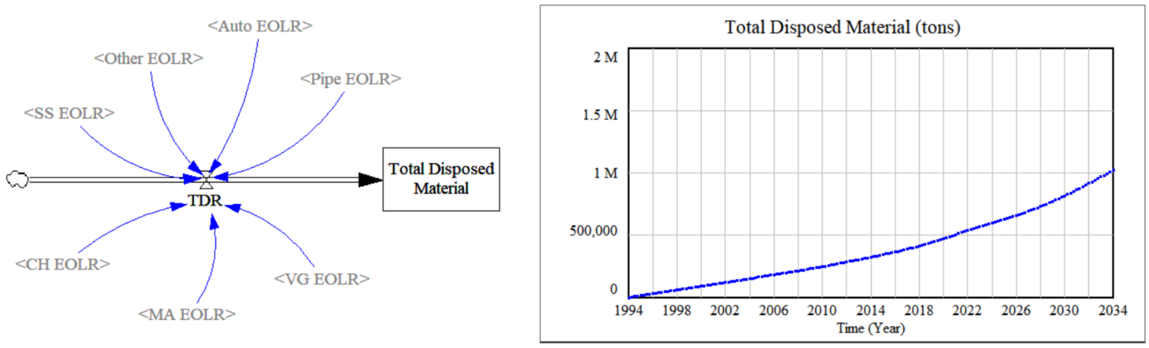
Figure 43. Developed Primary System Dynamics Model of Niobium Material Flow

5.2. ***Primary Model Simulation Results***

This section provides describtion of obtained simulation results from the developed primary system dynamics model. Due to the fact that the study has considered modern functional recycling activities neglegible, it was decided to conduct analysis of various scenarious.

The simulation of the developed primary model implies that the overall amount of scrap theoretically available for recycling will be assessed. However, in order to evaluate the possible amount of scrap, various scenarious of different certain situations will be considered.

The overall theoretically available amount of scrap may be evaluated taking into account all materail which has been disposed after the usage stage in different end-use areas of materail flow. The results of the assessment are presented in the figure 44 below.

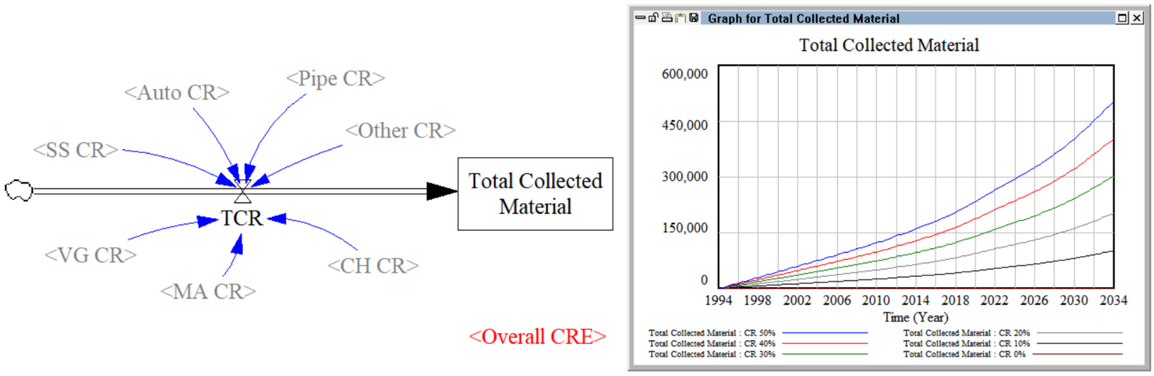


Source: Author

Figure 44. Total Disposed Material Simulation Results

In the left side of the figure, the additional structure included in the model in order to allow evaluation of the secondary variable 'Total Disposed Material' has been presented, while the graph illustrated in the right part describes the dynamics of the variable. For the considered in the model production rate of the material, 1 million tons of material could have been colleted and recycled.

While the obtained result may be seen sufficicent to answer the formulate RQ, the study offers to conduct an additional more precise evaluation, considering the available amount of scrap for various collection fractions.



Source: Author

Figure 45. Total Collected Material Simulation Results in Graphical Form

The figure 45 above, illustrates the results for several scenarious related to certain levels of material collection efficiency. The additional structure for evaluation of the variable 'Total Collected Material' has been presented on the left side of the figure, while the graph containing simulation results has been illustrated on the right.

As it may be seen, for a case of collection efficiceny at 30%, more than 300 000 tons of material could be collected for further recycling. The exemplary detailed data with simulation results for several last end time periods is presented in the figure 46 below.

Table

Time (Year)	2032.75	2033	2033.25	2033.5	2033.75	2034
"Total Collected Material" Runs:	CR 0%	CR 50%	CR 40%	CR 30%	CR 20%	CR 10%
Total Collected Material	0	0	0	0	0	0
: CR 50%	470210	476757	483381	490083	496936	503943
: CR 40%	376168	381406	386705	392066	397549	403154
: CR 30%	282126	286054	290029	294050	298162	302366
: CR 20%	188084	190703	193352	196033	198775	201577
: CR 10%	94042	95351.5	96676.2	98016.6	99387.3	100789

Source: Author

Figure 46. Total Collected Material Simulation Results

The figure 46 illustrates the table with results for various scenarious. Simulation results for 30% collection efficiency are shown in grey. Besides, the case with zero efficiceny (in blue) has been presented as well to illustrate that the model works properly.

To sum up, the developed primary system dynamics model has allowed to evaluate the amount of scrap theoretically available for recycling considering various scenarious. The RQ 3: *What amount of niobium scrap is (theoretically) available?* – has been answered and the modelling objective has been achieved.

5.3. ***Economic Extension of the Model***

This section describes the economic extension of the developed primary system dynamics model of niobium material flow.

5.3.1. *Modelling objective*

The developed extension of the system dynamics model allows to consider economic aspects of niobium recycling, while its simulation results provide in a relevant form an answer for the formulated RQ 4: *What are the possible economic benefits of an implementation of innovative recycling technologies for niobium?*

Therefore, the objective of the model (economic extension of the primary model) is to determine economic benefits possible to obtain from implementation of innovative niobium recycling technologies.

5.3.2. Assumptions and Limitations

Since the developed model is the extension of the primary system dynamics model, all the assumption and limitations discussed previously relate to the model as well.

Time boundaries of the model have not been changed. The initial time is 1994 year, while the end time is 2034 year.

The new assumptions and related to them limitations are going to be discussed further in the detailed description of the model. All of them are connected only to economic specifics and do not affect the quantitative, structural, and other parts of the developed primary model of niobium material flow.

The model provides extension majorly through development of additional structures and inclusion of new variables related to economic aspects of material flow and recycling.

5.3.3. Evaluation Principles

In order to determine economic benefits from implementation of innovative recycling technologies, the model should allow monetary evaluation of the material flow in several key points. Besides, due to the fact that the advancement of recycling technologies may lead to some increase in material recovery efficiency, various scenarios should be considered.

To determine possible benefits, it is necessary to limit quantity of theoretically possible options. Therefore, a strategy for evaluation of possible to achieve economic benefits has been developed.

Since the innovative recycling technologies may be viewed as more efficient in comparison to the actual ones, it was decided to assume that study will consider different technological option related to different levels of material recovery higher than 50%.

Due to the fact that the precise information on actual costs of recycling process as well as of the collection activities is not available, possibly because of the negligible level of functional recycling of niobium, it was decided to conduct economic evaluation of the increase in the recycling efficiency instead of calculations for actual and theoretical cases. This will allow to avoid inclusion of variables for which data is unavailable.

Thus, the developed approach will allow to calculate the difference between actual and innovative recycling technologies. In other words, the amount of material recycled due to the higher recovery efficiency will be assessed.

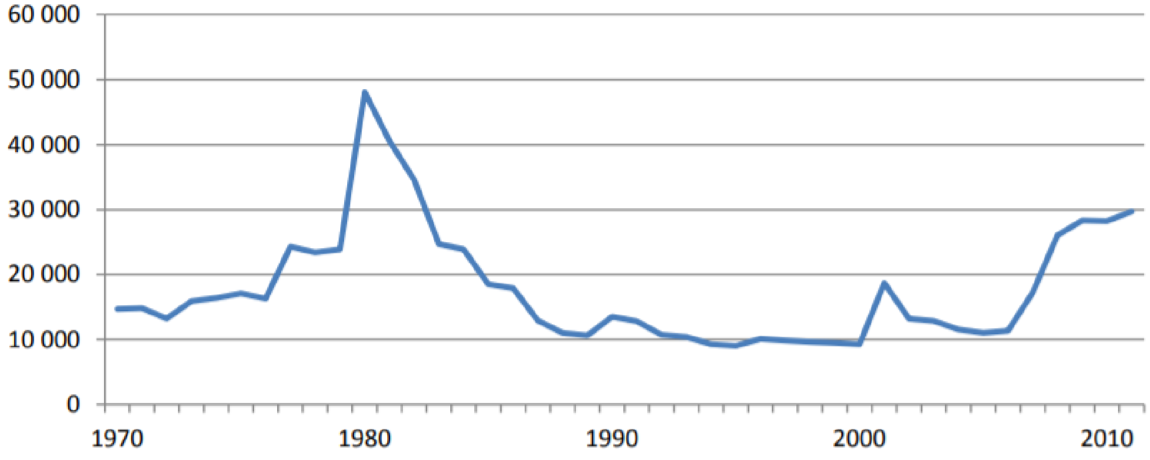
Next, it is necessary to consider market price of the material as well as the costs of its production, the comparison of which will allow to evaluate the margin. In addition, due to varying prices between products in considered end-use areas it was decided to evaluate possible benefits considering the price of SG FeNb, which strongly dominates the niobium market.

Finally, the margin may be seen as a converter to calculate the difference between recycled technologies in monetary terms, that may be considered a representative illustration for evaluation of economic benefits from implementation of innovative recycling technologies with theoretical properties.

5.3.4. Market Price and Production Costs

To begin with, market price of material and its long-term projection as well as the cost structure of the production process of material should be clarified. The description of the both may be found below.

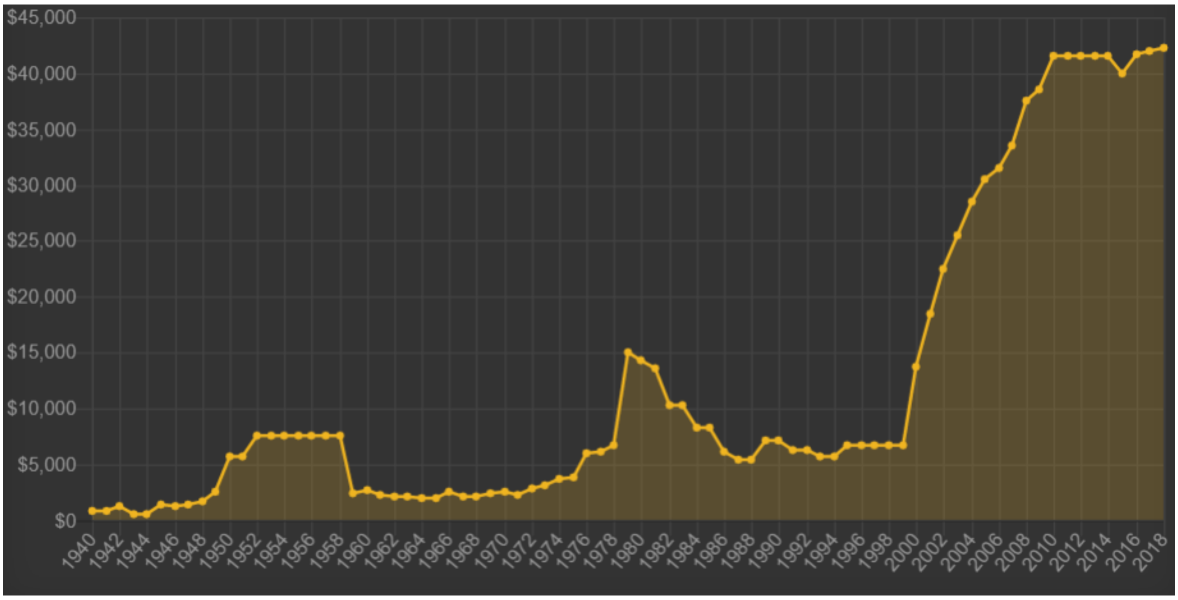
The information on historical market price of SG FeNb may be found in (European Commission, 2014a), which states that the material's price strongly increased in 1970s because of the demand for steelmaking mills. Then processing plants have been built in different countries and the supply from Brazil and Canada led to a relatively stable period with small spike in 2001.



Source: DSM Environmental Services, Inc., 2015 p.161

Figure 47. Historical Prices for a Ton of SG FeNb in US Dollars indexed to 1998 values

Another source illustrates the prices for a broader period of time, from 1940 till 2018. The prices are shown for a ton of Nb in SG FeNb form.

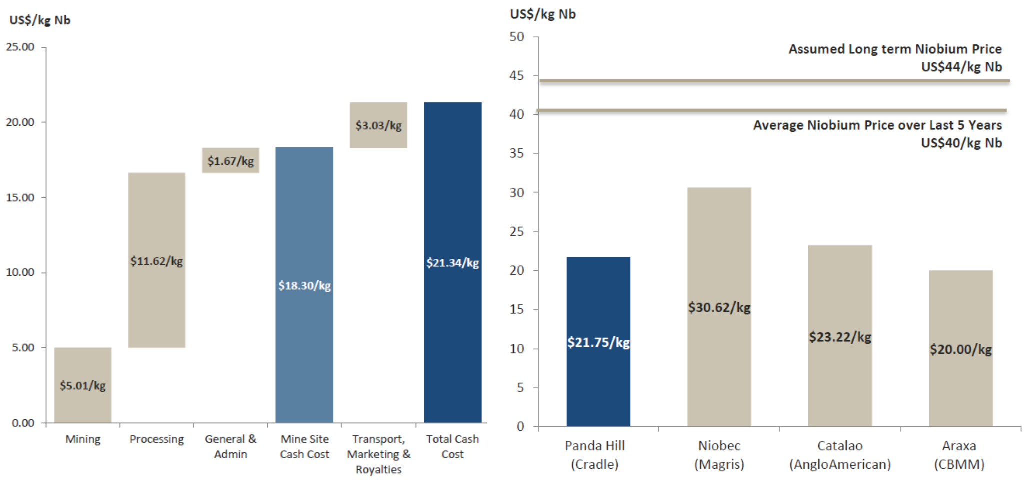


Source: Metalary, 2018

Figure 48. Price for a Ton of Nb in a Form of SG FeNb in US Dollars

Despite the movement of 2006 – 2008, which at first has been considered a spike and only later become clear to be systematic undervaluing of the material, the modern prices are stable and volatile at around 40 US Dollars per kg of Nb. (Cradle Resources Limited, 2015)

In addition to the discussion of the prices, the long-term price is considered to be 44 US Dollars per kg of Nb for SG FeNb form. (Cradle Resources Limited, 2015) This projection has been considered in the model.



Source: Cradle Resources Limited, 2016 (left); Cradle Resources Limited, 2015 (right)

Figure 49. Production Costs and its Structure

Besides, in addition to the price projection, the figure 49 (right part) illustrates a comprehensive evaluation of overall costs of the major world niobium mining companies which they take to extract and process one kg of Nb. The costs of operating companies are shown with grey bars, while the costs of Panda Hill mine, which is currently under development, is shown with a blue bar.

Moreover, the figure 49 (left part) represents the structure of the cost assessed for Panda Hill mine. As it may be seen, the total mine site costs are 18.30 US Dollars per kg of Nb, while the total accounts for 21.34 US Dollars per kg including transportation, marketing, and royalties.

In order to evaluate average costs, the study has conducted analysis taking into account not only the values but the annual production volumes as well. Table 10 below represents analysis results, which have been considered in the developed model.

Table 10. Average Production Costs

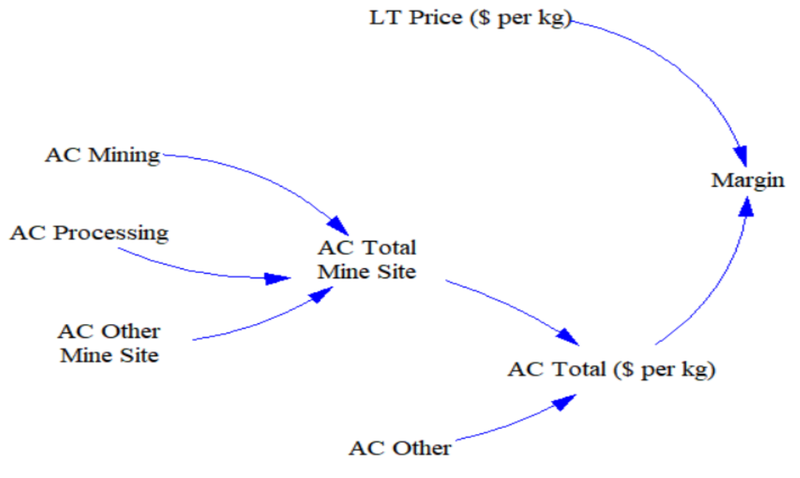
Costs for kg of Nb	Share	Value
Mining costs	23 %	**4,93 $**
Processing costs	54 %	**11,43 $**
Other mine site costs	8 %	**1,64 $**
Other costs (transportation, marketing, royalties)	14 %	**2,98 $**
Total costs	100 %	**21,00 $**

To sum up, this section has described historical and modern market prices for niobium as well the costs related to production of material. Besides, the detailed structure of the costs has been presented.

5.3.5. *Modelling Margin*

Since the information on the material price and production costs has been found, it is necessary to consider it in the model. Besides, in accordance with the developed strategy for evaluation of possible economic benefits, the margin should be calculated as a difference between the price and the total production costs.

The figure below represents a fragment of the developed model, illustrating how the information on price and costs has been translated into the model.



Source: Author

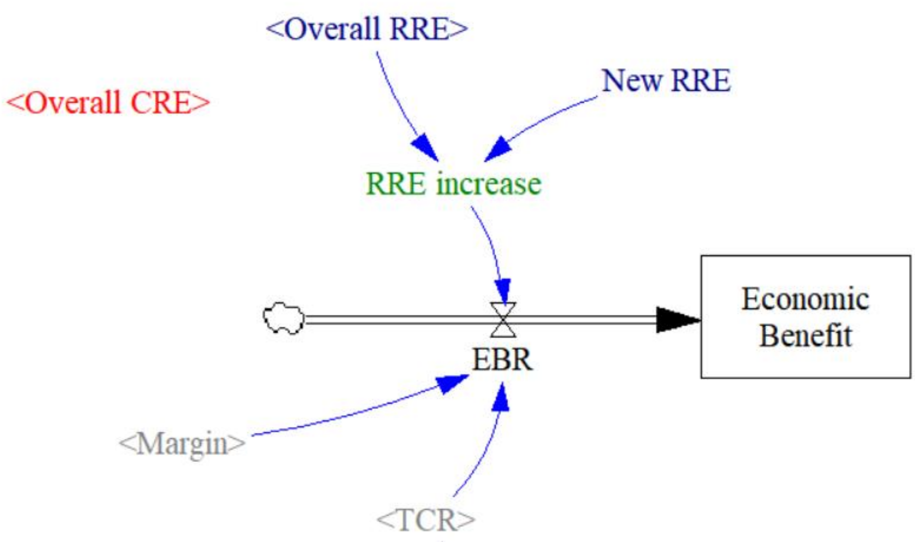
Figure 50. Fragment of the Model Structure of Costs

As it may be seen from the figure 50 above, the average production costs have been included in the model as independent variables, while the total average production costs of the material (variable 'AC Total ($ per kg)') has been calculated as a sum of those. The price has been considered as an independent variable as well. Finally, the margin is calculated as a difference between the variables related to price and total costs.

5.3.6. Modelling Economic Benefits

The next step is connected to modelling of economic benefits possible to achieve from implementation of innovative recycling technologies of niobium with certain material recovery rates.

First of all, the difference between the efficiency of an actual recycling technology and an innovative one should be calculated. The efficiency of an actual one is represented with a variable 'Overall RRE', which has been described in the previous sections of the study, while for the new one a variable 'New RRE' has been included in the model. The values represent efficiencies and their difference becomes the value of a variable 'RRE increase', which illustrates the increase of material recovery efficiency.



Source: Author

Figure 51. Fragment of the Model Economic Benefits

The figure 51 above illustrates a fragment of the developed model responsible for modelling economic benefits. The flow 'EBR', which stands for Economic Benefit Rate, is affected by the three variables; ‘REE increase’ and ‘Margin’ have been discussed in this section, while the variable ‘TCR’ represents a flow Total Collection Rate.

The flow ‘EBR’ is calculated as follows:

*‘EBR’ = ‘TCR’ * ‘RRE increase’ * ‘Margin’ * 1000*

Due to the fact that the material flow is being modelled in tons, while the margin has been calculated for kg, the equation includes an additional coefficient equal to one thousand. The units of the flow are US Dollars.

Thus, the flow ‘EBR’ comes to the stock ‘Economic Benefits’, which accumulates the possible to achieve from implementation of an innovative recycling technology benefits in monetary terms.

5.3.7. Summary

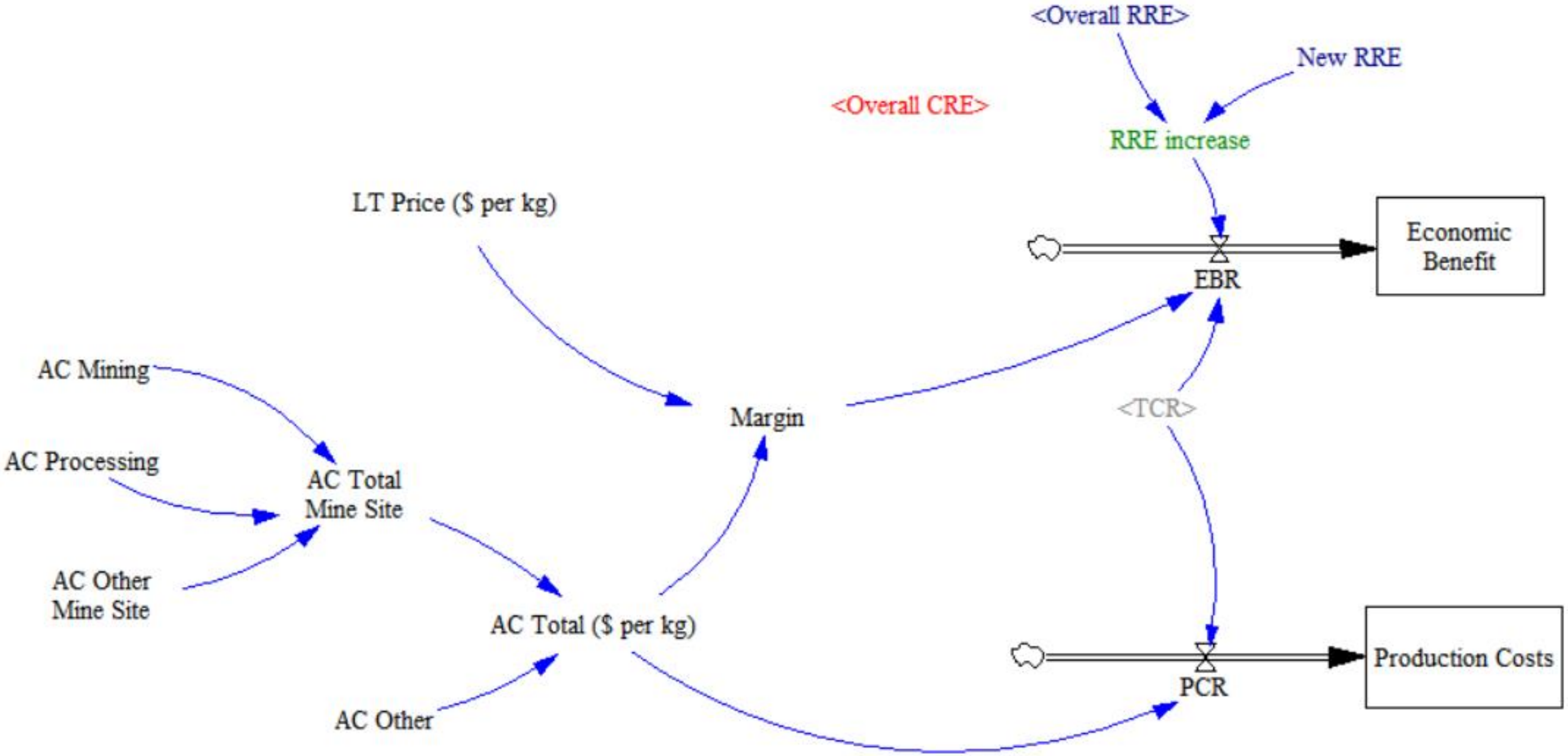
To sum up, this section has provided a detailed description of the developed economic extension of the primary system dynamics model. The modelling objective was to evaluate possible to achieve economic benefits from implementation of innovative recycling technologies of niobium.

In order to evaluate economic benefits from implementation of a new recycling technologies, in accordance with the developed evaluation strategy, it was decided to evaluate possible economic benefits from implementation of several recycling technologies with a certain material recovery efficiency levels.

The discussion about economic specifics considered in the model has included description of prices for niobium as well as of the production costs. Finally, the structure of the developed model has been explained as well as its logic.

Thus, the developed model allows to determine what possible to achieve economic benefits may be gained in case of implementation of innovative recycling technologies of niobium. Therefore, the modeling objective may be considered achieved.

In addition, the developed model has allowed to evaluate total costs related to production of material. The figure 52 below illustrates the developed economic extension of the primary system dynamics model in a holistic way.



Source: Author

Figure 52. The Developed Economic Extension of the Primary System Dynamics Model

5.4. ***Economic Extension Simulation Results***

This section describes the obtained from the developed economic extension of the primary system dynamics model simulation results.

In order to determine possible to achieve economic benefits, as it was mentioned in the previous section of the study, it was decided to consider several levels of material recovery efficiency representing implementation of various recycling technologies.

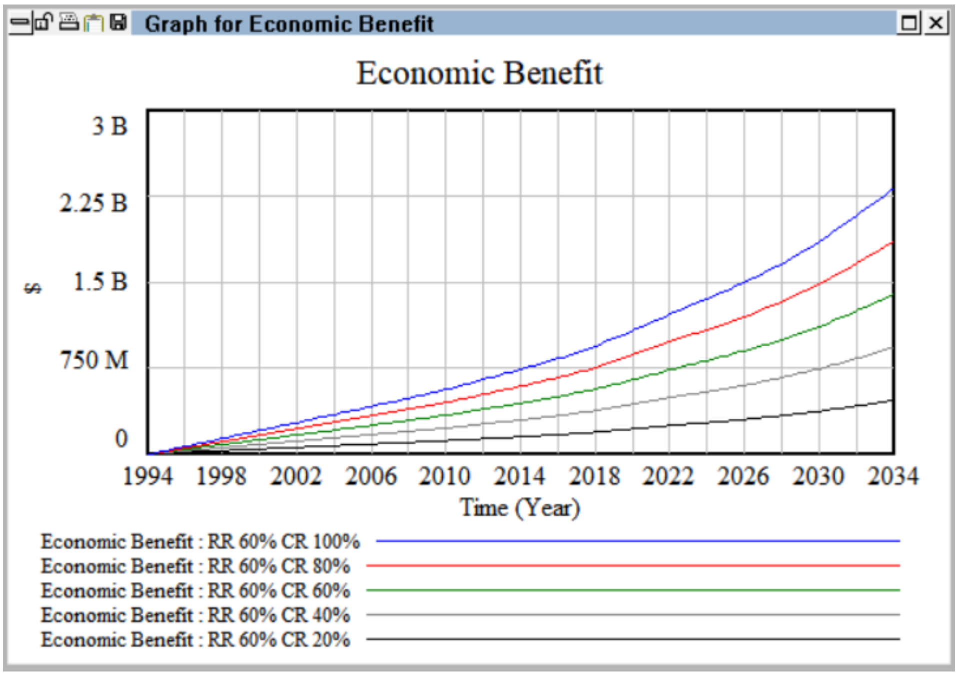
However, due to the fact that the actual collection of material for further functional recycling has been considered negligible as well, it was decided to consider various collection efficiency scenarios as well.

Therefore, taking into account that the efficiency of the actual niobium recycling has been considered 50%, the innovative recycling technologies was set at three levels: RR 60% for slight technological efficiency increase, RR 75% for medium technological efficiency increase, and RR 90% for significant technological efficiency increase.

Besides, five levels representing various scenarios of material collection efficiency for further recycling has been considered: CR 20%, CR 40%, CR 60%, CR 80%, and CR 100%. The scenario relating to 100% CR represents a theoretical case, when all the material is collected for further recycling, as an ideal result which may be seen as an unreachable aim.

Thus, the simulation results describing the potential economic benefits has been collected for 15 various scenarios related, while the variables 'New RRE' and 'Overall CRE' have been set at three and five certain levels respectively.

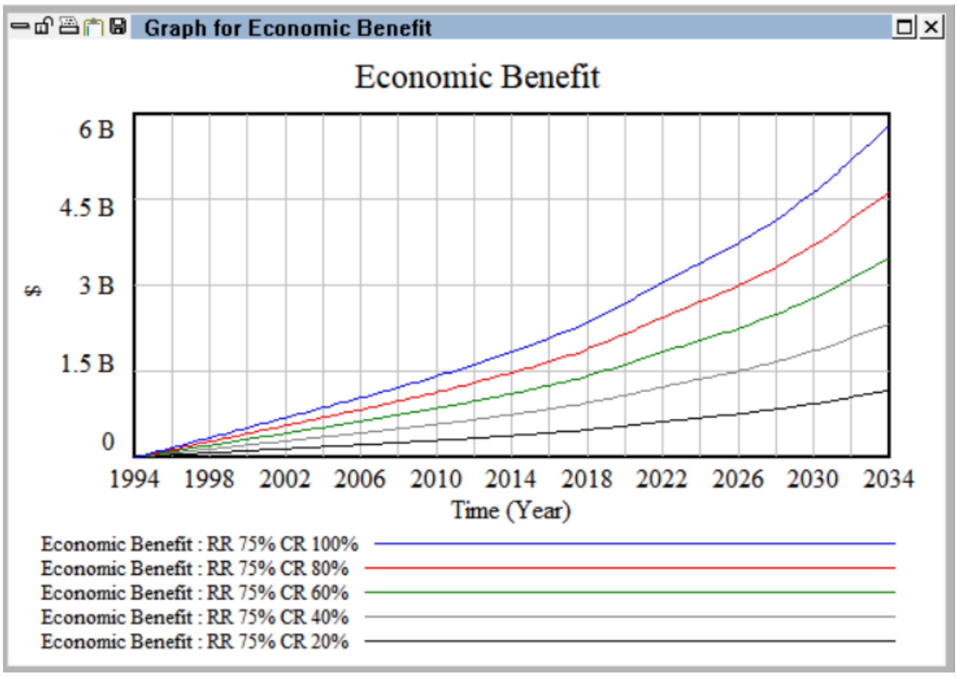
The simulation results for the RR 60% may be found in the figure 53 below. As it may be seen from the graph, at the end of the simulation in 2034, the increase in recovery efficiency in comparison to the actual level, even if 60% of the disposed material is collected, the benefits in monetary terms will reach almost 1.4 billion of USD. The economic benefits of the scenario are represented with a green line in the figure 53 below.



Source: Author

Figure 53. Economic Extension Simulation Results RR 60%

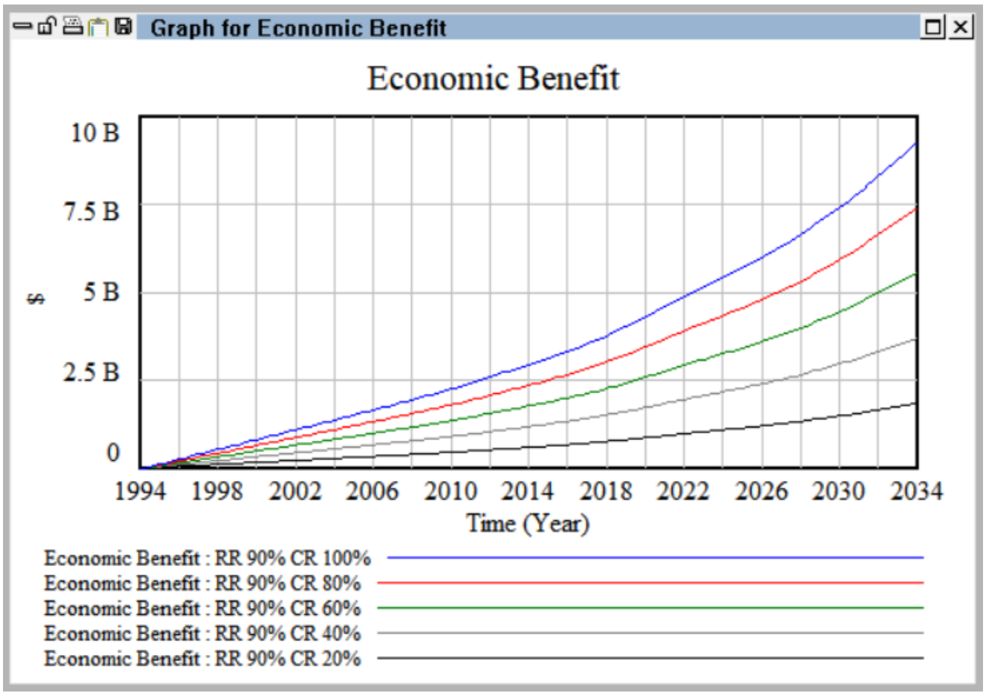
The figure 54 below represents simulation results for scenarios with RR 75%. In case the 60% of material is collected, the potential benefits in monetary terms will exceed 3 billion of USD. The case is shown with a green line.



Source: Author

Figure 54. Economic Extension Simulation Results RR 75%

Moreover, the third group of simulation results for RR 90% illustrating an implementation of an innovative recycling technology significantly more advanced than actual ones are presented in the figure 55 below. With 90% RR the collection of 60% will account for more than 5 billion USD.



Source: Author

Figure 55. Economic Extension Simulation Results RR 90%

Furthermore, in order to provide an explicit representation of the obtained, the table below has included all of the 15 totally considered cases with two factors varying at several levels. The cells represent economic benefits of an implementation of an innovative recycling technology with a certain level of material recovery efficiency for a case of collecting certain material from the total for further recycling. The values are shown in the billions of USD.

Table 11. Economic Benefits Simulation Results (in billions of USD)

		Material Recovery Efficiency		
		RR 60%	RR 75%	RR 90%
Material Collection Efficiency	CR 20%	**0.46**	**1.16**	**1.86**
	CR 40%	**0.93**	**2.32**	**3.71**
	CR 60%	**1.39**	**3.48**	**5.57**
	CR 80%	**1.86**	**4.64**	**7.43**
	CR 100%	**2.32**	**5.80**	**9.28**

As it may be seen from the table above, the most influencing factor is the efficiency of material recovery. In order to achieve the same monetary benefits, all the material should be collected for recycling with RR 60%, while the same result will be achieved by RR 75% but only from the collection of only 40%, that is a much more realistic scenario.

To conclude, the provided description of the simulation results obtained from the economic extension of the primary system dynamics model may be considered sufficient to become an explicit answer for the formulated research question.

Therefore, the RQ 4: *What are the possible economic benefits of an implementation of innovative recycling technologies for niobium?* – has been answered.

5.5. *Environmental Extension of the Model*

This section of the study is devoted to a description of an environmental extension of the primary system dynamics model and its development process.

5.5.1. *Modelling objective*

The developed environmental extension of the primary system dynamics model allows to evaluate possible to achieve environmental benefits in case of implementation of innovative niobium recycling technologies, while the simulation results may be seen sufficient to explicitly answer the formulated Research Question 5: *'What are the possible environmental benefits of an implementation of innovative recycling technologies for niobium?'*

Therefore, the objective of the developed model (environmental extension of the primary system dynamics model of material flow) was to determine environmental benefits possible to obtain from implementation of innovative niobium recycling technologies.

5.5.2. Assumptions and Limitations

Due to the fact that the developed model is the extension of the primary system dynamics model, all the assumption and limitations discussed previously relate to the model as well.

Besides, the time boundaries of the model have not been changed. The initial time is 1994 year, while the end time is 2034 year.

The new assumptions and related limitations are going to be further discussed in the detailed description of the model and the process of its development. All of them are connected only to environmental specifics and do not affect the developed primary model of niobium material flow including its quantitative, structural, and other parts.

The model provides extension majorly through development of additional structures and inclusion of new variables related to environmental aspects of niobium material flow.

5.5.3. Evaluation Principle

First of all, it is necessary to explain the considered approach for evaluation of the possible to achieve environmental benefits from implementation of innovative recycling technologies. Due to the absence of any precise information on the properties and specifics of the possible to implement innovative recycling technologies, it was necessary to limit the amount of possible options to certain set.

Therefore, the study has decided to consider several innovative recycling technologies with certain material recovery efficiency levels. The similar approach has been already utilized during the development of the economic extension of the primary system dynamics model.

Besides, it was decided to evaluate the benefits through assessment of the gap between the amounts of recycled material with actual and innovative recycling technologies. Thus, this approach allows to avoid the necessity to consider environmental specifics of the actual niobium recycling as well as the innovative ones, for which information is not available.

Furthermore, if the production of material may be assessed in various environmental terms, then the amount of material additionally recycled, due to the more efficient recycling technology with a higher level of material recovery efficiency, may be evaluated as well.

Taking into account all the described above, the developed evaluation strategy implies to consider in the model environmental impact related to production of the material via inclusion of the relevant variables. On the next step, the amount of material additionally recycled due to the more efficient innovative recycling technology should be evaluated.

Finally, since the recycled material may be utilized again, the demand for material production may be considered reduced on the amount of the additionally recycled material. Therefore, the assessment of the environmental impact of the reduced material production may be seen as the evaluation of the environmental benefits obtained from an implementation of innovative recycling technologies.

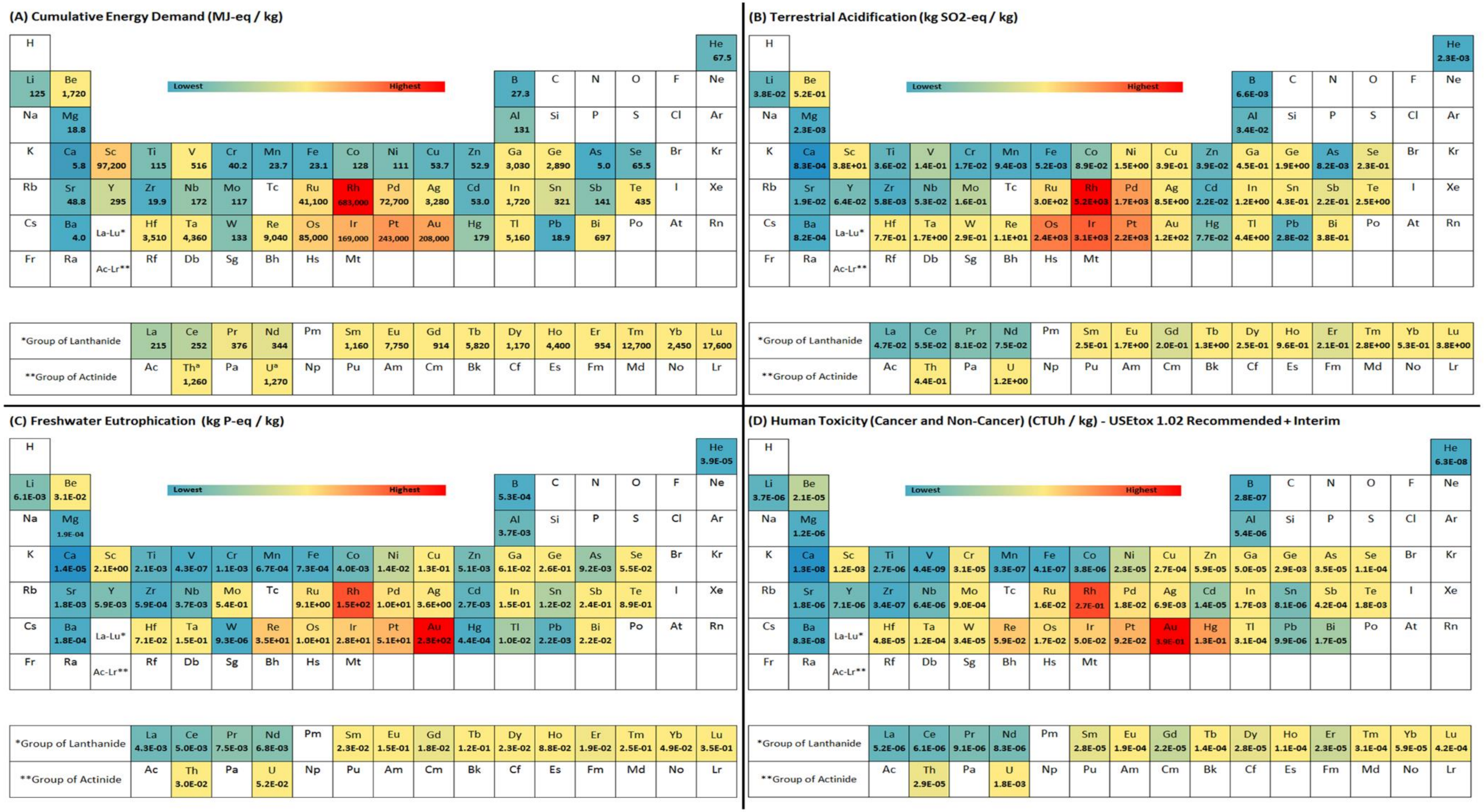
In addition, the described approach for evaluation of environmental benefits of innovative recycling technologies leads to an assumption, that the considered innovative technologies are identical to the actual one in environmental terms, while only the certain levels of material recovery efficiency are higher.

5.5.4. Environmental Impacts

First of all, in accordance with the developed evaluation strategy, the environmental impact of niobium production should be included in the model. This section describes the specifics related to environmental impacts as well as the way of their inclusion in the model.

In order to consider the environmental specifics, the in-depth study has been conducted. In accordance with the results of it, the study of Nuss et al. (2014) has been considered as the most comprehensive review including resumptive assessment of cradle-to-gate environmental burdens of niobium in several dimensions with a specific indicator related to each of those.

The study has considered to conduct the analysis of the environmental benefits in several terms and, therefore, has included in the model several indicators. The exemplary results of the analysis conducted in the study (Nuss et al., 2014) may be seen in the figure 56 below.



Source: Nuss et al., 2014

Figure 56. Exemplary Environmental Impacts Analysis Results Considered in the Model

The figure 56 above represents the periodic table with environmental impacts of analyzed materials such as Cumulative Energy Demand, Terrestrial Acidification, Freshwater Eutrophication, and Human Toxicity. Besides, each of the presented indicators have its own measurement units.

The considered in the model indicators for evaluation of possible environmental benefits have included the following:

1. Global Warming Potential
2. Cumulative Energy Demand
3. Terrestrial Acidification
4. Freshwater Eutrophication

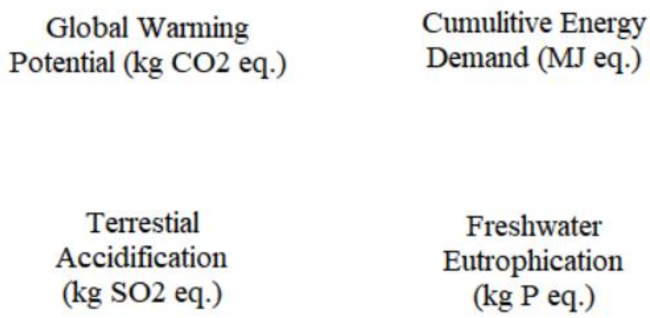
The additional information on the included indicators such as its measurements units and the considered values is shown in the table 12 below.

Table 12. Environmental Impacts

Indicator	Measurement Units	Value per kg	Value per ton
Global Warming Potential	kg CO_2 – eq.	12.5	12 500
Cumulative Energy Demand	MJ – eq.	172	172 000
Terrestrial Acidification	kg SO_2 – eq.	5.3 E-02	53
Freshwater Eutrophication	kg P – eq.	3.7 E-03	3.7

The table 12 above has included information taken from (Nuss et al., 2014). Besides, it is essential to clarify that all the considered indicators are represented by the equivalent values in kilograms (kg) of Carbon Dioxide (CO_2), Mega Joules (MJ), kg of Sulfur dioxide (SO_2), and kg of Phosphorus (P).

On the next step, all the considered variables have been included in the developed model through various variables, which may be seen in the figure 57 below.



Source: Author

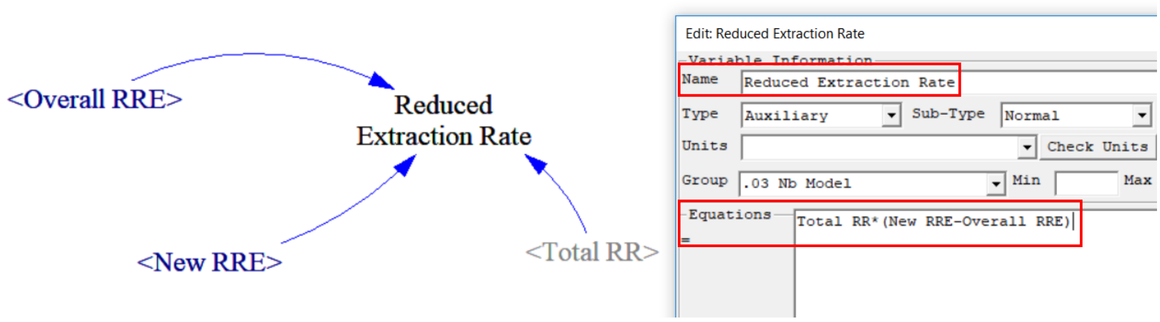
Figure 57. Related to Environmental Indicators Variables

To sum up, this section has described the environmental aspects illustrated with certain environmental indicators and the related to them variables included in the model as well as their measurement units and values.

5.5.5. Modelling Environmental Benefits

Since the environmental indicators has been included in the model, on the next step, it is necessary to describe how the developed model has allowed to evaluate environmental benefits possible to achieve from implementation of innovative recycling technologies.

First of all, in accordance with the developed evaluation strategy, the amount of material additionally recycled because of the higher level of material recovery efficiency related to an implementation of a certain recycling technology should be evaluated. The figure 58 below represents the additionally developed structure for this purpose.



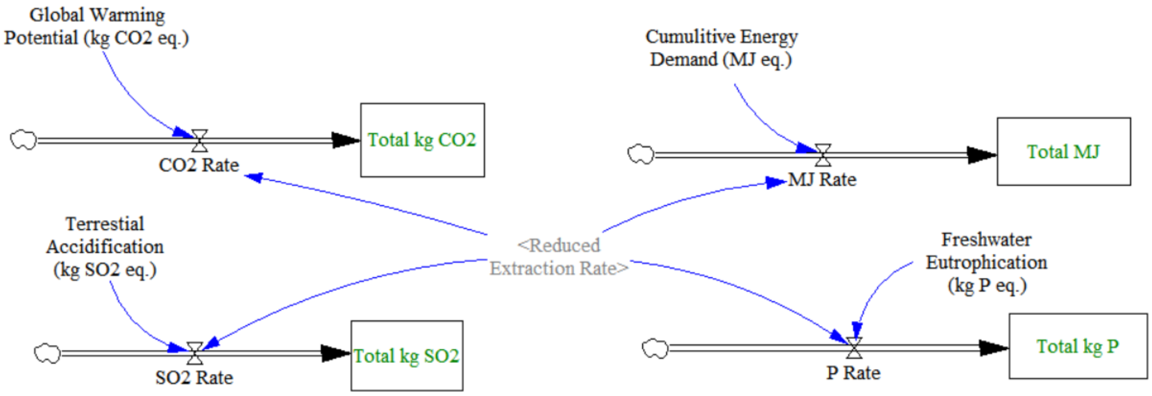
Source: Author

Figure 58. Fragment of the Environmental Extension of the Model

The variable 'Reduced Extraction Rate' represents the amount on which the demand for material extraction would have been additionally decreased due to implementation of an innovative recycling technology with a higher level of material recovery efficiency. Moreover, the variable is influenced by other three variables shown in the figure 58 above as well as its equation, which has been additionally marked with a red rectangular.

Finally, the developed fragments with variables related to environmental impact indicators and the reduced extraction may be combined in order to evaluate possible to achieve environmental benefits from implementation of innovative recycling technologies.

The figure 59 below represents the structure of the developed model devoted to evaluation of environmental benefits in accordance with each of the considered indicators.



Source: Author

Figure 59. Fragment of the Environmental Extension of the Model

As it may be seen from the figure 59 above, for each considered indicator the specific stock and rate have been included in the model. The values of environmental impact variables are multiplied on the amount of material that could be reduced in case of implementation of an innovative recycling technology.

Thus, the possible to achieve environmental benefits have been evaluated in the developed environmental extension of the primary system dynamics model of material flow from four different viewpoints.

5.5.6. Summary

In conclusion, this section has provided a detailed description of the developed environmental extension of the primary system dynamics model. The modelling objective was to evaluate possible to achieve environmental benefits from implementation of innovative recycling technologies of niobium.

In accordance with the developed evaluation strategy, the environmental benefits possible to achieve from implementation of innovative recycling technologies with higher level of material recovery efficiency have been evaluated in four dimensions related to various environmental impacts assessed with a specific indicator.

First of all, after the evaluation strategy and its main principles have been introduced, the considered in the model indicators of material environmental impact related to its production have been discussed as well as their measurement units, values, and included in the model variables.

On the next step, the fragments of the developed model related to evaluation of the additionally recycled material considered equal to an amount on which the material production has been reduced and the assessment of environmental benefits have been presented.

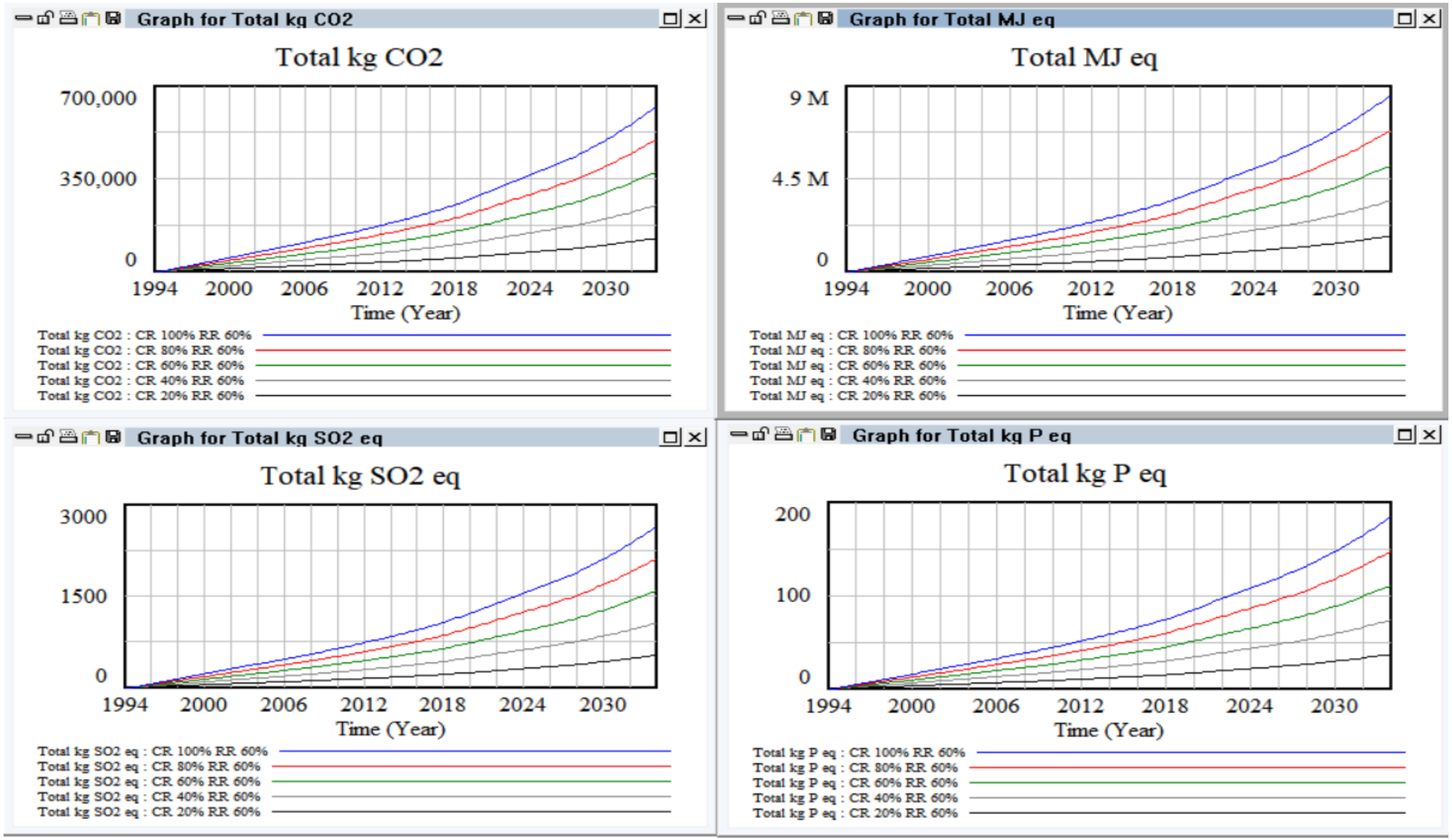
Thus, the developed economic extension of the primary system dynamics model allows to evaluate environmental benefits possible to obtain in case of implementation of innovative recycling technologies with various levels of material recovery efficiency. Furthermore, the environmental benefits have been evaluated in four different dimensions related to a specific indicator of material environmental impact. Therefore, the objective of the developed economic extension may be seen successfully achieved.

5.6. ***Environmental Extension Simulation Results***

This section of the study describes the obtained from the developed environmental extension of the primary system dynamics model of material flow simulation results.

In order to evaluate possible to achieve from implementation of innovative recycling technologies environmental benefits, several levels of material recovery efficiency illustrating cases of implementation of various recycling technologies have been considered.

Therefore, a set of material recovery levels, similar to the one that has been utilized during the evaluation of possible economic benefits, has been considered: RR 60% for slight technological efficiency increase, RR 75% for medium technological efficiency increase, and RR 90% for significant technological efficiency increase.



Source: Author

Figure 60. Environmental Extension of the Model Exemplary Simulation Results

Besides, the same various levels of material collection have been considered during the evaluation of possible environmental benefits: CR 20%, CR 40%, CR 60%, CR 80%, and CR 100%.

Thus, the fifteen various scenarios have been considered for evaluation of possible to achieve environmental benefits. In addition, the assessment has been done in four evaluation dimensions related to specific environmental impact indicators, such as:

1. Global Warming Potential (GWP)
2. Cumulative Energy Demand (CED)
3. Terrestrial Acidification (TA)
4. Freshwater Eutrophication (FE)

The exemplary simulation results obtained from the developed model describing the environmental benefits with four indicators for a scenario related to implementation of a slightly more efficient recycling technology with RR 60% and for different collection levels have been illustrated in the figure 60 above: the top left graph provides simulation results for GWP in kg of CO_2 – eq., the top right for CED in MJ – eq., the bottom left for TA in kg of SO_2 – eq., and the bottom right for FE in kg of P – eq.

While the figure 60 above provides an exemplary illustration of the obtained simulation results in a graphical form, the detailed review of environmental benefits for all considered scenarios may be found in the table 13 below. All the values in cells are grouped in accordance with the benefits related to a certain environmental impact indicator (the first column) and considered in the scenario material recovery efficiency level and material collection efficiency.

Moreover, in order to provide simulation results in the more convenient way, some of the measurement units have been adapted to the scale of gained result. The units of GWP have been changed from kg of CO_2 – eq. to tons of CO_2 – eq., while the units of CED from MJ – eq. to TJ – eq. (1 million of MJ is equal to a tera Joule, TG)

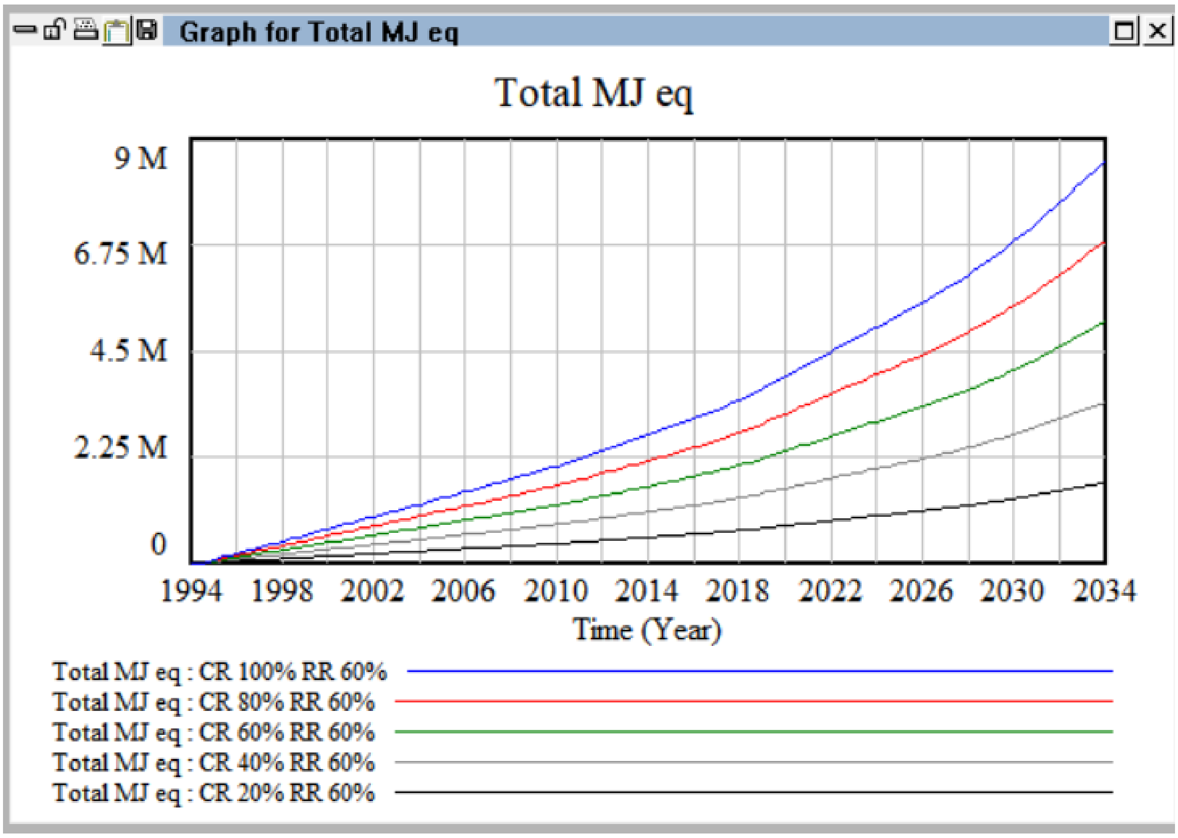
Table 13. Environmental Benefits Simulation Results

Environmental Impact Indicator	**Material Collection Efficiency**	**Material Recovery Efficiency**		
		RR 60%	***RR 75%***	***RR 90%***
Global Warming Potential (tones CO_2 – eq.)	***CR 20%***	124.2	310.6	496.9
	CR 40%	248.5	621.2	993.9
	CR 60%	372.7	931.8	1490.8
	CR 80%	496.9	1242.3	1987.7
	CR 100%	621.2	1552.9	2484.7
Cumulative Energy Demand (TJ – eq.)	***CR 20%***	1.7	4.3	6.8
	CR 40%	3.4	8.6	13.7
	CR 60%	5.1	12.8	20.5
	CR 80%	6.8	17.1	27.4
	CR 100%	8.6	21.3	34.2
Terrestrial Acidification (kg SO_2 – eq.)	***CR 20%***	527	1317	2107
	CR 40%	1054	2634	4214
	CR 60%	1580	3951	6321
	CR 80%	2107	5268	8428
	CR 100%	2634	6584	10535
Freshwater Eutrophication (kg P – eq.)	***CR 20%***	36.8	91.9	147.1
	CR 40%	73.6	183.9	294.2
	CR 60%	110.3	275.8	441.3
	CR 80%	147.1	367.7	588.4
	CR 100%	183.9	459.7	735.5

Aa it may be seen from the table 13 above, in case of implementation of a recycling technology with a significantly higher level of material recovery efficiency (RR 90%) and collection for further functional recycling of only 20% of the disposed material the following environmental benefits could be obtained:

1. Global Warming Potential: **496.6** tons of CO_2 – eq. reduced
2. Cumulative Energy Demand: **6800** MJ – eq. reduced
3. Terrestrial Acidification: **2107** kg of SO_2 – eq. reduced
4. Freshwater Eutrophication: **147.1** kg of P – eq. reduced

Furthermore, the efficiency of recycling technology may be seen a crucial factor affecting the material flow. For instance, recycling technology with RR 90% applied to 20% of the disposed material will lead to approximately the same results as in a case of recycling 80% of disposed material with a technology with RR 60%. The figure 61 below represents simulation results for a scenario with RR 60%. The case of CR 80% is shown with a red line.



Source: Author

Figure 61. Cumulative Energy Demand Simulation Results for RR 60%

To sum up, the provided description of the simulation results obtained from the environmental extension of the primary system dynamics model may be considered sufficient to become an explicit answer for the formulated research question.

Therefore, the RQ 5: *What are the possible environmental benefits of an implementation of innovative recycling technologies for niobium?* – has been answered.

6. CONCLUSIONS

This chapter concludes the conducted research and provides brief and overall description of the gained results. Since the formulated research question of the study has been answered, the major goal may be seen successfully achieved. The global flow of niobium material flow has been assessed and modelled, which allowed to evaluate the possible to achieve economic and environmental benefits from possible implementation of innovative recycling technologies.

The constantly growing pressure on environment forces to implement innovative approaches, which could allow constant technological advancements and high life standards as well as preservation of the balance in a long-term. Therefore, rational use of natural resources may be viewed as an integral part of sustainable development included in the strategic agendas of the developed and developing countries.

Since recycling may substantially reduce the need for virgin materials, it can be viewed as an instrument for ensuring rational use of natural resources. Besides, for some materials recycling is a lucrative option from an economic point of view. In addition, one should not overlook the other possible benefits related to environmental and social aspects. Thus, recycling has been considered sustainable from economic, environmental, and social viewpoints.

Concerns about raw materials and availability of those represent a strategic issue which has gained significant attention all over the world. Since the possible shortages may lead to severe and harmful consequences for industries and whole national economies, after the rigorous selection processes various countries have adopted lists of critical material. However, due to scarcity of sources and other influencing factors, some of the raw materials have been included in all major lists and may be seen critical on the global scale.

This study was aimed to analyze possible to achieve economic and environmental benefits in case of implementation of innovative recycling technologies, while niobium has been selected as a case study material for the research. Niobium is a widely applied in various industries material due to its prominent properties, which has been included into the lists of critical materials adopted in different countries and regions.

The main research question of the study has been formulated as follows: "*What are the economic and environmental benefits possible to achieve from the implementation of innovative recycling technologies for niobium*?"

However, in order to answer the question in a clear and explicit way, the main research question has been translated into series of smaller and more precise research questions related to a specific area under the investigation. All of the formulated research questions have been successfully answered, while the related to them objectives have been achieved. The more detailed discussion about the corresponding issues may be found in the section 3 of this study Methodology.

The major results of the study include several findings. First of all, the conceptual model of the niobium material flow describes the structure of the flow on the global level and provides a clear overview of the material's lifecycle including specific applications in different industries and related product forms. Conceptual model has been based on the information gained during a comprehensive in-depth case study of niobium specifics, which allowed to reveal crucial for the research data.

Moreover, the additional studies conducted to provide an answer for the second research question related to investigation of the available niobium recycling technologies, have been utilized in order to elaborate the conceptual model. Thus, the refined conceptual model of niobium material flow has been gained, which may be viewed as a second major result of the study. The refined version includes information related to niobium recycling specifics: actual recovery rate related to niobium recycling, the specific industries and niobium products that tend to be recycled with a notable level, as well as the further detailed structure of the material flow concerning the flows of recycled material.

The next stage of the research was devoted to development of a system dynamics simulation model, which could allow quantitative assessment of the global niobium material flow. The structure of the material flow in the developed model has been based on the findings from the previous steps, while the refined conceptual model may be seen as a major source. The developed system dynamics model is aimed to simulate the flow of the material through different steps and process during a wide period of time taking into account the specifics of niobium life cycle. The successful development of the model and the gained simulation results were necessary to answer the third research question related to evaluation of the amount of the niobium scrap available.

The discussed above model may be viewed as a primary system dynamics simulation model of niobium material flow, while the next step of the research was related to answering the fourth research question formulated as follows: “*What are possible economic benefits of implementation of innovative recycling technologies for niobium?”*

In order to provide an answer for the research question, the primary model was further developed. The obtained economic extension of the model was aimed to assess various possible recycling scenarios in monetary terms. In order to conduct such assessment, first of all, it was necessary to evaluate how lucrative is it to provide material via recycling process instead of traditional production related to mining operations of virgin material. For this purpose, the costs of traditional production including mining, processing, and other expenses were compared to recycling costs; while on the next step the margin has been utilized to the cumulative total amount of material additionally recycled due to the implementation of a more efficient innovative recycling technology in every scenario considered. Thus, the possible to achieve economic benefits from implementation of niobium recycling have been evaluated.

Another major result of the study derived from answering the fifth research question related to evaluation of the possible to achieve environmental benefits from implementation of innovative niobium recycling technologies. In order to answer the research question, the system dynamics model should have been additionally refined. The environmental benefits possible to gain from implementation of innovative technologies have been calculated by translating the total amount of material recycled in every particular scenario into environmental terms. To some extent, the idea of such evaluation may be seen similar to the one utilized for evaluation of economic benefits. However, in this case, instead of monetary value, the set of four major environmental indicators has been considered. Thus, since the possible to achieve environmental benefits have been evaluated in four environmental dimensions, the research objective related to the formulated question has been successfully achieved, while the environmental extension of the system dynamics model may be as well viewed as one of the major results of the research.

Thus, the following models as well as the related to them simulation results and additional findings may be considered the major results of the study, which allowed to explicitly answer all the formulated research questions and achieve associated to them research objectives:

- Conceptual Model of Niobium Material Flow (primary and refined);
- Primary System Dynamics Simulation Model of Niobium Material Flow;
- Economic Extension of the System Dynamics Simulation Model;
- Environmental Extension of the System Dynamics Simulation Model.

The list of the formulated research questions and appropriate research objectives may be found in the table 1 presented in the section 1 Introduction.

One of the main reasons for adoption niobium as a critical material in various countries derives from scarcity of its sources, which would be economically lucrative for mining and further processing, while more than 90% of niobium products produced in Brazil. Therefore, the major sources are seriously limited and may be easily disrupted in case of any unstable situation in the producing countries. Since the actual market price is not high and slightly fluctuates without any signs for substantial growth in the next years, the development of new niobium producing sites is not going to increase over the next years as well, although there are some new players going to enter the market.

The relatively low market price of the material in comparison with gold, platinum, or other precious materials, as well as the low costs of material mining and further processing, may be seen as one of the main barriers for expansion of niobium recycling. Another barrier lies in the area of how the material applied in various industries. Since niobium is widely used as an alloying element, it makes it difficult and expensive to recycle the material. In addition, in the majority of cases, the alloying fraction of niobium may be very low and does not exceed even 1%. Thus, the recycling of material is justified only for a limited sector of the products, which do not represent the majority of the market. The detailed description of the distribution of material end-uses may be found in the table 5 presented in the section 4 Conceptual Model of Niobium Material Flow.

However, although the volumes of niobium recycling are considered at the low level, the possible to gain economic benefits through implementation of innovative recycling technologies which would allow the recycling process of niobium with a higher recovery rate may be significant. The detailed description of the simulation results related to the evaluation of possible economic benefits for various considered scenarios may be found in the section 5.3 Economic Extension of the Model.

Besides, more efficient niobium recycling may as well lead to notable environmental benefits, since the recycled material will come to the stock and decrease the need for mining and further material processing. Therefore, the environmental pressure will be ceased on the amount equal to the amount generated during the production of material including mining and processing stages for the volume additionally recycled as a result of a recycling technology with a higher recovery rate. The detailed description of the possible environmental benefits may be found in the section 5.4 Environmental Extension of the Model.

To sum up, the main research question as well as the formulated lower-level research questions have been answered while the related objectives have been successfully achieved. The study has presented a clear representation of the case study for niobium, its life cycle, structure of material flow, recycling specifics. The material flow has been modelled which allowed to quantitatively assess the amount of material on every stage as well as the volume of material recycled and disposed. Besides, the primary model has been extended in the ways that the possible to achieve economic and environmental benefits in case of implementation of innovative niobium recycling technologies have been evaluated. Thus, the research may be viewed successfully completed.

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