LAPPEENRANTA UNIVERSITY OF TECHNOLOGY

School of Business and Management

Industrial Engineering and Management

Global Management of Innovation and Technology

MASTER’S THESIS

RHODIUM MATERIAL FLOW ANALYSIS

First supervisor: Professor Andrzej Kraslawski

Second supervisor**:** Professor Eeva Jernström

Date: 20.09.2017, Lappeenranta, Finland.

Author: Aleksandr Bessudnov

Address: Bulvar Krasnykh Zor' 5, 11, 192131 St. Petersburg, Russia

ABSTRACT

Author: Aleksandr Bessudnov

Title: Rhodium material flow analysis

Year: 2017

Place: Lappeenranta. Lappeenranta University of Technology

Type: Master's Thesis

Specification: 106 pages including 41 figures, 13 tables and 1 appendix

First supervisor: Prof. Andrzej Kraslawski

Second supervisor: Prof. Eeva Jernström

Key words: critical raw materials, platinum group metals, rhodium recycling, autocatalysts recycling, dynamics material flow model, material flow analysis.

Topical issues of materials utilization becoming increasingly significant and come from ore degradation and scarcity as well as being reinforced by the demand growth on raw materials and end-products manufactured from them. Such materials are known as critical raw materials and are depicted by significantly impacting the economy in a global scale and are also characterized by high risks of supply shortages. Rhodium, renowned for its chemical and physical properties, is also affected by criticality. This is a rare representative of platinum-group metals and has a vital meaning for electronics, medical, glass and automotive industries. Currently, rhodium recycling is viewed as a measure to push the metal from the zone of criticality. However, to what extent that makes economic sense is unclear in most cases and what further systematic influence the increase in rhodium recycling could create requires clarification.

The goal of the thesis is to analyze the material flow of rhodium and to create a material flow model based on a number of analyzed scientific works, dedicated to critical raw materials, and on open source data provided by Johnson Matthey, International Association of Platinum Group Metals and Stillwater Mining Company. Such model is designed to provide conceptual and quantitative support for decision-makers in the field of rhodium mining and recycling.

ACKNOWLEDGEMENTS

The Master’s Thesis is a part of a research dedicated to the topical issues of critical raw materials recycling. It was an incredible experience to participate in the real scientific research and achieve results which have practical meaning for business, governmental and academic areas.

The work on the thesis was challenging as its objectives required both author’s expertise and exploration of new fields of science. This challenge birthed great interest to the research and resulted in the generation of new knowledge as well as several publications on critical raw materials (Bessudnov et al. 2017; Faisal et al, 2017; Elwali et al. 2017; Krehovetckii et al. 2017).

I would like to express my deepest gratitude to a person, without whom this thesis, research and the experience I have gained through the work, would not be possible – to professor Andrzej Kraslawski. His feedback and guidance were always valuable to me, without which I would not succeed.

Biggest thanks to Saud Al Faisal, Mohammad El Wali and Zlatan Mujkić - the research team who helped to facilitate the work and with whom it was an absolute pleasure to collaborate.

I am also grateful to Saeed Rahimpour Golroudbary for his guidance on simulation modeling as well as to Tania Bossi, who is a representative of International Platinum Group Metals Association, and Colton Bangs, representative of Umicore company, for suggested literature and data sources as well as for expert clarifications on questions I had during the work.

Additionally, I am grateful for discussions we had on system dynamics and platinum-group metals with professor Iosif Tukkel, the head of Master’s Programm (Managing Innovative Processes) in Peter the Great St.Petersburg Polytechnic University.

TABLE OF CONTENTS

LIST OF SYMBOLS AND ABBREVATIONS

CRM – critical raw materials

PGM – platinum group metals

PGM-3 – platinum, palladium and rhodium

IPA – International Platinum Group Metals Association

SO2eq. – sulfur dioxide equivalent gases

CO2eq. – carbon dioxide equivalent gases

MPA – material pinch analysis

PP – primary production

SP – secondary production

RR – recovery rate

PMP – pyrometallurgical processes

HMP – hydrometallurgical processes

In the thesis, secondary production and recycling are used as synonyms. However, technological recycling or recycling process assume metal extraction from scrap. Scrap, rhodium scrap and spent autocatalyst or autocatalyst scrap are used as synonyms.

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

1.1 Background

The economy of any country is highly dependent on materials, which are widely applied in different industries such as electronics, chemical, glass, medical and automotive.

Category of materials, on which current thesis is based, is known as critical raw materials (CRM). Such materials assume that the risk of their scarcity is high and their impact on the economy is greater than of those materials that are not categorized as critical.

Commonly two types of risks are associated with critical raw materials.

The first is the “supply risk”, which summarizes risks related to:

- Political and economic stability supplying countries;
- Production volume of supplying countries;
- Possibility to substitute material with other materials;
- Recycling coefficient – proportion of materials, which were extracted by recycling technologies in comparison to the total extracted amount of material in a specific year.

The second is the “ecological risk”, which assumes that environmental-protection measures taken by supplying countries endanger the supply of critical materials.

It is obvious that for every country the list of CRM will vary and can range from 25 to 56 materials. For instance, the following metals are defined as critical for the EU: antimony, beryllium, indium, magnesium, cobalt, niobium, gallium, tantalum, rare earth metals, graphite, platinum group metals and others.

In (European Commission, 2010) a diagram is demonstrated, which shows different materials in terms of their criticality based on their supply risk and economic importance. This diagram is presented in figure 1.1.

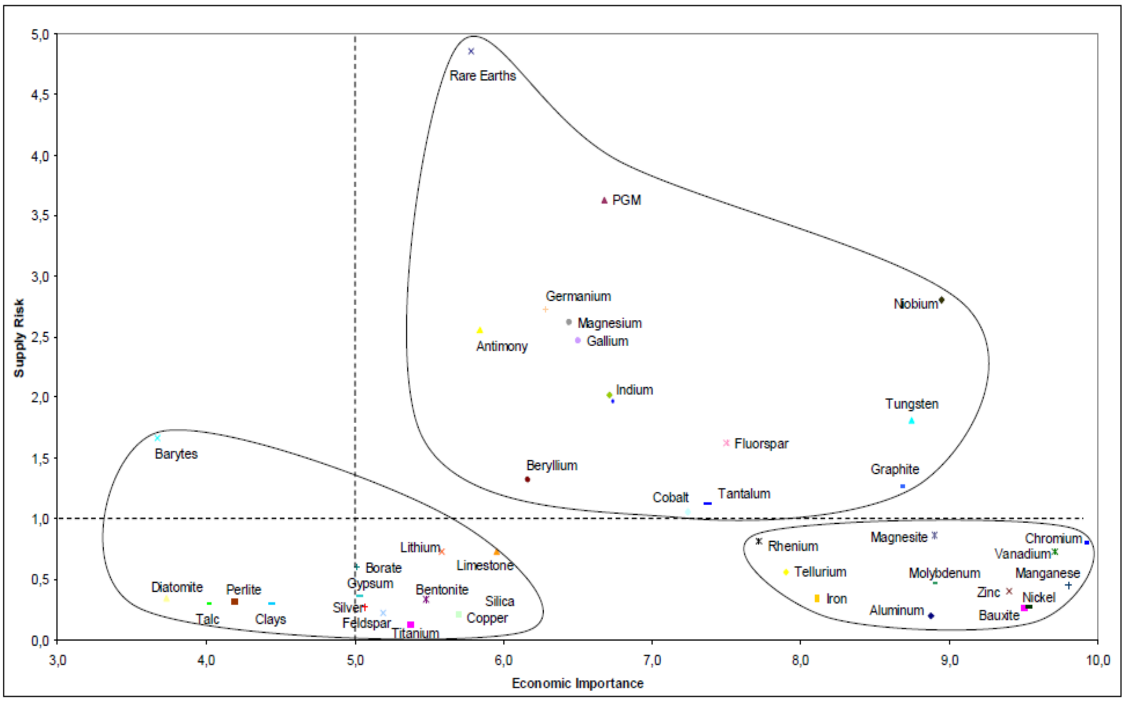

Figure 2.1 – CRM diagram. Source: European Commission, 2010

It is considered that fourteen materials located at the top right corner of the diagram are critical raw materials. Researchers in (European Commission, 2010) mention that ecological risk is not taken into the account on the diagram since at the moment it would not affect the position of materials on the diagram.

Materials in the bottom left corner can quickly shift into the top right corner and become CRM.

Supply risk is relatively high for CRM due to the fact that the majority of production of such materials is concentrated in the hands of just a few countries: China (rare earth), South Africa (80% of rhodium mining), Russia (30% of PGM mining) and Brazil (niobium and tantalum). Moreover, China is known for its deliberate reduction of supply levels into the European Union despite their responsibilities before World Trade Organization. Materials mentioned above, are hard to substitute as well as their recycling coefficient is rather low.

The thesis bases its work on platinum-group metals (PGM), specifically around rhodium. These metals are renowned for their physical and chemical properties especially for their resistivity to corrosion and catalytic activity.

As shown on fig.1.1 platinum-group metals are also considered to be critical raw materials. PGM consist of six metals: platinum (Pt), palladium (Pd), rhodium (Rd), ruthenium (Ru), iridium (Ir) and osmium (Os). These metals are usually mined together in a raw form of natural alloys and are one of the rarest metals (USGS). Together with silver and gold, they are categorized as precious metals. In natural conditions, these metals are met in the form of natural alloys.

Most of the supply of PGM comes from South Africa, Russia, Canada and USA. South Africa is the only country mining all six PGM in substantial amounts.

Figure 1.2 illustrates industries consuming PGM. PGM's ability to catalytic activity made them widely applied in chemical and fuel-processing industries, which use such metals as catalysts in the production of chemicals and petroleum products. Since 1970 automotive manufacturers use automotive catalysts (autocatalysts), which consist of platinum, palladium and rhodium to reduce dangerous exhaust fumes caused by vehicles (Krivenko and Glotov, 2000).

It is due to autocatalysts demand the scarcity of platinum, palladium and rhodium has a place to be, since automotive industry is being the main consumption sector for these PGM. According to the International Platinum Group Metals Association (IPA), "automotive catalysts convert up to 90% of harmful exhaust fumes such as hydrocarbons, nitric oxides and carbon monoxide into less harmful nitrogen, carbon dioxide and water vapor" (*IPA on environmental impact*).

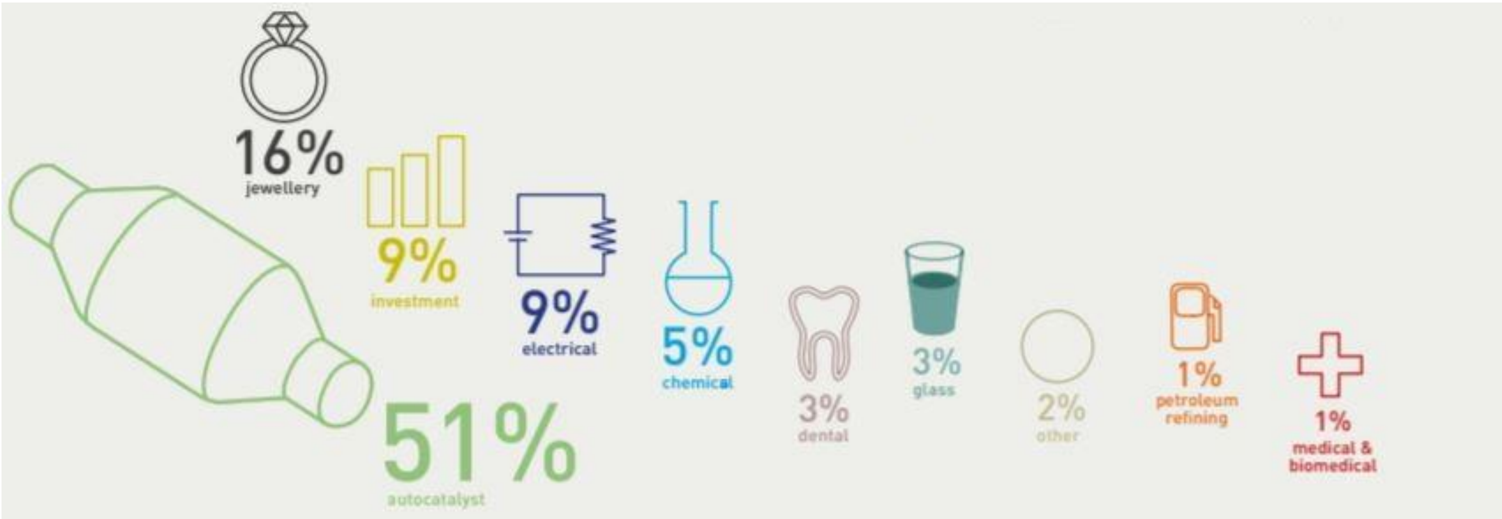

Figure 2.2 – PGM applications. Source: IPA on environmental impact

1.2 Research problem and objectives

The research on critical materials starts to be an actual and substantial field in the studies of contemporary technology, economics and management.

Knowledge on the role of critical raw materials in solving real technical problems is essential for solving the issues resulting from their scarcity. This knowledge can be gained through an analysis of materials flow in the global economy. The knowledge of the material streams flowing between the various industries of the economy, analyzed in the context of the products life cycle, allows identifying the economically justified ratio of the primary and recycled critical materials. This information should be used as one of the basic factors in decision making on in mining and development of the technologies facilitating the scrap collection and recycling processes.

The actuality of the topical issues of CRM recycling can be supported by a number of scientific works appearing on an annual basis. However, one can find a research problem in a lack of works dedicated to rare representatives of platinum-group metals, such as rhodium, for instance. There are several works analyzing the material flow of PGM-3: platinum, palladium and rhodium. Such works, usually, represent problems with material scarcity from the point of view of ore degradation, and do not allow to understand the flow of material independently and come to conclusions of economic matter in a short-term period.

Thus, **the goal of the thesis** is to conduct material flow analysis of rhodium on a global scale**.**

Having this goal in mind, the following objectives appear in line:

1. To determine rhodium scrap available for recycling.
2. To assess the expected recycling costs.
3. To compare different recycling processing technologies from the perspective of their profitability.
4. To establish limiting condition of rhodium recycling.

1.3 Research methodology

Table 1.1 contains research objectives with relevant research questions as well as research methods.

Table 2.1 Research objectives, questions and methods.

Research objectives	Research questions	Research methods
To determine rhodium scrap available for recycling.	What rhodium scrap quantities are available for recycling?	Quantitative method
To assess the expected recycling costs.	What are the expected costs of implementing the recycling system?	
To compare different recycling processing technologies from the perspective of their profitability.	What are the available recycling technologies?	
To establish limiting condition of rhodium recycling.	What are the limiting conditions of recycling?	

Having formulated the research problem, goal, objectives and questions it is advised to identify sub-questions in order to get a wider view on the topical issue *(Stringer, 2014)*. The first three research questions are rather strict and are to be answered directly, however, the last research question “What are the limiting conditions of recycling?” requires clarification and assumes answers on several sub-questions:

1. Is recycling economically justifiable and more profitable than mining?
2. What are the expected hidden losses of recycling, if such are relevant?
3. Is environmental impact caused by recycling insignificant?
4. What are the trends of scrap stock and the systematic impact caused by reduced mining volumes (comparison scenario)?

Material flow analysis assumes construction of a model based on which the answer on all of the research questions is supposed to be given in a numerical form and, thus quantitative methods are to be applied. The way these methods can be applied will depend on the relevant approach to research. Approaches, methods and relevant instruments are going to be chosen after studying previous research in the field of critical raw materials.

Data collection is going to be dominated by primary data. Since the scope of research is targeting rhodium streams in the global economy, it is reasonable to study open-access company annual reports on the topic for data such as rhodium supply and demand, price, costs and revenues. This can be referred to as a multiple case study research strategy, which is based on the in-depth study of data and processes inherent to rhodium global flows.

Secondary data sources are going to be used as well. Such would mostly include adaptation and calculations based on primary data, such could be, calculation per unit as usually company reports present data in complex and summarized way.

Now it time to develop the research design of the study in order to clearly understand steps which are to be taken and processes conducted to reach desired goals *(Saunders et al., 2009)*.

The research design is illustrated in figure 1.1. Having depicted the problem, goals and objectives are set, based on which research questions are developed. After the study of existing modern literature sources, understanding on applicable methods appears. Next step is to gather relevant data for chosen method and further to build a model, which should be designed in a way to both visualize the goal of the research and based on which it will be possible to achieve the desired results and come up to a conclusion on research questions. The last stage is to provide recommendations for further studies, which reflect new research problem.

Fig. 1.1 missing an important element – feedback loops/paths. In fact, the stages are interconnected, for instance, after literature review or data collection, it might be reasonable to adjust research questions or even the problem.

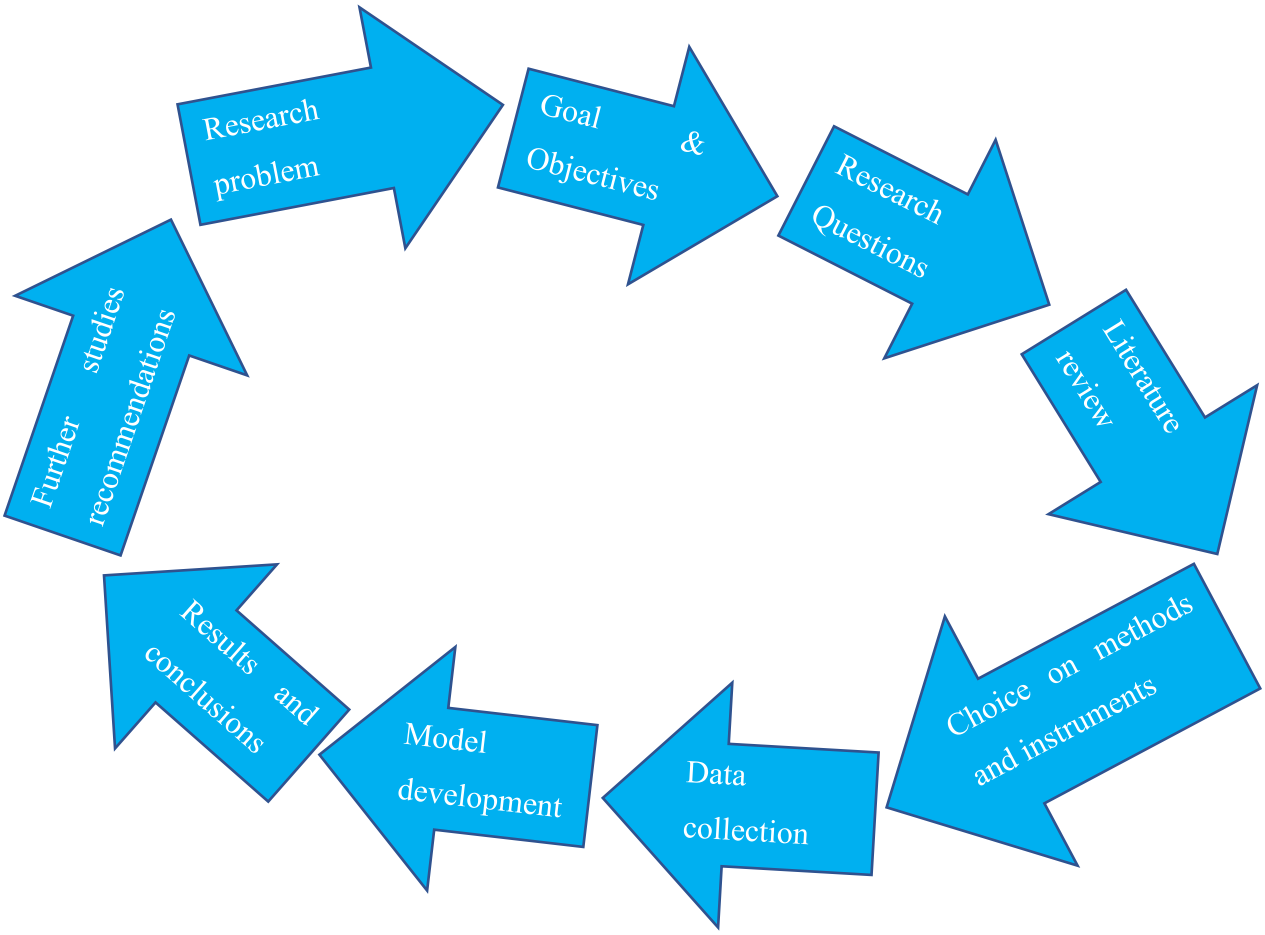

Figure 2.3 Research design

2. LITERATURE REVIEW

This chapter reviews scientific works and previous research of authors, who work in the field of critical raw materials. Researchers set their goal to analyze the material flow of different critical raw materials and come to conclusions of ecological and economic matters. Such information is invaluable in understanding authors' research questions and how chosen methods and instruments allowed to reach their goals.

The most significant factor determining material as CRM is a high risk of the supply deficit on the market. Many researchers view recycling of scrap as a good alternative to mining by both economic and ecological criteria.

The work *(Hatayama et al., 2012)* shows the importance of aluminum recycling now and in the future as well as how a change in the supply of primary metal (metal from mining) impacts on the environment. Although at the moment aluminum is not considered to be CRM, it still has a high influence on the economy as shown by authors in (*European Commission, 2010)*. For the assessment of the potential for aluminum recycling and the change in demand, authors applied a method in their research know as material pinch analysis (MPA). Authors demonstrate how a decline in demand influences on recycling levels and what amount will be eventually unrecycled. To deal with the problem of non-functional scrap authors suggest improving separation of scrap during its collection process.

The main conclusion of *(Hatayama et al., 2012)* was that a proper recycling system could significantly solve issues with the recycling of functional scrap, which in return will lower the necessity of aluminum primary production and as a result the energy consumption costs will be lower, moreover, reduced negative environmental impact, caused by accumulation of CO2 equivalent gases, can be expected. However, the paper examines large period (up to 2030), whereas material pinch analysis is commonly applied to identify the required amount of material for recycling in the nearest time *(Ekvall et al., 2014)* and not for building forecasts. Also, no quantitative assessment was given to evaluate the impact of the change in primary and secondary production of aluminum on economy and ecology.

Authors in *(Singhvi et al., 2002)* apply pinch analysis for the aggregate planning of metals production, without focusing on a particular metal but rather demonstrating how this method can be applied for determining the necessary extent of material stock for demand satisfaction. However, in this case, it is unclear why mathematical optimization cannot be used or what are the cons of MPA above it. It is also mentioned that MPA can serve as a sound basis for mathematical optimization.

Just like *(Hatayama et al., 2012),* scientific work *(Ekvall et al., 2014)* tries to present the problem with material scarcity and propose a solution in recycling. In *(Ekvall et al., 2014)* MPA of steel conducted by authors distinguishes several categories of steel applications. These categories depend on the quality of steel. For instance, copper which is also present in steel will also remain in the material after recycling, which can lead to a decreased f6unctionality of steel due to material losses after recycling process and can dramatically affect the quality of steel. Authors mention that steel contamination coefficient is a very important characteristic for conducting material pinch analysis. This coefficient serves as criteria for the determination to which industry the recycled steel can be applied. This leads to an idea that such quality grade is what makes MPA possibly useful. Authors also notice that there is a condition when MPA is not applicable, such condition could be an inability to measure and establish recycled material quality with one single grade such as level of copper in steel for instance.

Lingyu et al. (2013) view zinc as a material of a high demand in China with significant strategic meaning for country's stable economic development. Authors highlight a distinct metal scarcity and in order to provide a quantitative assessment of zinc stock in China as well as to analyze the process of scrap collection and recycling for building forecasts, conduct material flow analysis (MFA). For MFA tools of system dynamics are used, which lead to a creation of dynamics model. Such model allowed to conclude that "in the future zinc consumption would increase by 27% by the year of 2020 in comparison to 2004" (*Lingyu et al. (2013)*). Generation of zinc scrap would increase by the similar amount. It is considered, that growing recycling levels would help to increase zinc supply not only for China but also to other countries. Have China not improved the recycling rate for zinc, country will not be able to satisfy the industrial demand in the future, making China highly dependent on import of primary zinc. The method of dynamics modeling allowed researchers to answer a topical question on the sufficiency of material stock in the present moment, and moreover to forecast the upcoming changes in the material flow.

In *(European Commission, 2010)* by ad-hoc working group, tungsten was classified as a critical raw material due to low export quotas from China and a lack of material-substitutes. Tungsten is a CRM which is widely applied in wear-proof materials and instruments as well as in numerous alloys. Authors in *(Leal-Ayala et al., 2015)* proposed a goal to analyze the material flow of tungsten. Based on MFA it is evident that the improvement of mining technologies (now, material losses are up to 40% due to imperfect technological process) and enhancement of both scrap collection efficiency as well as of recycling technologies will allow moving tungsten from the zone of CRM (see figure 1.1). MFA assessment was made with the tool known as the Sankey diagram. Such method is an efficient tool for visualization, which illustrates MFA as a flow of metal account for the whole life cycle starting from mining and ending in recycling or landfill. Most important is that the width of flow (on chart) is proportional to the amount of material relevant for each specific stage of the life cycle. Because this method, it is vividly depicted how the amount of mined tungsten is dramatically higher than that amount of metal which will end in end-user due to high process losses in primary production.

Paper *(Hao et al., 2017)* is dedicated to the material flow of lithium, which is a metal mostly utilized in the so called "green technologies". A bright example of such technologies would be electric cars (for example, Tesla cars), production of which directly depends on the production of lithium-ion batteries. *Hao et al. (2017)* demonstrate MFA of lithium for China, which represents almost a half of the global demand. Authors in their research, applied Sankey diagram approach to build a conceptual model for material flow of lithium and based on this graphical method showed and concluded that China's demand for metal would increase with a diffusion of electric cars thus making country dependent on import of metal. Authors mentioned that lithium can become CRM taking in to account the all-increasing global lithium demand. Sankey diagram also allowed to analyze the generation of lithium scrap in China, which lead authors to a conclusion of relevancy of a recycling system for tackling the issue with the deficit of metal supply.

Authors in *(Riddle et al., 2015)* using agent-based modeling for evaluation of situation around critical raw materials and focus on the importance of knowledge on the supply chain of CRM for the analysis of supply deficit. The CRMs which are referred to in the paper are rare earth metals: neodymium and dysprosium. Such metals are used for a production of permanent magnets and electric motor vehicles. *Riddle et al. (2015)* determined five stages in their model, in which agents are interacting with each other: stages of mining, recycling, production of permanent magnets, end-production production and demand. Results of modeling are presented in the form of simulated scenarios of demand, price and technological process changes depending on their different parameters. The paper shows, how agent-based simulation modeling can take into account details in decision-making on various stages of rare earth metals life cycle for analysis of CRM in the market.

Based on a historical data, both retrospective and "what if" scenarios were developed for analysis of increasing demand and changes of rare earth content in end-product. One of the most significant scientific results achieved by authors was a chart illustrating the dependence of CRM price on the content of metal in a final product or near-end product as well as how prices on neodymium and dysprosium are interconnected and interdependent.

Just like in *(Riddle et al., 2015)* authors of *(Swain et al., 2015)* describe the issue with the criticality of neodymium. However, *Swain et al. (2015)* regard the metal in the case of the Republic of Korea rather than on a global scale. The method chosen by authors differs from that of *Riddle et al. (2015)* – instead of a dynamics model, a static conceptual model is developed. Such model and flow charts represent levels of neodymium stock on different stages of metal life cycle. The chosen approach allowed authors to study the material flow of metal in details and as a result concluded that Korean industry is currently in a high dependence on metals import ("just under 70% of the electronics industry is consuming neodymium" *Riddle et al. (2015)*). Moreover, the metal's market is viewed as a deficit one due to rapidly growing demand trends and the absence of substitutes. Authors also show the potential for neodymium recycling as a measure for filling in the gap between primary metal supply and demand. According to authors' assessment, only 5% of demand is satisfied by secondary metal. The main result of scientific work was a list of conclusions on the state of import and export levels in different industries as well as recommendations on the improvement of governmental data bases and statistical reports. Such data would allow building not only conceptual models but also dynamics models for forecasting and retrospective scenarios as well as sensitivity analysis, similar to the model in *(Riddle et al., 2015)*.

Material flow analysis of indium is conducted by *Choi et al. (2016)*. In this case, authors are using a system dynamics model for the assessment of the material flow CRM. Indium finds its application in devices which are working based on principles of photovoltaics. Authors analyze the change of world indium stock and demand based on several trends describing the change in technologies and energy consumption in a fifty-years' time. The paper showed different ways of the development of supply and demand, which illustrate that despite there is a sufficient level of primary indium now, the demand in the future will exceed the capabilities of supply. The main advantage of dynamics model in *(Choi et al., 2016)* before model of *Lingyu et al. (2013)* is the factor characterizing the influence of technological development on supply and demand, moreover specific technologies are determined (in this case connected to photovoltaics) which cause the major impact on changes in demand. Authors mention that due to the lack of supply CRM price significantly increases, thus, to some extent, the demand is lowered, known as “the balancing loop” effect in system dynamics, where the system tries to reach equilibrium by reducing or increasing one of the parameters *(Monat and Gannon, 2015)*. However, in a long-time period, indium remains to be a CRM and is exposed to supply deficit. Unfortunately, authors do not give quantitative assessment of that extent and neither scenarios demonstrating how the potential for recycling could increase the indium supply.

The paper (*Gsodam et al., 2014)* focuses on the material flow analysis of silver in the scale of Austria. Silver renowned for its chemical properties finds more and more applications nowadays. There are no silver mining facilities in Austria, and the country is entirely dependent on import. *Gsodam et al. (2014)* have built a static conceptual model of the material flow of silver based on statistical data. Such model can be a useful basis for the development of dynamics model similar to models of *Riddle et al., 2015* and *Choi et al., 2016.* The model is designed to support the decision-making process of those responsible for legislation and technical regulation regarding silver resources management. The work resembles *(Hao et al., 2017; Swain et al., 2015)* since it describes the metal’s flow in the country, showing the amount of material imported and more importantly how the end product is exported. The authors concluded that the issue with potential a deficit as well as import dependence can be solved with the development of recycling technologies, yet no economic or ecological assessment was provided.

Another conceptual model for MFA was built by researchers in *(Bicanová et al., 2015)*. In this case, material flow analysis of lead for the Czech Republic is conducted. Authors used data from several governmental documents regarding country’s strategic development. As a result, it was proved that lead is a critical metal for the country, thus metal scarcity leads to dependence on lead import. Authors consider the creation of the closed-loop recycling chain what reflects the idea of a circular economy when industry self-sustains its need in raw materials through the recycling of products near their end of life cycle. That is exactly why it so crucial to ensure that scrap collection and recycling processes are efficient. Despite that no criteria or assessment of the processes effectiveness were given in the paper, authors, with the use of their model, were able to emphasize "bottlenecks" and give directions on where, in the material flow, it is more reasonable to put the major effort for improvement.

In comparison to previous works, (*Bicanová et al. 2015)* notices the importance of monetary motivation, which stimulates scrap collection for recycling. Also, authors give insights on possible costs appearing due to material scarcity in the time of innovative technological development of industries, consuming silver; however even a brief economic analysis is not presented.

Much like *Hao et al. (2017)*, work of *Ziemann et al. (2012)* is dedicated to the topical issues of lithium scarcity owing to increased global interest in "green technologies". The paper describes world material flow analysis of lithium. Such MFA allowed to determine the potential in lithium recycling as well as designate the most impactful factors influencing the effectiveness of the metal utilization. Ziemann et al. *(2012)* mention that despite sufficiency of lithium in earth crust there is a high probability of world facing material scarcity (see fig. 1.1 – lithium is near the criticality zone), and recommedation to all countries could be to strengthen and expand recycling process on lithium extraction from scrap. Similar to *(Bicanová et al., 2015)* the authors' conceptual model helps to identify "systems bottlenecks" in the material flow with the incentive of enhancing decision-making process on where to enhance strategies for effective resource management.

Ziemann et al. (2012) claim that their model is not able to provide quantitative economic assessment, yet again it is evident that such model is essential for the development of dynamics model. In addition to that, speaking of the potential for lithium recycling, authors use categorical data on metal content in scrap such as "very much" and "very little", thus it is evident that there is not enough information in the field of CRM, for now.

One of the scientific works devoted to the criticality of platinum-group metals is *(Kim 2013)*. The author views life cycle of palladium in the Republic of Korea as the most well-studied metal of PGM in terms of material flow analysis. Based on a static flow model proposed by Kim, an analysis of the available palladium stock in the country as well as on import and export conducted, moreover palladium content in end-products and scrap generation process are analyzed. All this information is essential for tackling the issue with the potential for metal recycling. The main application of this metal in the Korean Republic is in the field of automotive catalysts (up to "80% of total consumption"). Considering the forecast of automotive industry development, the palladium demand has a trend to increase with increased automotive production volumes just like in electronics. "Palladium scrap collection levels reach approximately 88%, yet most the collected scrap is being exported", leaving the country with an average of 23% collected scrap. The author theorizes that by improving the recycling chain (also considers that secondary production is a major force), it is possible not only to raise previously stated figures but also to move the metal from the zone of criticality. Kim also mentions an ecological impact caused by palladium recycling. Per the author, Korean secondary production focuses on hydrometallurgical processes for metal extraction from scrap (which is uncommon for the rest of the world, yet about this there will be a further notice in the thesis), what has negatively reflected on the environment; however, no quantitative assessments of such impact were presented.

The research *(Sverdrup et al. 2016)* was focused on the evaluation of the long-term development of mining industry, demand and platinum-group metals recycling (in this case PGM-3: platinum, palladium and rhodium). The material flow analysis of PGM was conducted with the use of simulation modeling in system dynamics modeling software – STELLA. With modeling, it was shown that in between 2020 and 2050 the PGM mining would reach its peak and to satisfy the demand it will be necessary to enhance mining and recycling technologies (it is considered to lead to reduced metal losses). As noticed by authors, PGM ore content will decrease as mining site depletes. For instance, "value in PGM ore in hundred years will decrease by 30% making mining economically unjustified" (*Sverdrup et al., 2016).* Authors state that their dynamics model is not suited to perform PGM MFA in a short-term period. As it is clearly shown on one of the charts in the paper that recycling rate is going to increase, where as in a short-term period it is far more likely to remain flat (figure and charts for recycling rates will be shown further in the thesis). In the paper PGM are often viewed together as a whole, since they are mined together in one natural alloy, however it can mislead that there is one recycling rate for all PGM, where in truth it varies for each metal individually. The model contains cost for primary PGM production, yet no dynamic assessment of changes in mining industry profitability is done, which could have been rather important and enlightening considering statement about reduced economic justification of primary production in time. Also, unfortunately, the impact of improvement in recycling and scrap collection was not assessed. In general, the main goal of the research was achieved – to analyse the stock changes of natural PGM resources in long term-period up to the year of 2400.

In *(Saurat and Bringezu 2008)* и *(Saurat and Bringezu 2009)* authors conduct material flow analysis of PGM-3 (platinum, palladium and rhodium) in order to assess ecological impact caused by primary and secondary PGM production on the environment. Results achieved by *Saurat and Bringezu* allow comparing environmental friendliness of mining to recycling as well as to assess how the environment is influenced by products manufactured from PGM – autocatalysts. An important finding was that despite autocatalyst do reduce the harm caused by vehicle exhaust on human health, such devices, even by a small fraction, contribute to increased greenhouse gases (CO2 equivalent gases) generation.

On several criteria, authors analyze the impact of primary and secondary production on the environment from the perspective of different countries. It was estimated that while Russian PGM producers contribute to the SO2eq. gases generation the most, their CO2.eq generation levels are the lowest in the world. *Saurat Bringezu* in their works demonstrated the importance of recycling for the better of world's ecology. A very interesting observation also concluded from works: the majority of PGM secondary production is located in the EU and on the one hand having bigger recycling rates would seem likea priority, on the other hand optimizing recycling chains and thus increasing scrap collection rates is more important, since the huge chunk of automobiles produced in the EU are exported to countries where secondary production is poorly developed or non-existent. That and the fact that demand can increase leads to the understanding that, howsoever ecologically unfriendly PGM primary production is, it is impossible to replace it with recycling altogether.

By the end of the literature review, it is visible that many researchers who base their work on material flow analysis view secondary production as a solution to the issue of material scarcity. Most of the works narrow down to general conclusions and do not provide quantitate assessment of the economic and ecological matter. In the presented models, there is a common line which is characterized by the lack of scenarios capable of evaluating economic and ecologic impacts of reduced mining levels and transition to a different recycling technological process.

The Master's Thesis is dedicated to the topical issues of platinum-group metals being critical raw material, yet the analysis will be based on rhodium specifically, due to the following reasons:

- There are several scientific works (for example, (*Kim 2013; Sverdrup et al. 2016; Saurat and Bringezu 2008; Saurat and Bringezu 2009*)) on PGM-3, primarily analyzing situation on recycling and mining for platinum and palladium;
- The data regarding mining and recycling levels for iridium and ruthenium was not found. As for osmium, even the data on demand is absent.

3. METHODS AND INSTRUMENTS FOR THE GOAL ACHIEVEMENT

In the course of the literature review, it was revealed that the main method adapted by authors for addressing issues with metals' criticality was material flow analysis. Such method helped authors to choose reliable tools and instruments in order to answer desired research questions. Commonly authors would use a construction of models to develop different behavioral scenarios of the main factors (such as demand, supply, metal price, etc.) connected to mining and recycling industries.

3.1 Method – material flow analysis

Brunner and Rechberger (2004) defined material flow analysis as "a systematic assessment of the flows and stocks of materials within a system defined in space and time". Material flow has a similar meaning to life cycle and assumes the transfer of material mass from the moment of its extraction from earth crust to the moment of its arrival at a landfill or returning back into the industry through recycling chains. More specifically material can flow through stages of primary ore treatment, smelting, transfer to end-product, recycling, moreover fraction of material can be lost due to technological imperfection processes of mining, manufacturing of end-product and recycling. It is considered that life cycle analysis differs from MFA mainly by the depth of details as well as MFA is focused on simplicity of data presentation.

MFA can be applied for achieving the following goals as per *(Gregory MIT)*:

- Strategy development for reduction of air contamination levels;
- Assessment of material's life cycle on the environment;
- Model of losses on stages of material's lifecycle;
- Assessment of the effectiveness of recycling;
- etc.

According to *Gregory MIT,* MFA is a suitable method for analysis of material transfer within a system. Such analysis allows understanding the behavior of the system especially if to combine it with economic analysis and analysis of product and energy consumption.

Moreover, MFA can help to solve the following issues:

- Presenting system in a less complex way and, in the meantime, preserving the base for reasonable decision-making;
- Quantitative assessment of material's life cycle;
- Illustration of material flows and stocks in logical and understandable way;
- Appliance of MFA's results for controlling and distribution of resources and waste;
- etc.

3.2 Approaches to material flow analysis application

The question might appear on how to realize MFA method. From the literature review it was evident, that there are three approaches for the method's implementation:

1. Static approach
2. Dynamic approach
3. Mixed approach

Static approaches assume building a conceptual model in a predefined time frame. Generally, such frame means a specific month or a year and all the data on supply, demand and price are viewed from the perspective of that month/year, although theoretical approximation for upcoming time periods is possible based on statistical analysis.

The most typical instrument for static approach would be Sankey diagrams, which allow presenting material flow through "arrows" (flows in diagram's notation) of different width based on a material's mass on a particular stage of life cycle.

Dynamic approach incarnates in dynamics model. *Park et al. (2011)* mention that this approach can be applied for quantitative assessment of the past (and thus building a retrospective model), a situation as it is now as well as for creating forecasting scenarios of system's development. The major factor that differs this approach from previous is the life cycle time, which is responsible for achieving results based on time changes in models *(Park et al. 2011).*

Besides scientific works which were studied in the literature review, dynamics approach was used in older works for MFA of not only critical raw materials. For example, *Davis et al. (2007)* applied dynamics approach analysis of iron and steel in England in 2007, and *Spatari* *et al. (2005)* conducted a quantitative analysis of copper material flow regarding copper mined in the 20th century in North America.

As for mixed approaches, as it goes from the name, they are combining both static and dynamic approaches. Generally, in this case, conceptual model serve as an accumulation of knowledge on metal's life cycle and processes inherent to it, whereas dynamics model is based on previous model and is filled with data and equations, what in return helps to build different charts and behavioral scenarios such as change in metal stock in case of increased demand.

In the Master's thesis, a mixed approach is going to be applied for material flow analysis of rhodium.

3.3 Instruments for material flow analysis

Static conceptual model is going to be constructed with the aid of Microsoft Vision 2016 software. The main goal is to present process inherent to rhodium's life cycle in a graphical and evident way.

Based on the conceptual model a model of system dynamics will be built via Ithink modeling software (software example on - Isee systems website). This will allow to study rhodium material flow as a complex system in time and carry out necessary calculations based on a number of assumptions and available data. The choice of the software is motivated by the author's competencies in the field of simulation modeling in system dynamics in Ithink.

As per *(Brunner and Rechberger 2004; Park et al. 2011)* the MF method is done in four steps:

1. The specification of system's boundaries and product's classification.
2. The specification of material's flow time on each stage of the life cycle.
3. Determining how scrap is generation and in what amounts.
4. Analysis of results presented graphically. Conclusions are formed from quantitative results and interpreted qualitative.

Step 1. Material flow of rhodium, which is a CRM for the majority of countries, is viewed on a global scale. Time frames of model are defined in between 2016 and 2021, since the idea is to look at a short-time period and to show an impact on the stock changes, environment and economic indicators (such as, unearned profit or gained profit from reaching higher recycling rates) based on model's parameter changes.

Also, the choice of time scale was influenced by the availability of data and the existence of similar works:

- The most cited data source on rhodium is annual reports of Johnson Matthey company *(JM annual reports)*, based on which one can come to a conclusion on the upcoming levels of demand, recycling etc. in "a short-time period", for which an above-mentioned interval was chosen.
- In *(Sverdrup et al. 2016)* authors have already created a dynamics model for PGM-3 for a long-time period (up to the year of 2400, and main conclusions for the period of 2030-2080). In addition to that, authors claimed, that decision based on their model is not suitable for short-time periods of time, especially ones of the economic matter.

Step 2: Rhodium material flow time on different stages of life cycle will be taken as one year, since data is available on an annual basis. Thus, all data on productivity in different stages (for instance, rhodium mining level – 23 tonnes per year) are noted in "per year". However, individual attention is given to time in the part of the model responsible for scrap generation, yet it will be explained further in the relevant chapter.

Step 3: Information, connected with scrap generation is directly influencing the answer on one of the research questions of the master's thesis, and thus scrap generation as well as relevant forecast, will be explained further in the thesis.

Step 4: Analysis of result assumes a conclusion based on charts, built via modeling.

The algorithm of solving research questions of thesis is similar to steps recommended by *(Brunner and Rechberger; Park et al. 2011)* as well as resembles the developed research design and is present on figure 3.1

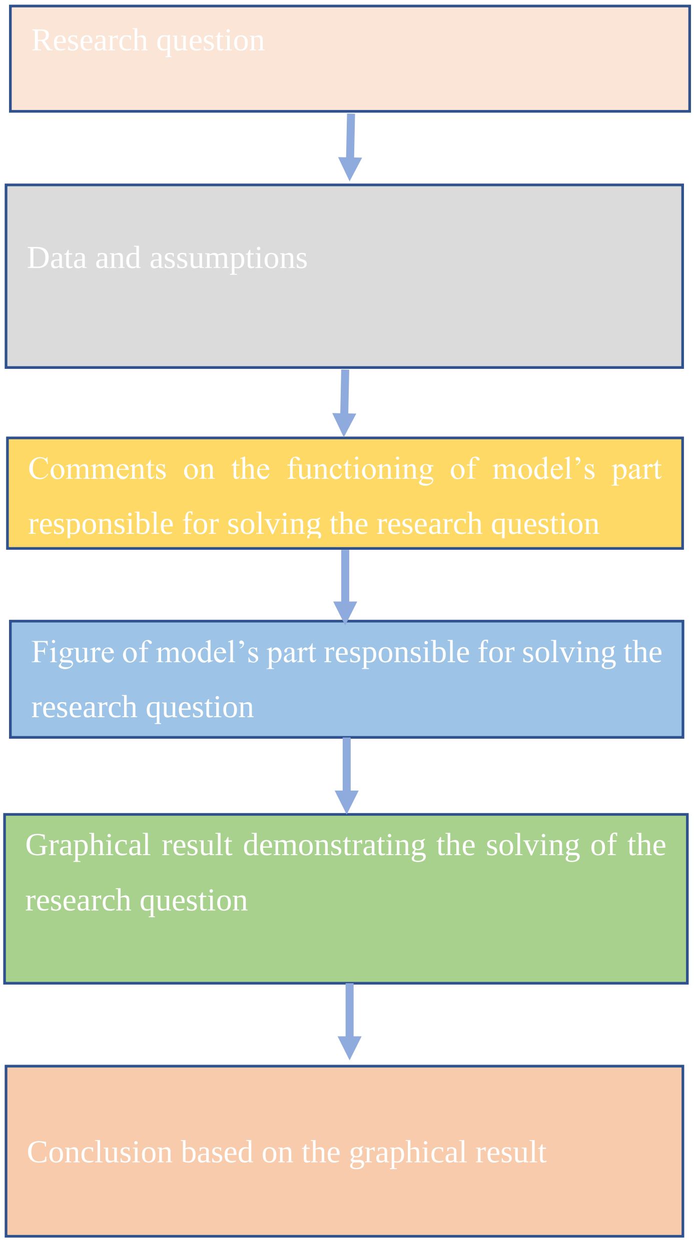

Figure 3.1 – The algorithm of solving research questions of the master's thesis

4. CONCEPTUAL RHODIUM MATERIAL FLOW MODEL

As mentioned before, the conceptual model is built for the understanding of the main processes of rhodium's life cycle and serves as a basis for the development of a model of system dynamics. The model is shown on figure 4.2., and chapter 4.1-4.3 describe the main processes of the life cycle.

4.1 Primary rhodium production

In primary state, rhodium is not met in nature *(Annual Report 2012)*, but rhodium forms a natural alloy with the other PGM along with copper, nickel and sometimes with gold and silver. Therefore, mining companies view rhodium as a byproduct of platinum, palladium or nickel ore mining. The majority of PGM resources is concentrated in the South Africa. Approximately 60% of PGM primary production accounts for the Republic of South Africa (RSA) *(Annual Report 2012)*, whereas up to 25% of PGM is mining in Russia from nickel ore, the rest is produced in Zimbabwe and Northern America. Based on the data for 2016 *(JM PGM market review 2016)* it is possible to make a pie chart (figure 4.1) illustrating rhodium proportional production in the world. For 2016 primary production level reach 23.1 tonnes, in comparison gold was mined in quantities of 2500 tonnes for the same year, what can lead to a more evident understanding of the rarity of the metal.

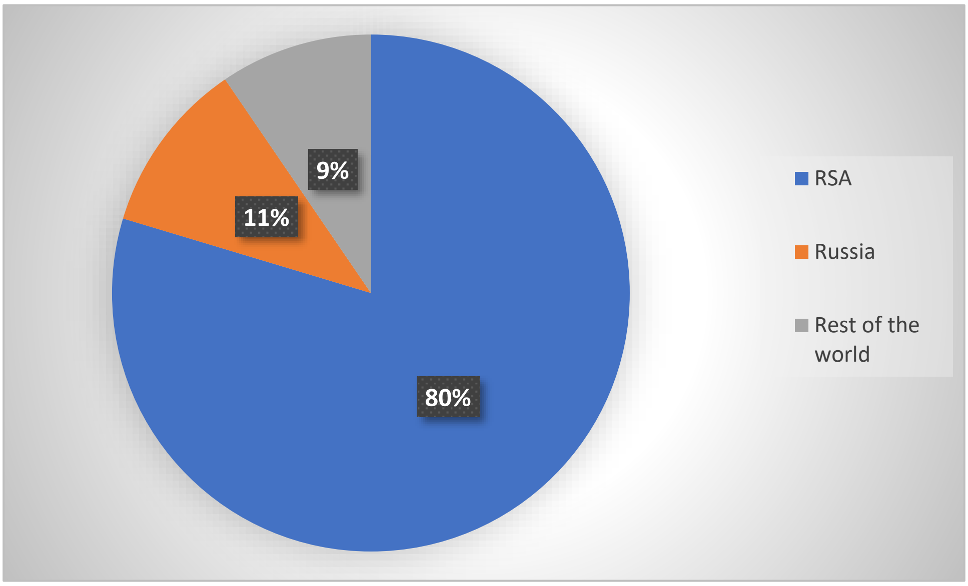

Figure 4.1 – Global rhodium primary production in 2016

The product of rhodium primary production is a refined rhodium in the form of a dust, which is then transferred to manufacturers of end-products from PGM.

According to the International Platinum-Group Metals Association *(IPA fact sheets)*, costs of PGM extraction are far greater than those of other metals, resulting in their expensiveness.

4.2 Manufacturing of end-products from rhodium

The literature review showed, that the main consumer of rhodium is automotive industry, and more specifically, autocatalysts producers, who use rhodium in autocatalysts to reduce the harm caused by exhaust fumes of gasoline vehicles.

Data on rhodium demand for the period of 2011-2016 is presented in table 4.1.

Table 4.1 Rhodium demand (by consumption sectors). Source: JM PGM market review for the November 2016

	2011	**2012**	**2013**	**2014**	**2015**	**2016**
Autocatalyst	22,60	24,10	24,00	24,60	23,70	24,20
Chemical industry products	2,10	2,50	2,70	2,90	3,10	3,10
Electronics	0,10	0,20	0,10	0,10	0,10	0,10
Glass industry	2,10	1,00	1,40	1,80	1,20	1,60
Others	0,70	2,00	2,80	1,20	1,00	0,80

From the table above, it is evident that automotive catalysts account for approximately 80% of total rhodium demand. The second highest rhodium-consuming industry is chemical industry, which finds use in rhodium as of catalyst for chemical reactions as well as in the production of petroleum products. “Others” include dental medicine, jewelry and investment.

4.3 Secondary rhodium production

Having scanned the Internet and studied the scientific works of well-known authors in the field of metals recycling (for instance, *(Graedel et al. 2011: UNEP 2011)*) it is possible to observe that rhodium can be extracted from all sort of scrap even from electronics and spent chemical catalysts. However, in this case, it will appear that rhodium is not a critical metal at all and rhodium stock balance on the market will always bounce in the favor of surplus.

In fact, those are theoretical recycling rates and it is possible to restore rhodium mass from spent chemical catalysts but it may not be economically justified at the moment. On this topic, a group of researcher from Lappeenranta University of Technology and the author conducted a research and finalized it into paper presented at the international conference in the National Mining University of Saint-Petersburg, dedicated to topical issues of natural resources use. The paper describes the potential for rhodium recycling based on the data resulted from the dynamic model and came to a conclusion that if it is possible to implement theoretical recycling rates then issue with rhodium supply deficit could be solved *(Bessudnov et al. 2017).*

At the moment, rhodium extraction from scrap is implemented only for spent autocatalysts *(Saurat et al. 2009; BIO 2015; IPA on secondary production)*, it was also confirmed via e-mail correspondence with a representative of the Belgium refinery company Umicore. Moreover, recycling of automotive catalysts is a less complicated process compared to recycling of other rhodium-containing products *(UNEP 2009).*

Secondary rhodium production includes two main stages:

1. Autocatalyst scrap (further, just “scrap”) collection.
2. Rhodium extraction from scrap – technological recycling.

Scrap collection is a unified process of several processes: vehicle dismantling process (detachment of autocatalyst from a vehicle) in specialized scrap-yards, scrap purchasing process by collector companies, which can also solely work on process of final autocatalyst detachment from metal-box in which autocatalyst is located.

Researchers have come to a conclusion that more than 50% of all accumulated scrap in the world is collected *(UNEP 2011)*, rest can be considered to be metal loses.

Technological recycling also included several stages: autocatalyst smelting, an input of attractor-metals for rhodium separation and extraction from a group of metals contained on autocatalyst based on differences in temperatures smelting as well stage of metal purification. Another technological process chain is possible, on which a further mention will be given in a chapter where a research question on different recycling technologies and their economic justification is going to be answered.

It is worth mentioning that 83% recycling rate is considered to be the minimum rhodium recovery coefficient (RC) that is economically justified (in other words, technological process with RC less than 83% is unprofitable).

In the master's thesis, secondary production and recycling are used as synonyms and include stages of scrap collection and technological scrap recycling. Yet, technological recycling or recycling process assume the process of metal extraction/recovery from scrap.

Scrap, rhodium scrap and unspent automotive catalysts are used as synonyms.

Conceptual model of rhodium's life cycle for 2016 is illustrated on figure 4.2

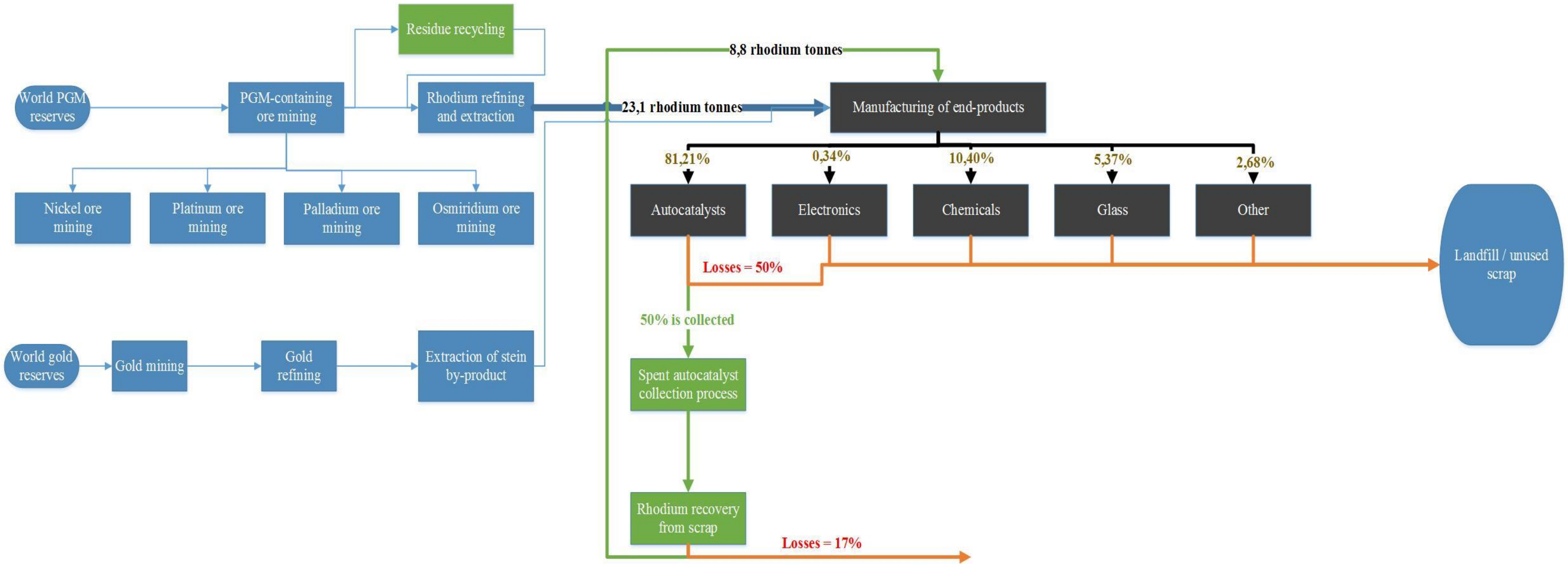

Figure 4.2 – Conceptual rhodium flow model

5. DYNAMICS MATERIAL FLOW MODEL

Model as a whole is presented in the appendix on figures A.1.1-A.1.4.

In this chapter, the research questions of the master's thesis are going to be answered through quantitative assessment presented in a graphical way. The general algorithm for answering research questions is demonstrated on fig.3.1. As shown on the figure, in the upcoming sub-chapters fragments or parts of the dynamic model will be shown and depict the direct objective solving. Naturally, the model has other elements which have indirect meaning in scenarios making and results achieving, without which the model would not function correctly, such fragments are going to be viewed after results in a separate chapter.

Simulation modeling in system dynamics logic is a computational method to problem-solving serving both as a conceptual reflection of a system and a tool for quantitative calculations. *(Neuwirth et al. 2015)*

Dynamics models are commonly described by stocks and flows *(Sterman, 2000)*.

Stocks are simulating an accumulation of a given parameter (scrap, money, material, energy etc.). Stocks are changing based on the difference between inflows and outflows. Based on stocks change a decision-maker can come to conclusions.

Flows represent the velocity of stock's accumulation or depletion (production rate, birth rate, consumption rate etc.). Equations or parameters animate flows.

In fact, there are more elements of dynamics model, but stocks and flows are the heart and soul of a model and allow to simulate interdependencies inside a system *(Thakker et al. 2012)* and make it a great approach for material flow analysis. Knowledge of flows based on conceptual model and case studies of rhodium-producing companies make it possible to model desired stock changes in a material flow.

Main assumptions of the dynamics model:

- Simulation runs are made for five years, expect some specific scenarios;
- The year of 2016 is set as the initial year of the model (year "zero") from which simulation starts;
- The majority of numerical data in model's nodes are constants (taken for 2016), besides several of which a further explanation will be given. It was planned to use a

distribution of values at first, yet for identification of which it is necessary to have at least 30 observations and for demand and supply, for instance, there are stable observation for only seven to nine years. A statistical analysis on identifying distribution type for supply and demand was conducted using Minitab software, and, it resulted in the unavailability of identifying distribution types. Thus, constant values are to be used. Also for research questions, which are viewed on a global scale, much more essentially are not as precise values but rather their relevant values allowing to compare different scenarios;

- Data provided by Johnson Matthey (which is, probably, the most cited and only acknowledged source of empirical data on platinum-group metals), suggest the minimum deviation in demand for 2017 and short-time period after as well as stable flat numbers for recycling and primary production volumes which can once again prove the possibility of using constant numbers in the model;
- Data on total costs of both primary and secondary production are taken from the annual financial report of the Stillwater Mining Company for the year of 2015;
- Data on supply, demand and their forecasted values are taken from annual reports of the Johnson Matthey company for the period 1985 to 2016 and 2017 plus "short time-period" respectively.

5.1 Determining scrap availability for recycling

Research question: What rhodium scrap quantities are available for recycling? (further, "RQ 1").

Data for the RQ 1.

Data used for RQ 1 are based on reports of Johnson Matthey company and are in open access on the website of the company. Previously a reference as given to the annual report for the year of 2016, which contains the information on supply and demand for rhodium. In the period of 2011 to 2016, yet this data is insufficient to evaluate scrap quantities which could be recycled since rhodium was being used in autocatalyst production since 1985. That is why a closer look into archival data is made and on its basis, a table (table 5.1) is adapted only for autocatalyst segment in the period of 1985 to 2016.

Table 5.1. Supply and demand for rhodium, in tonnes. Sources: JM PGM 2016; JM archive; JM 1985-1999; JM 2000-2004; JM 2004-2013.

Year	Demand (autocatalysts)	Total Demand	Primary production volume	Secondary production volume
1985	4,20	7,5	7,00	0,00
1986	5,80	8,3	8,60	0,00
1987	7,00	9,3	9,70	0,10
1988	7,20	9,6	9,90	0,20
1989	8,20	10,4	10,10	0,20
1990	10,40	12,6	11,50	0,40
1991	9,40	11,3	10,80	0,50
1992	9,50	10,9	11,80	0,70
1993	11,10	12,2	11,70	0,80
1994	11,80	13	13,30	1,10
1995	14,40	15,8	13,60	1,20
1996	13,20	16,1	14,80	1,40
1997	13,00	16,04	19,78	1,52
1998	15,02	17,54	16,48	1,77
1999	15,83	18,44	15,58	2,02
2000	24,67	27,71	23,86	2,46
2001	17,60	20,74	18,79	2,73
2002	18,63	21,49	19,13	3,08
2003	20,53	23,14	22,52	3,86
2004	20,53	23,14	22,52	3,86
2005	23,58	27,03	22,39	4,35
2006	25,80	30	23,50	4,30
2007	26,80	31,3	24,90	5,30
2008	27,60	32,2	25,60	6,00
2009	23,90	27,9	21,60	7,10
2010	19,30	22,4	23,90	5,80

Table 5.2 (continued)

2011	22,60	27,6	22,80	7,50
2012	24,10	29,8	22,40	7,8
2013	24,00	31	21,70	8,60
2014	24,60	30,6	19,10	9,50
2015	23,70	29,1	23,50	8,50
2016	24,20	29,8	23,10	8,80

Table 5.2 contains information about the data, which was used in the model's fragments responsible for answering research question 1. Equations are explained in comments section.

Table 5.2 Input data table for the RQ1

Element	Element type	Data input/initial value	Figure №
Autocatalyst production	Flow	equation	Fig. 5.1
Autocatalyst demand	Value	24,2 tonnes	Fig. 5.1
Autocatalyst demand level increase	Value	CGROWTH (5)	Fig. 5.1
Autocatalyst rhodium	Conveyor stock	Transit time: 9,75 years	Fig. 5.1
Autocatalyst Scrap Generation	Conveyor outflow	Transit time: 9,75 years	Fig. 5.1
New scrap	Stock	266,50 tonnes	Fig. 5.1
New scrap flow	Flow	Graphical function	Fig. 5.1
Scrap	Stock	0	Fig. 5.1
Generation of unused scrap	Flow	equation	Fig. 5.1
Unused scrap	Stock	140,95 tonnes	Fig. 5.1
Generation of usable scrap	Flow	equation	Fig. 5.1
Usable scrap	Stock	140,95 tonnes	Fig. 5.1
Collectible scrap fraction	Value	50%	Fig. 5.1

Assumptions and constraints of the RQ 1.

Data on rhodium generation are used for the period of 1985 to 2016.

Rhodium demand (autocatalysts producers) is considered as a realm amount of produced rhodium-containing products, which is in a functional state for recycling.

Researchers in (UNEP 2009) demonstrated that only more than 50% of all autocatalyst scrap, which is being used in the process of technological recycling, is, in fact, being collected by collector companies. Since fraction is not specified and numbers are not given, it will be considered in the model that 50% of scrap can be collected for recycling.

Scrap generation quantity depends on three aspects:

1. Old scrap (considered as a stock) accumulated in the period of 1985 to 2006.
2. New scrap, which, in reality, is not scrap yet, but it is a fraction of the global rhodium mass, that is currently (for 2016) being used in functioning vehicles in the period of 2006-2016, yet this fraction will become real scrap in the upcoming years (2016, 2017 etc.). Time periods in this and previous aspect are motivated by that fact that autocatalysts life cycle time is considered to be approximately ten years as per European Automobile Manufacturers Association (EAMA).
3. 2017 scrap – scrap that is generated in 2017 and onwards.

Part of the model, responsible for answering research question 1 is present on figure 5.1.

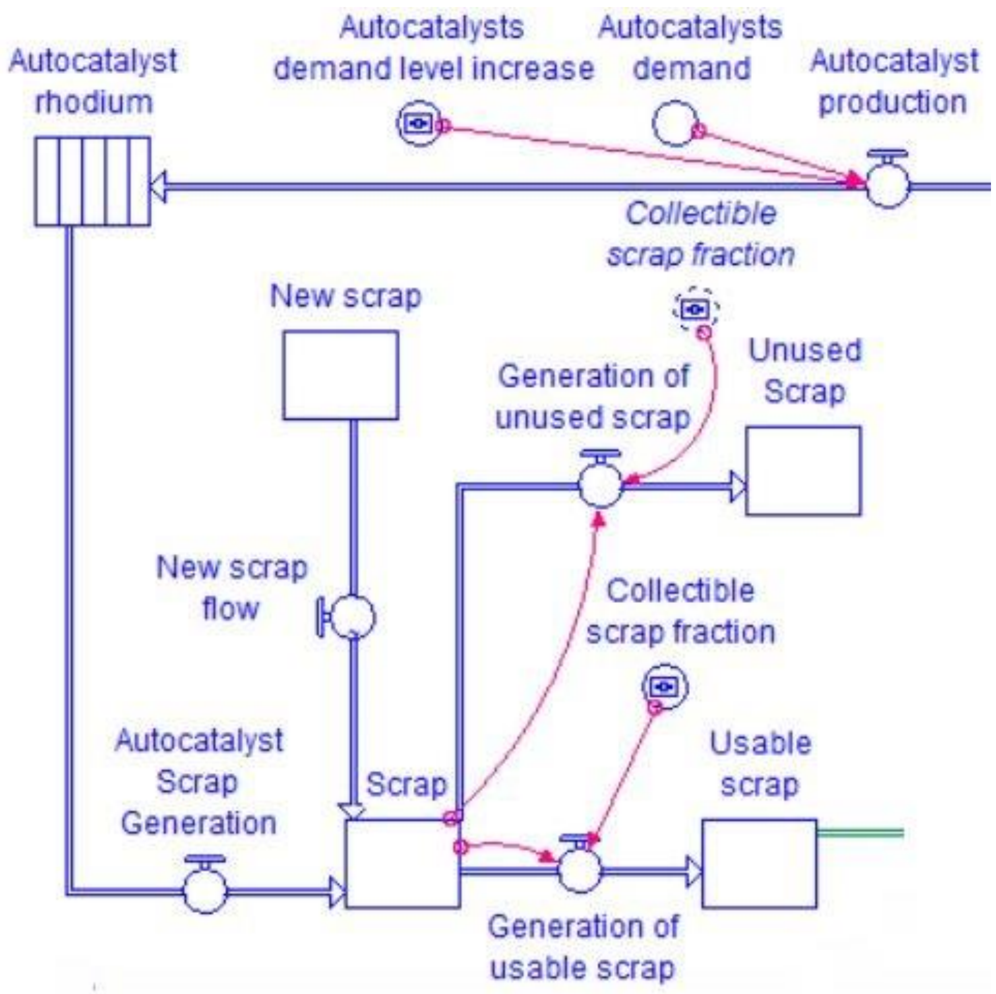

Figure 5.1 – Fragment of the model for RQ1

Comments on the functioning of the model's fragment and equations for RQ1.

"Autocatalysts production" assumes rhodium mass contained in autocatalysts. Such flow will be explained precisely in the chapter on the indirect parts of the model. The flow has importance for RQ1 as a source of constant scrap inflow from produced automotive catalysts.

"Autocatalyst rhodium" is a transferring type of stock and characterizes the amount of metal which transferred from the state of autocatalyst into the state of scrap, considering the delay time caused by metal's life cycle time. The delay is taken as 9,75 years for gasoline vehicle as per EAMA. The initial value for this stock is based on 2016 and equals 23,7 tonnes of rhodium.

"New scrap" – rhodium stock, which will become scrap since 2016. Initial value is set to 266,6 tonnes based on calculations from table 5.1.

"New scrap flow" is a flow, mimicking a process of rhodium transition from autocatalyst into scrap during the period of 2006 to 2016. The value of this stock is set as a variable, described by a graphical function (figure 5.2). which demonstrated scrap inflow starting from the year of 2017 and in the ten upcoming years.

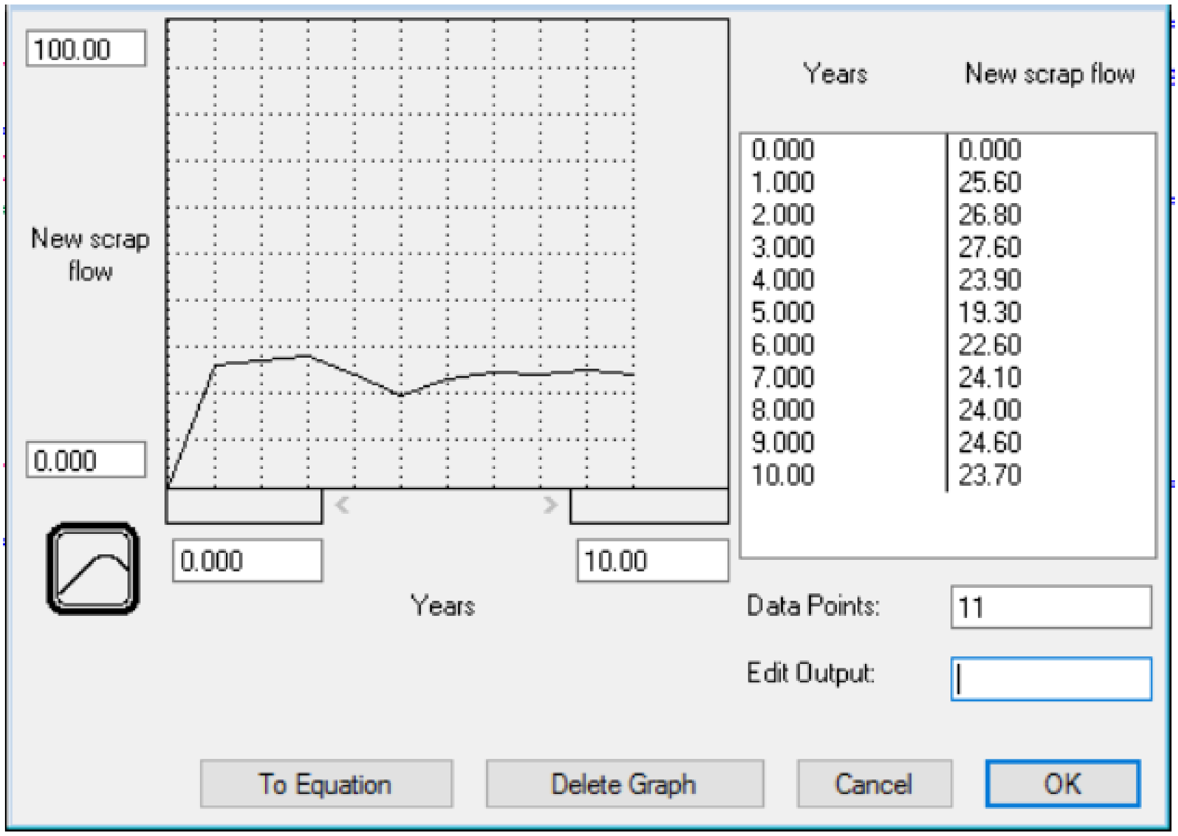

Figure 5.2 – Graphical function of new scrap inflow since 2017 (in tonnes)

"Scrap" is a stock, which summarizes all scrap as described by the three aspects. The initial value is set to zero, since it is more logical to have this stock pre-allocated on potentially usable and unusable scrap in the early periods of the modeling.

Then the "Scrap" allocates into two states:

- "Usable scrap" – is a fraction of scrap that will be collected and further recycled. Initial value is set to 141 tonnes;
- "Unused scrap" – is fraction of scrap that will not be collected and further unrecycled. The initial value is set to 141 tonnes.

Flows “Generation of usable scrap” and “Generation of unused scrap” are controlled by “Collectible scrap fraction” coefficient. Initial value is set to 50%.

“Generation of useable scrap” = “Scrap” * “Collectible scrap fraction”

“Generation of unused scrap” = “Scrap” * (1 - “Collectible scrap fraction”)

The figure 5.3 is graphical result, demonstration the answer for RQ1.

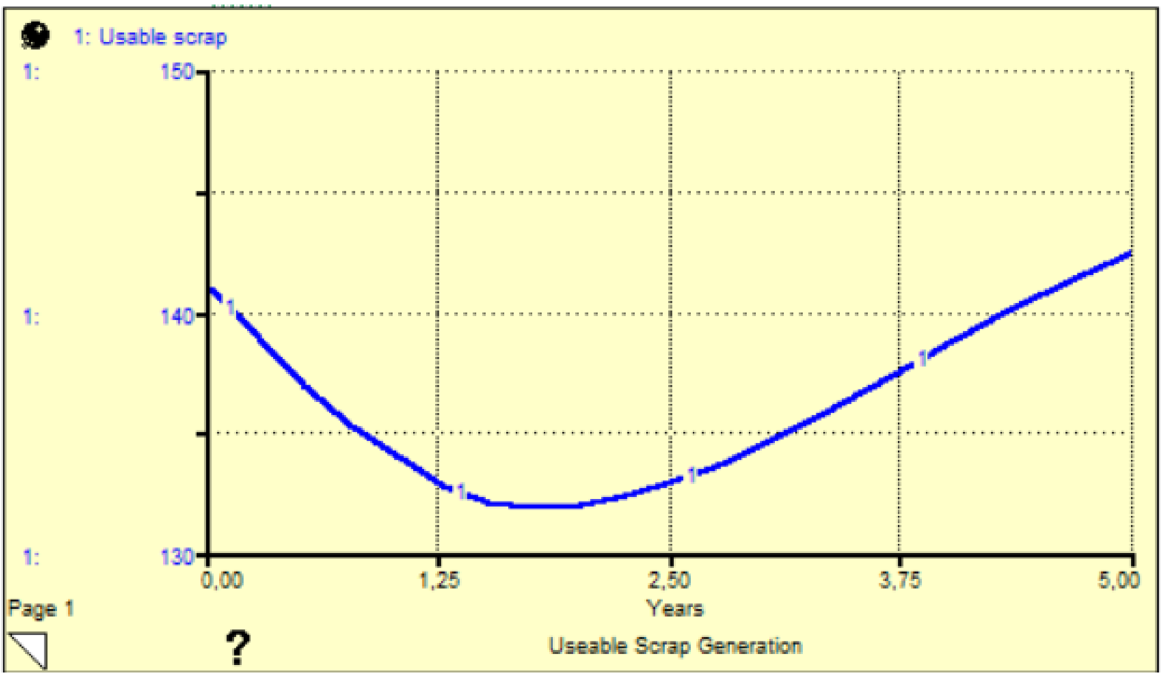

Figure 5.3 – The change of usable scrap stock during five year’s period (in tonnes).

Conclusion on the RQ1.

Figure 5.3 illustrates how world rhodium scrap stock changes through a five year’s period, namely that usable part of scrap, which consists more than 50% of total scrap stock. Mainly, that is due to the fact, that the majority of rhodium is recycled in the EU, for instance on refinery factories of Johnson Matthey, Heraus or Umicore, just like the manufacturing of automobiles, which contain autocatalysts. However, a large mass of vehicles is exported from the EU and, therefore, the potentially recyclable scrap settle in countries, which are not focusing on secondary PGM production or lacking developed collecting and technological recycling processes.

From the chart on the fig. 5.3 one can see a decrease in usable scrap stock by up to 6% (from 141 tonnes to 132 tonnes) during the period of 2016 to 2018. This can be explained by the presence of a common factor to all complex systems – the delay time, more specifically, the life cycle time. The autocatalysts production in the period appeared to be greater than that during the generation of old scrap, therefore the scrap inflow appeared to be lower than the outflow (due to the time lag it was not able to meet the grown-up demand). However, starting from the end of 2018, the increase of the usable scrap stockpiling is evident and it raised to 142 tonnes. This happened due to the inflow of new scrap, generated since the year of 2006, which is remarkable for its increased autocatalysts production and amplified recycling rates (see figure 5.4 for recycling trend since 2006).

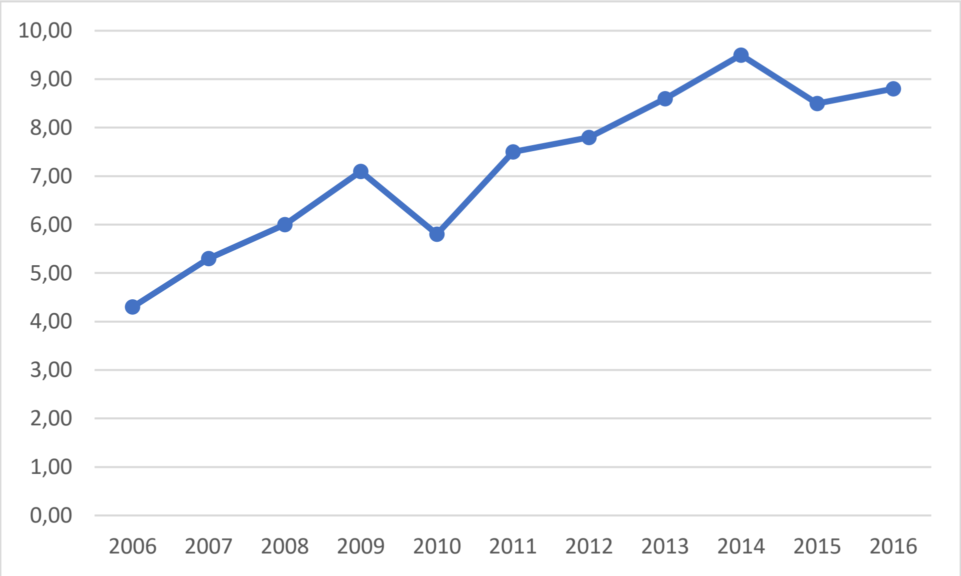

Figure 5.4 – Recycling growth trend since 2006 (in tonnes)

5.2 The assessment of the expected secondary production costs

Research question: What are the expected costs of implementing the recycling system? (further, “RQ 2”).

Data for the RQ 2.

In the literature review, it has been established that currently there is a lack of scientific works, which describe primary and secondary rhodium production costs per one unit.

Data on recycling costs used in the economic part of the model are taken and calculated based on the open-source annual financial report of the USA Stillwater Mining Company (SMC 2015).

Having scanned and screened the report *(SMC 2015)*, it is possible to make a table (table 5.3).

Table 5.3. Platinum-group metals production costs. Source: SMC 2015

	Produced PGM volume (in troy ounce)	Total costs (in US dollars)
Primary production	539 800	293 955 000
Secondary production	551 100	300 710 000

As mentioned before, rhodium is mined as a by-product of platinum, palladium, or nickel mining, as well as met in natural alloy with other metals. That and since SMC 2015 does not specify costs per unit for each metal individually, it will be considered that costs per unit of specific PGM are the same (costs per unit of rhodium equals those of palladium, platinum etc.)

Calculations per unit lead to the following:

- Primary production (PP) rhodium costs per troy ounce - 545$
- Secondary production (SP) rhodium costs per troy ounce - 546$

As observable, the difference in costs between rhodium PP and SP is approximately one dollar, which may seem as a hardly noticeable difference and can lead to misleading conclusions (such of a kind that recycling is, indeed, should be view as a “salvation” in terms of its eco-friendliness and even economic justifications.

There should be no rush and it is worth to have a closer look at how actually “small” that one dollar difference is. Firstly, this simple calculation is based on the real **data** provided by the company, thus every single cent has a meaning and **value**. Secondly, the unit of measure is a troy ounce, which is just over 31,10 grammes (BV website) and can easily fit in one’s hand palm, what means that the **economies of scale** will be a big impact factor in the economic justification. And finally, speaking of PP and SP, the production itself is a process, meaning that one dollar will multiple greatly in time – **time scale**. Further, with dynamics model, a quantitative comparative assessment will be given to show how one dollar accumulates will scale economies and time (see chapter 5.4).

Besides per unit costs, it is necessary to understand what contributes to those costs to compare different recycling technologies (chapter 5.3).

Unfortunately, no costs distribution for PGM recycling was found, however, if to consider rhodium similarities in PP and SP with other metal which is also renowned for its availability to recycling, such as lead, one can find out that the major contribution to the mining and recycling costs, as claimed by *Rich (1995)*, is brought in by the “material and labor costs” – 35% of total costs on average and “energy consumption costs” – 10% of total costs.

The remaining 55% of the recycling costs is suggested to attribute to the scrap collection process, for instance, in *(Platt et al. 1991; Ryan et al. 2010)* authors mention that the biggest costs in the recycling of PGM are concentrated around scrap collection costs (mainly, transportation). *WS 2009* presents data on Russian scrap-collecting companies, which were purchasing spent automotive catalyst for approximately 8 dollars per unit (“scrap purchasing costs”) in 2009.

Since most data on costs is for the year for 2015, it makes sense to adjust scrap purchasing costs also to 2015. For that purpose, proportional changes calculations are going to be used (see table 5.4).

Rhodium is extracted from autocatalyst along with platinum and palladium (*IPA on autocatalysts and PGMs; Bartak 1996).* In 2009 the price of a troy ounce of platinum was approximately 987$, palladium – 210$ and Rh -1150$ (*Infomine)*. Considering that one troy ounce is 31,15 grammes, and, as per *Stanković and Comninellis (2011),* autocatalyst contains 1,8 grammes of PGM including 0,75 grammes of platinum, 0,75 grammes palladium and 0,3 grammes rhodium, it is possible to make the following calculations for 2009:

- Platinum value in one spent average autocatalyst – 23,02$
- Palladium value in one spent average autocatalyst – 4,9$
- Rhodium value in one spent average autocatalyst – 10,73$
- PGM value in one spent average autocatalyst – 38,65$

Thus, scrap collector companies paid 20% (8$ of 38,65$) of autocatalysts value to the seller for the purchase of one item.

In 2015 average PGM prices differed from those of 2009: one troy ounce of platinum was priced of 890$, pallidum – 802$ and rhodium – 560$ (*Infomine).* If to consider that collector companies were still paying 20% of autocatalyst's value in 2015 then "scrap purchasing costs" per unit would be approximately 9,3 $ in 2015.

Table 5.4 Calculated scrap purchasing costs in 2009 and 2015.

	2009 (data)	**2015 (calculations)**
Costs of purchasing one autocatalyst ($)	8	9,3
Platinum price ($/gramme)	30,7	27,7
Palladium price ($/gramme)	6,5	24,9
Rhodium price ($/gramme)	35,8	17,4
Platinum value in autocatalyst ($/0,75 grammes)	23	20,8
Palladium value in autocatalyst ($/0,75 grammes)	4,9	18,7
Rhodium value in autocatalyst ($/0,3 grammes)	10,7	5,2

Table 5.4 (continued)

PGM value in autocatalyst ($/1,8 grammes)	38,7	44,7
Purchasing cost as a fraction from PGM value in autocatalyst	20%	20%

If to convert secondary rhodium production costs per troy ounce (546$) into 1,8 grammes (an equivalent of PGM content in autocatalyst), then recycling costs would constitute approximately 31,53$ per 1,8 grammes. Consequently, recycling costs can be categorized into four groups:

1. **Labour and material costs**: 35% of total costs and 11,04 $ per autocatalyst.
2. **Energy consumption costs**: 10% of total costs and 3,15 $ per autocatalyst.
3. **Scrap purchasing costs**: 9,25$ per autocatalyst, what constitutes 29% of total costs.
4. The rest of the can be set as **scrap collection costs**: 26% of total costs and 8,09 $ per autocatalyst.

Table 5.5 contains information about the data, which was used in the model's fragments responsible for answering research question 1. Equations are explained in the comments section.

Table 5.5 Input data table for the RQ 2

Element	Element type	Data input/initial value	Figure №
Secondary production costs	Stock	0	Fig. 5.5
Secondary production costs generation	Flow	equation	Fig. 5.5
Scrap collection rate	Flow	equation	Fig. 5.5
Technological recycling costs	Value	equation	Fig. 5.5
Labour and material costs	Value	61,40107 $/tonne	Fig. 5.5
Rhodium recovery rate	Value	83%	Fig. 5.5
Energy consumption costs	Value	17,54316 $/tonne	Fig. 5.5

Table 5.5 (continued)

Hydrometallurgical process costs	Value	49%	Fig. 5.5
Scrap purchasing costs	Value	42,8417 $/tonne	Fig. 5.5
Scrap collection costs	Value	equation	Fig. 5.5
Scrap collection costs change	Value	0	Fig. 5.5

Assumptions and constraints of the RQ 2.

Since costs numbers were based on Stillwater Mining Company, economic calculation in the model fall under single case study, which means that generalizability of results can be endangered. However, it can be considered that the deviation in costs of this particular company from others is insignificant due to company's operation in a competitive environment and more importantly, such calculations are to contribute into comparison scenarios and are less focused value in precise number.

The data on supply, demand and recycling volume is taken for 2016 which is also the starting year for simulation of the model, yet data on costs and revenue are taken for the year of 2015, since that was the latest year for which such data was found. This may affect the precision of the model.

Figure on costs category "scrap purchasing costs" was initially known for the year of 2009 and the case of Russian collector companies. Although proportional calculation allowed to adjust this category to other costs, it may suffer precision and adequacy (due to generalizability issue). Deviations are not expected to be significant.

Fragment of the model which functions on the above data for the RQ 2 is present on figure 5.5.

Comments on the functioning of the model's fragment and equations for the RQ2.

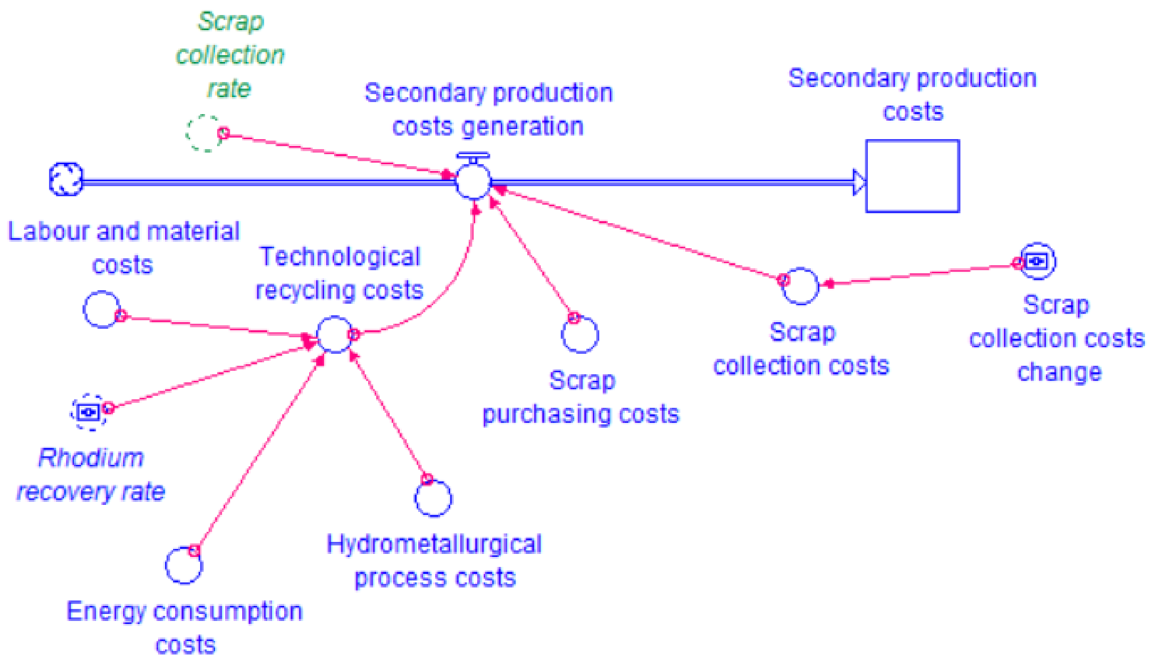

Figure 5.5 – RQ2 modeling fragment

"Secondary production costs generating" is a flow defined by the following equation:

"Scrap collection rate" * ("Scrap collection costs" + "Scrap purchasing costs" + "Scrap Technological recycling costs"), where "Technological recycling costs" = "Labour and material costs" + "Energy consumption costs".

"Scarp collection rate" is calculated as: "Recycled rhodium demand" / "Rhodium recovery rate". Namely, the more rhodium secondary production is able to recover (extract) from scrap, the less scrap inflow is required for recycling. On the importance of rhodium recovery rate (RC) see next chapter of the master's thesis.

Values in costs are set as those in previous calculations adjusted to tonnes.

"Hydrometallurgical process costs" and "Rhodium scrap recovery rate" do not influence the functioning of the model's fragment for RQ2, yet has an important meaning for further RQs.

"Scrap collection costs change" – is an element, which will help to build comparison scenarios for economic justification of recycling. Here a decision maker can set the monitored or expected change value and see how it will reflect either on profitability or the whole system.

Figure 5.6 represent a graphical result, which illustrates answer on RQ2, namely, demonstrating recycling costs in form of the bar chart. Dynamics model has no exceptional necessity for the RQ2, since the idea for this RQ was to fill in the gap of the lack of data on recycling costs and for that matter, calculations presented above are sufficient. Nevertheless, the fragment of the model can be viewed as indirect without functioning of which it would be impossible to build charts and make calculations on the upcoming RQs.

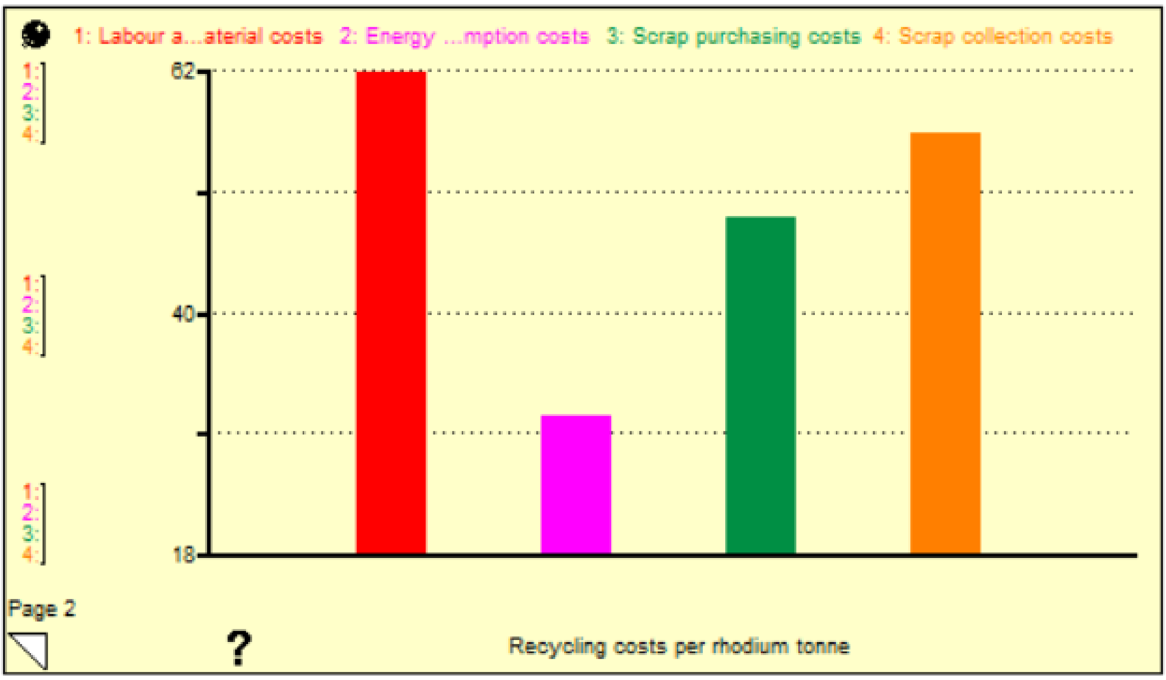

Figure 5.6 – Rhodium recycling costs per tonne (in 10^5 US dollars)

Conclusion on the RQ2.

Scrap recycling costs (rhodium extraction/recovery from spent autocatalyst) were categorized into costs connected with labour and material as well as energy consumption costs

Scrap collection costs are usually associated with scrap dismantling and transportation. The lower the level of technological recycling (metal recovery rate) the higher collection costs are, since more scrap would be required to satisfy rhodium demand.

Scrap purchasing costs relate to purchasing of spent automotive catalysts by collector companies from end-users or scrap yards. This costs category could be included in scrap collection costs, however, this is not done so, due to the fact that from the modeling point of view, a certain interest could be in a specific scenario – “how recycling becomes more profitable due to reduced scrap collection costs”; in this case, it is not recommended to lower scrap purchasing costs since they serve as a monetary motivation for people to sell their spent autocatalyst rather than sending them to landfills.

Although such categorization of recycling costs on four categories is not diverse, it shows the major costs group which influence the profitability of recycling. Such costs should not be view as a complete set of costs, since, obviously, there are others, yet based on literature sources, those four categories seem to be the most significant and will play a huge role in decision making regarding the implementation of recycling system or changing recycling or mining volumes due those costs changes.

5.3 The comparison of different recycling processing technologies from the perspective of their profitability

Research question: What are the available recycling technologies? (further, “RQ 3”).

Rhodium extraction from spent automotive catalysts is done via pyrometallurgical or hydrometallurgical processes.

Pyrometallurgical process (PMP) assumes scrap heating by over 1500 degrees Celsius so that it enters a melted state. Then it is combined with collector-metal (such metal could be nickel, iron, lead or copper) in order to separate and extract rhodium from the alloy of metals in scrap (*Bolinski 1991*). Finally, collector-metal is detached from rhodium and therefore the valuable metal is extracted.

Hydrometallurgical process (HMP) is characterized by a metal detachment from scrap by the means of chloride and oxidants usage *(Ray 2012)*.

Data for the RQ 3.

Here data relates to recovery rates and possible costs of different processing technologies.

Lillkung and Aromaa (2012) demonstrated the application of different oxidants in a hydrometallurgical process. In one of their experiments rhodium recovery rate reached 98%. *Harjanto et al. (2006)* in their critical literature review refer to authors claimed to have reached rhodium RR of 82%, 89% and 99%; in their own research, they showed how utilization of different oxidant types allows extracting different quantities of rhodium from scrap. In their own experiments of HMP, they reached 86% RR for rhodium.

A diversity of rhodium recovery rates during technological recycling via pyrometallurgical process was not found. *Kolliopoulos et al. (2014)* graphically demonstrate PMP depicting how time affects recovery rates and in their works one can see rhodium RR ranging in between 70% and 82,%. *Bolinski (1991)* mentioned in his thesis that 83% rhodium RR is the minimum necessary RR for autocatalysts recycling to be economically justified.

HMP is considered to be eco-friendlier from the point of view of CO2eqv. and SO2eqv. Emissions, and in the meantime, it opens possibilities for higher RR in comparison to PMP. However, authors in (*Bolinski 1991; Kolliopoulos et al. 2014; Rumpold and Antrekowitsch 2012; Fornalczyk and Saternus 2013*) conclude that PMP in the field of autocatalysts recycling dominate on HMP, moreover, HMP are almost not practically used for recycling of any platinum-group metals (by now).

Gupta and Mukherjee (1990) present comparison characteristics of hydrometallurgical and pyrometallurgical processes, and as one of the disadvantages of HMP authors list the following: “there is no economic gain in subsituting a pyrometallurgical plant, processing a reasonably high-grade resource, with a hydrometallurgical one”. *Kriek et al. (1994)* also emphasizes the costliness of HMP due to their complexity.

Quantitative comparison of profitability of recycling technologies will be made based on one scientific work dedicated to the copper recycling – (*Haque et al. 2012*). Despite, that metal focused by authors is not rhodium, copper is also being recovered from scrap via pyrometallurgical and hydrometallurgical processes. The most important conclusion of *Haque et al. (2012)* was that costs of HMP process were almost twice as high (approximately 49% higher) in comparison to PMP. In addition to that, authors based their techno-economical calculation on two assumptions. The first was that labour and material costs as well as energy and water consumption are equal for both recycling processes, yet it is a known fact that energy as well as water consumption costs are higher for HMP (*Gupta and Mukherjee (1990)* listed material and energy consumption costs as greater than those of PMP, where as *Ghosh and Ray (1991)* demonstrated energy consumption costs superiority of HMP over PMP zinc secondary production). The second considered that half of all spent chemical during HMP could be reused; this 50% reuse coefficient was used as approximate, since authors could not find existing data on it, and so in fact reuse of chemicals can be less, not to mention spent acids and acid water utilization costs inherent to HMP and thus further resulting in HMP being even costlier than PMP.

It is also worth mentioning that, for every percentage increase in metal recovery rate, recycling costs will also increase and, at some point, this increase in costs could be described by exponential growth law. This effect is known as diminishing returns, and has a very important meaning for decision makers: while higher recovery rate allows to lower expenses on scrap collection (since less scrap is needed to be processed, the more metal can be recovered from one unit), it required greater investments and supporting costs as being superior technology. For example, having looked at waste recycling, one can find that the costs of transition from 95% RR to 100% recovery of desired material from household wastes, in other words, the improvement of RR by five last percent will be greater than costs on 95% RR (*Manser and Keeling 1996*). *Porter J.W (1997)* also debates on zero-waste recycling and highlights the skyrocketing of recycling with diminishing returns. Unfortunately, for now, no information on the scale of diminishing returns in recycling and rhodium recycling, specifically, was found.

Table 5.6 contains information about the data, which was used in the model's fragments responsible for answering research question 1. Equations are explained in the comments section.

Table 5.6 Input table for the RQ 3

Element	Element type	Data input/initial value	Figure №
Scrap collection rate	Flow	equation	Fig. 5.7, 5.8
Purchased scrap	Stock	8 tonnes	Fig. 5.7
Secondary rhodium flow	Flow	equation	Fig. 5.7, 5.9
Rhodium recovery rate	Value	83%	Fig. 5.7
Rhodium losses generation	Flow	equation	Fig. 5.7
Rhodium recycling losses	Stock	0	Fig. 5.7
Scrap collection costs accumulation	Flow	equation	Fig. 5.8
Scrap collection costs accumulated	Stock	0	Fig. 5.8
Scrap collection costs	Value	equation	Fig. 5.8
Scrap collection costs change	Value	0	Fig. 5.8
Secondary production revenue generation	Flow	equation	Fig. 5.9, 5.10
Secondary production revenue	Stock	0	Fig. 5.9
Rhodium price	Value	700 $/troy ounce	Fig. 5.9
Secondary production costs generation	Flow	equation	Fig. 5.8, 5.10
Secondary production profit generation	Flow	equation	Fig. 5.10

Table 5.6 (continued)

Secondary production profit	Stock	0	Fig. 5.10

Assumptions and constraints of the RQ 3.

In the dynamic model, rhodium RR is set to 83% as a base RR and depicts a pyrometallurgical process of autocatalysts recycling.

Rhodium RR greater than 85% are considered to be inherent to hydrometallurgical processes.

Costs on different recycling technologies are categorized on:

1. Pyrometallurgical processing costs (numbers are taken from chapter 5.2, where technological costs are described by labour and material costs as well as energy consumption costs).
2. Hydrometallurgical processing costs (energy consumption and labour and material costs are 49% higher than those of PMP). Also, based on only one scientific work as no others were found.

Diminishing returns are not taken into account due to lack of data and technological recycling costs for HP are going to be the same for all recovery rates, which is despite being imprecise, will still allow seeing how higher RR reduce total recycling costs (by lowered expenses on scrap collection process).

Rhodium price is taken as an average for 2016, which was approximately 700$ per troy ounce (*Infomine*).

The model fragments, responsible for scenarios-making for the RQ3 are present on figures 5.7, 5.8, 5.9 and 5.10.

Comments on the functioning of the model's fragment and equations for the RQ3.

The model's fragment on 5.7 is notable for its elements: "Used scrap", "Secondary rhodium demand", "Scrap collection rate", "Rhodium recovery rate" and "Secondary rhodium".

The higher the value of “Rhodium recovery rate” the lower the flow “Scrap collection rate”, thus scrap collection costs will be since, less scrap will be needed to be collected. “Secondary rhodium demand” is calculated as a deficit gap between total rhodium demand and primary rhodium supply (equations are explained in indirect parts of the model).

“Scrap collection rate” flow is a typical process with material loss and is described the following equation: “Secondary rhodium demand” / “Rhodium recovery rate”.

“Purchased scrap” is a stock of purchased scrap, which is further going to be recycled. “Secondary rhodium flow” – is a flow of rhodium which was recovered during the recycling process.

“Rhodium losses generation” is an outflow from “Purchases scrap” stock, describing imperfection of the recycling process.

“Rhodium losses generation” = “Purchased scrap” *(1- “Rhodium recovery rate”), i.e. fraction of purchased scrap that will be lost during recycling process.

“Rhodium recycling losses” is a stock accumulating metal losses from imperfect recycling technologies. It will be further used to calculate unearned profit.

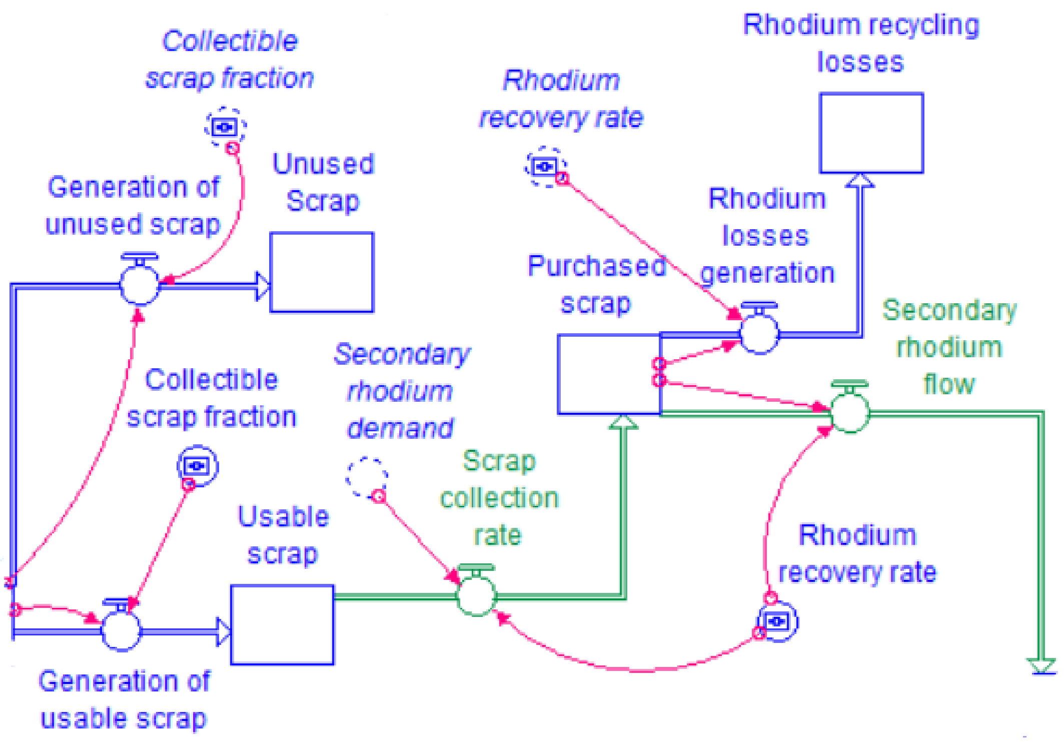

Figure 5.7 – RQ 3 model fragment 3 (scrap collection level and secondary rhodium flow calculations)

The model's fragment on figure 5.8 was previously partly described. It is responsible for calculating total recycling costs: scrap collection costs and technological autocatalyst recycling.

Before, the fragment was used just to describe the costs inherent to secondary rhodium production. Now a more detailed view is going to be provided.

"Recycling costs generation" is a flow which calculates total recycling costs based on the scrap collection rate and four costs categories described in chapter 5.2.

"Recycling costs generation" = "Scrap collection rate" * ("Scrap technological recycling costs" + "Scrap purchasing costs" + "Scrap collection costs")

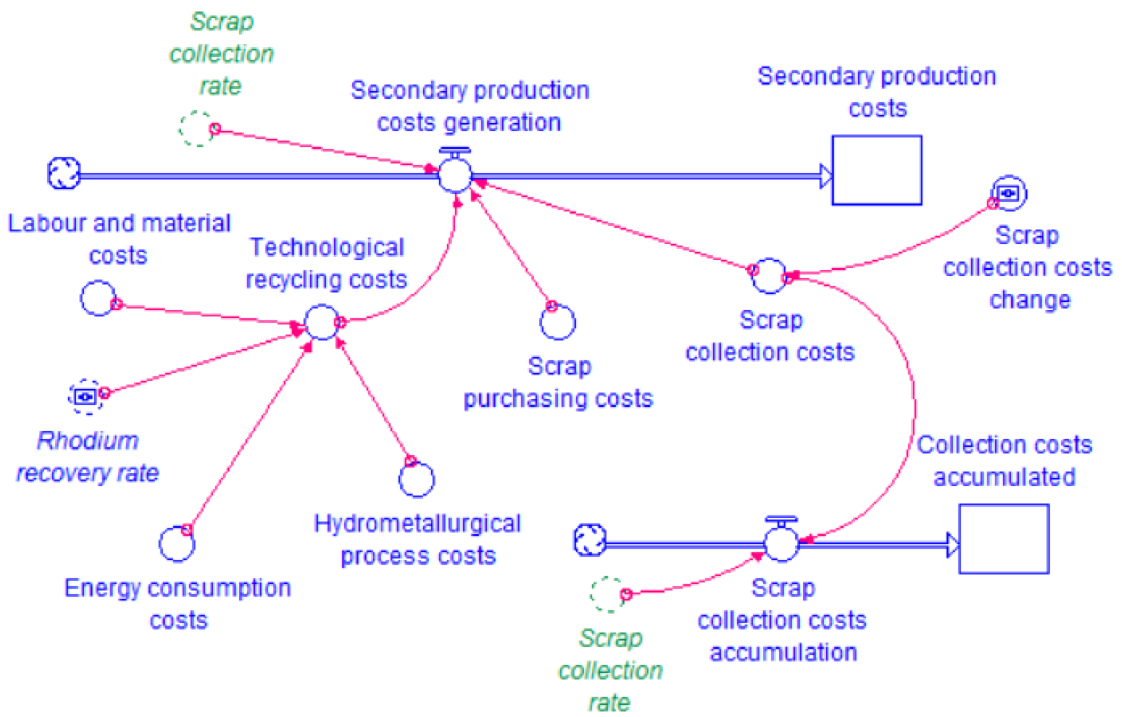

Figure 5.8 - Fragment for the RQ 2 and 3 (costs calculation)

“Scrap technological recycling costs” is an element calculating costs based on a special condition (depending which RR is set by decision maker) and is described by the following equation:

If (“Rhodium recovery rate” > = 0.85) then (“Energy consumption costs” + “Labour and material costs”) + (“Energy consumption costs” + “Labour and material costs”) * “Hydrometallurgical process costs”) else ((“Energy consumption costs” + “Labour and material costs”)

“Hydrometallurgical process costs” is an element with the value set to 0.49; not actual costs value but rather serves as costs change fraction.

The model assumes that if RR is greater than 85%, then scrap is processed via HMP and, thus energy consumption and labour and material costs are increased by 49%.

“Scrap collection costs change” is an element which can be used by decision maker to set deviation from base number in fraction or percentage to see how significantly it will reflect on total profit (from both mining and recycling) or perhaps a certain percentage decrease in costs can make recycling far profitable than mining or one technological process dominant of the other. This help to identify by how much scrap collection costs should be reduced in order to reach desired goals and to see if it is worth working on costs reduction or not. This way, “Scrap collection costs” is described by equation: 53,64569 - 53,64569 * “Scrap collection costs change”. Since initial change value is zero, the base scenario is simple read by the model as without change, yet change value can be set to any fraction by the decision maker in order to develop relevant scenarios.

The fragment on figure 5.9 calculates revenue generated by secondary rhodium production.

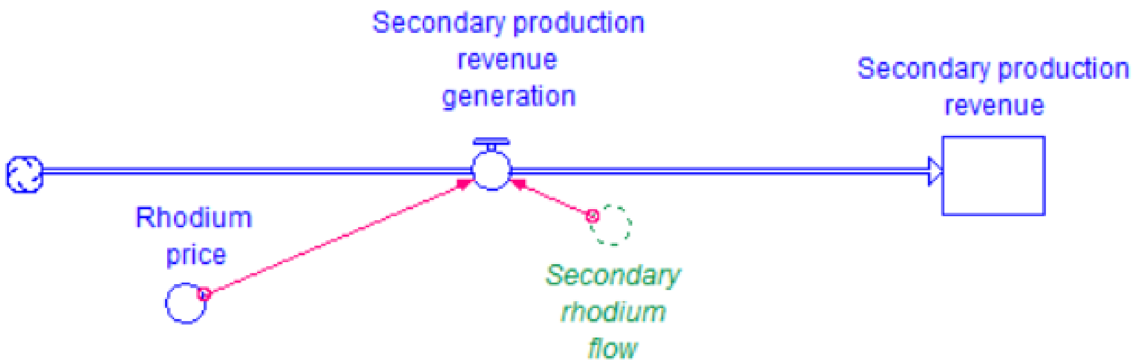

Figure 5.9 – RQ 3 fragment of the model (revenue calculation)

“Secondary production revenue generation” = “Rhodium price” * “Secondary rhodium flow”

“Rhodium price” is a constant with value set to 700 $ per rhodium troy ounce and adjusted for tonne.

“Second rhodium flow” = “Rhodium recovery rate” * “Secondary rhodium” (see. fig. 5.7), i.e. demand purchases that fraction of rhodium which was recovered from autocatalysts.

The fragment on the figure 5.10 calculates profit, generated by secondary rhodium production.

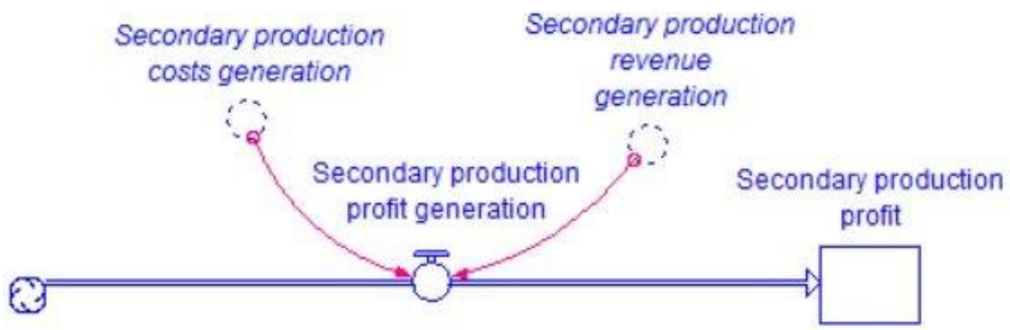

Figure 5.10 – RQ 3 fragment (profit calculation)

“Secondary production profit” = “Secondary production revenue generation” - “Secondary production costs generation”

The figure 5.11 representы a graphical result, which illustrates answer on the RQ3.

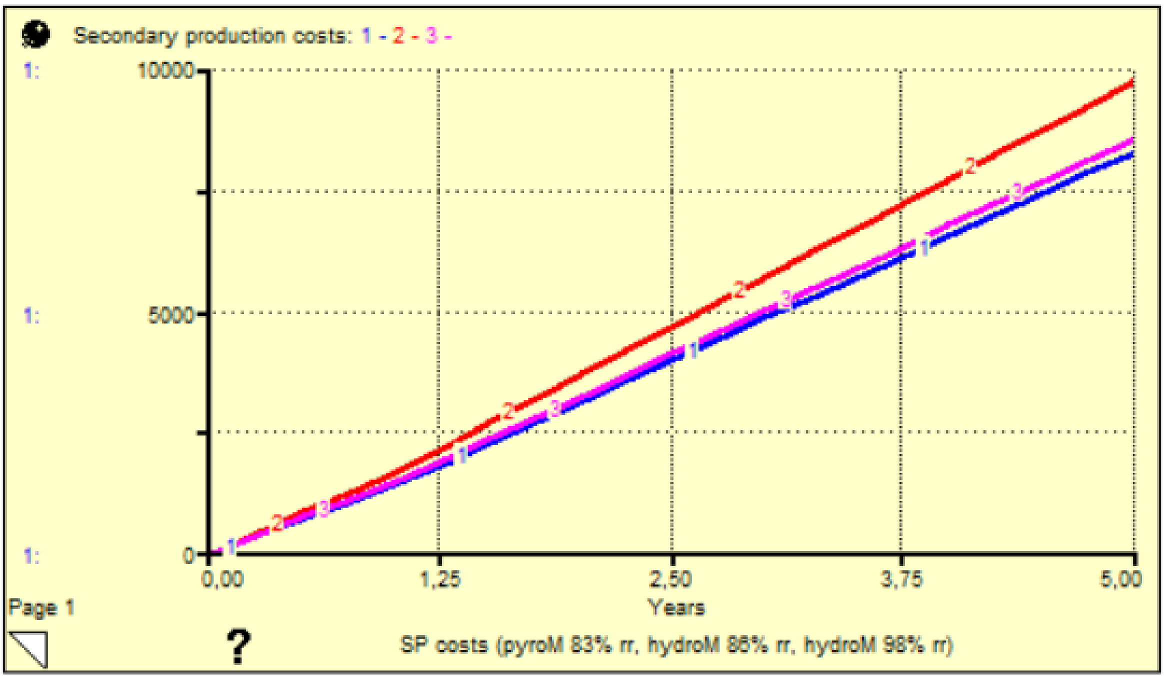

Figure 5.11 – Costs comparison of different recycling technologies (in 10^5 US dollars)

The chart quantitatively compares costs of PMP recycling (blue curve - rhodium RR 83%) and HMP (red curve rhodium RR 86% and purple curve - 98%).

Conclusion on the RQ3.

The domination of pyrometallurgical processes is explained by lower costs on rhodium extraction from scrap, despite greater collection costs as a result of lower recovery rates (figure 5.12).

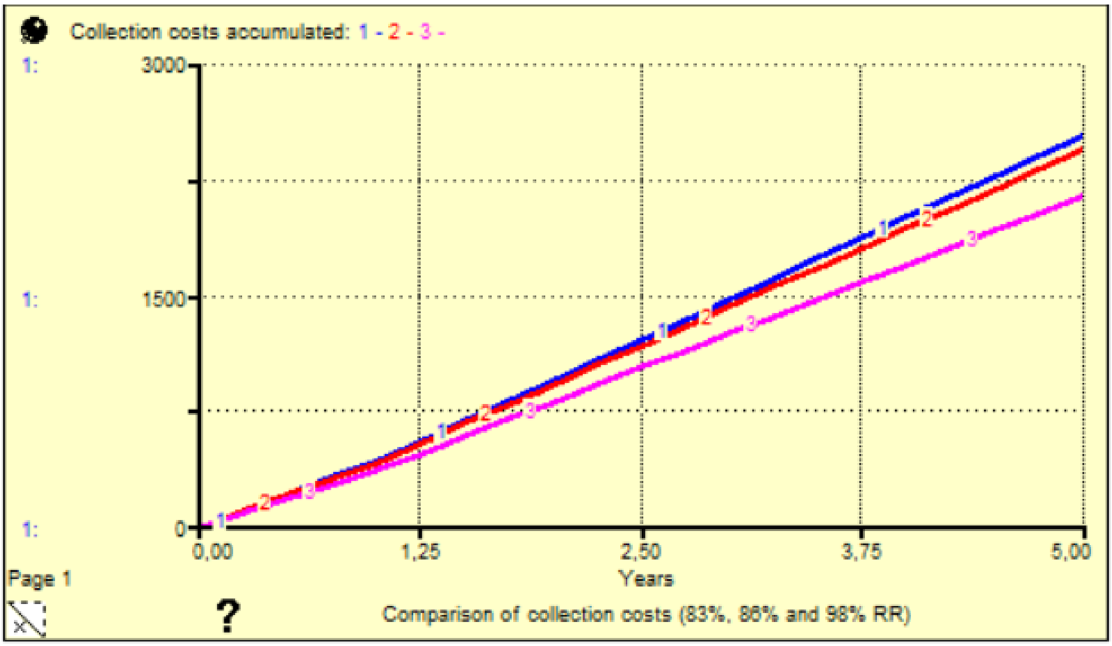

Figure 5.12 – Collection costs comparison.

PMP collection costs accumulated for five years resulted in $254 million, whereas this number reduced to $246 million and to $215 million, using 86% and 98% RR respectively.

Total costs of PMP for five years accumulated by up to $832 million, whereas costs of 86% RR HMP – $979 million, which is 13% more. At the same time, total costs for HMP with 98% recovery rate reached $859 million, what makes it 3% more than costs of classical PMP recycling.

Hydrometallurgical process with 98% rhodium recovery rate lowers the gap in costs difference between the two processes. However, the calculation was made based on a paper on copper recycling, where authors also based their calculation around a number of assumptions, and I fact 98% RR could be far costlier rather than calculated by the model.

Therefore, the value of higher rhodium recovery rates during hydrometallurgical processes turned up to be economically uncompetitive with pyrometallurgical processes (savings on collection cost with 86% RR were only $8 million whereas 147$ loss was made on technological recycling costs in comparison with baseline classical pyrometallurgical process.

5.4 Identifying limiting conditions of recycling

Research question: What are the limiting conditions of recycling (further, "RQ 4")?

In fact, RQ 4 assumes comparison of primary and secondary rhodium production from the perspective of:

1) Profitability comparison (further, "RQ 4-1").
2) Assessment of unearned profit due to imperfect recycling technologies (further, "RQ 4-2").
3) Environmental impact caused by rhodium production (further, "RQ 4-3").
4) Depletion of scrap stock and systematic impact of increasing recycling volumes at the expense of lowering mining levels (further, "RQ 4-4").

Data for RQs 4-1 and 4-2.

For this matter data on supply and demand, price, production costs and rhodium recovery rate is needed. Such data was overviewed in research questions 1-3.

Assumptions and constraints for RQs 4-1 and 4-2.

The model considers the ideal-case situation on market, when supply and demand are equal. According to *JM PGM (2016)*, total rhodium demand will rise by 5% starting since 2017, whereas primary production volumes will remain flat. So, it falls on secondary production to satisfy the increased demand.

5.4.1 Profitability comparison of primary and secondary production

Data input for RQ 4-1 is present in table 5.7.

Table 5.7 Input data for RQ 4-1

Element	Element type	Data input/initial value	Figure №
Primary production costs	Stock	0	Fig. 5.12
Primary production costs generation	Flow	equation	Fig. 5.12, 5.13

Table 5.7 (continued)

Costs per primary rhodium tonne	Value	175,08075 * 10^5	Fig. 5.12
Primary production rate	Flow	equation	Fig. 5.12
Primary production revenue	Stock	0	Fig. 5.12
Primary production revenue generation	Flow	equation	Fig. 5.12, 5.13
Rhodium price	Value	700 $/troy ounce	Fig. 5.12
Primary production profit	Stock	0	Fig. 5.13
Primary production profit generation	Flow	equation	Fig. 5.13
Total profit	Stock	0	Fig. 5.14
Total profit generaion	Flow	equation	Fig. 5.14

Comments on the functioning of the model's fragment and equations for RQs 4-1.

The figure 5.12 illustrates part of the model, which calculates costs and revenue from primary rhodium production, using the following equations:

"Primary production costs" is a stock which describes PP costs accumulated throughout the modeled years. It fills through the flow "Primary production costs generation":

"Primary production costs generation" = "Costs per primary rhodium tonne" * "Primary production rate"

"Costs per primary rhodium tonne" were calculated as a sum of costs from previous chapters.

"Primary production rate" is explained in indirect parts of the model.

"Primary production revenue" is a stock which describes PP revenue accumulated throughout the modeled years. It fills through the flow "Primary production revenue generation":

“Primary production revenue generation” = “Rhodium price” * “Primary production rate”

The model’s fragment on the figure 5.13 calculates profit generated by primary production.

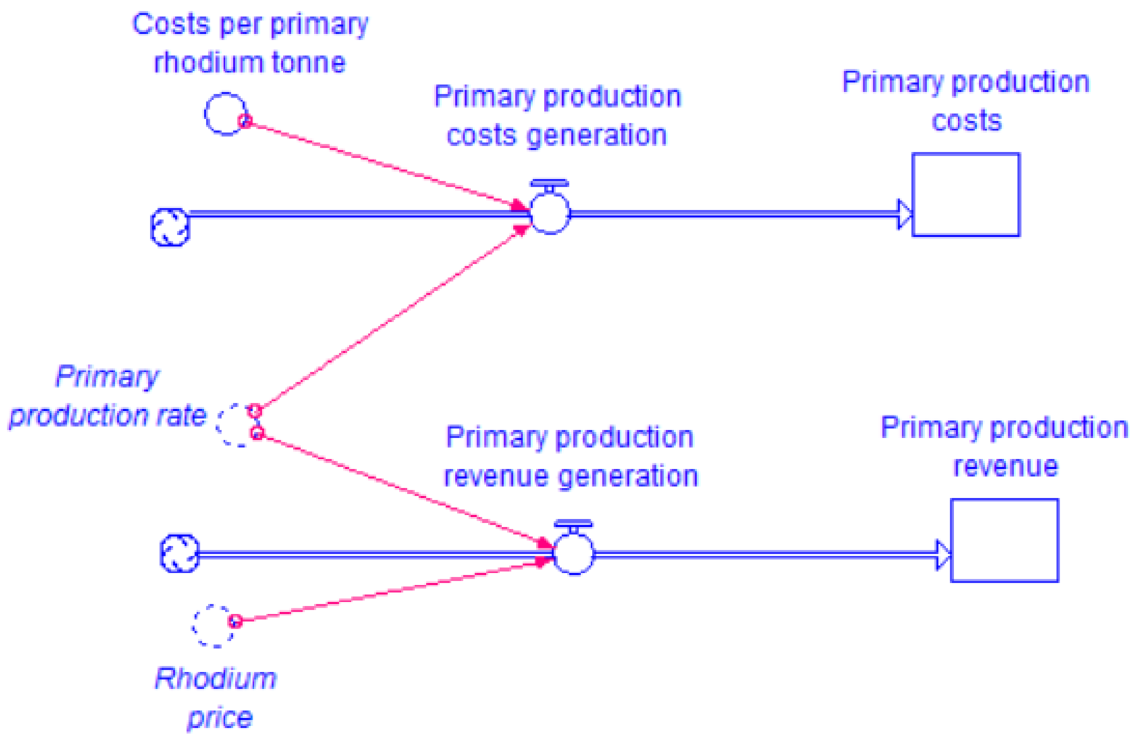

Figure 5.12 – The model’s fragment, calculating costs and revenue of primary rhodium production

Just like costs and revenue stocks, “Primary production profit” is a stock which describes PP profit accumulated throughout the modeled years. It fills through the flow “Primary production revenue generation”, which calculates as the difference between revenue and costs:

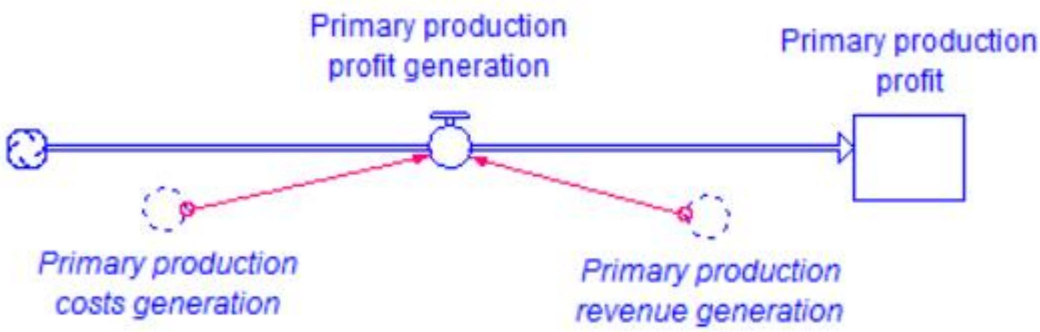

Figure 5.13 – The model's fragment, calculation primary production profit

"Primary production profit generation" = "Primary production revenue" – "Primary production costs generation"

Similar fragments for secondary production and present in the previous chapter.

The model's fragment, calculating total profit from rhodium production (i.e. from both mining and recycling) is shown on figure 5.14.

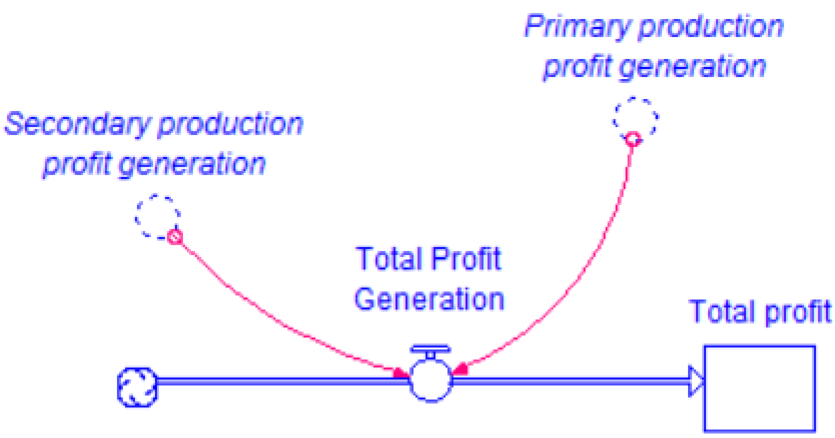

Figure 5.14 – The model's fragment, calculating total profit
(PP+SP)

"Total profit" is a stock, representing accumulated profit. The stock's inflow is "Total profit generation", which equals the sum of two flows: "Primary production profit generation" and "Secondary production profit generation".

“Total profit” = “Primary production profit generation” + “Secondary production profit generation”

The fragment (on fig. 5.14) is essential for the evaluation of primary production rate change’s influence on profit generated by both primary and secondary productions, for instance, to assess whether it will be profitable lowering PP volumes while increasing SP.

The chart on figure 5.15 compares PP and SP profits on a five-years period. This scenario is based on the previous data and forecasts of *JM PGM (2016).*

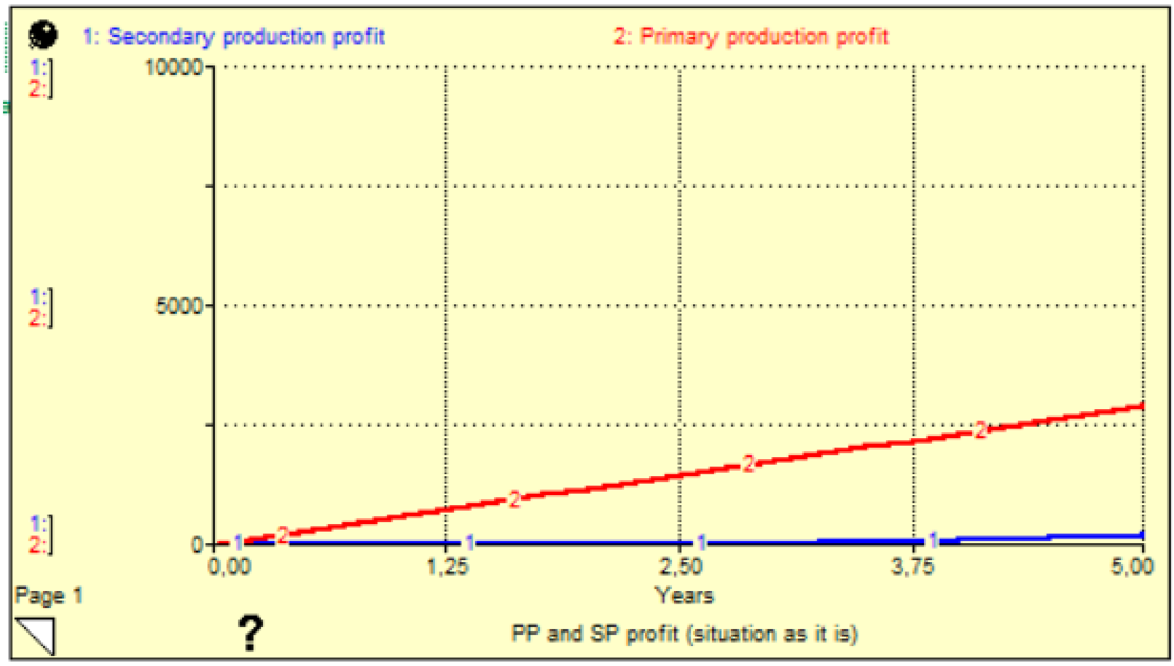

Figure 5.15 – Profit of primary and secondary production (in 10^5 US dollars)

From the chart above, it is visible that PP profit is significantly higher than that from autocatalysts recycling (accumulated PP profit is approximately 18 times higher). However, economies of scale highly affect the difference in profits. In order to minimize that aspect’s influence, it is suggested to make artificial scenarios which assume primary and secondary production volumes equal (figure 5.16).

The first scenario (blue curve) on fig. 5.16 illustrates total profit generation in according to the empirical and forecasts data available, as a result of which total profit generated by rhodium production accumulated by up to $608 million dollars for five years. The second scenarios (red curve) shows total profit generation if production volumes between primary and secondary productions were distributed as 50% on each. In this case, total profit accumulated only by up to $426 million dollars in five years, which just under 30% less than the profit of the realistic scenario.

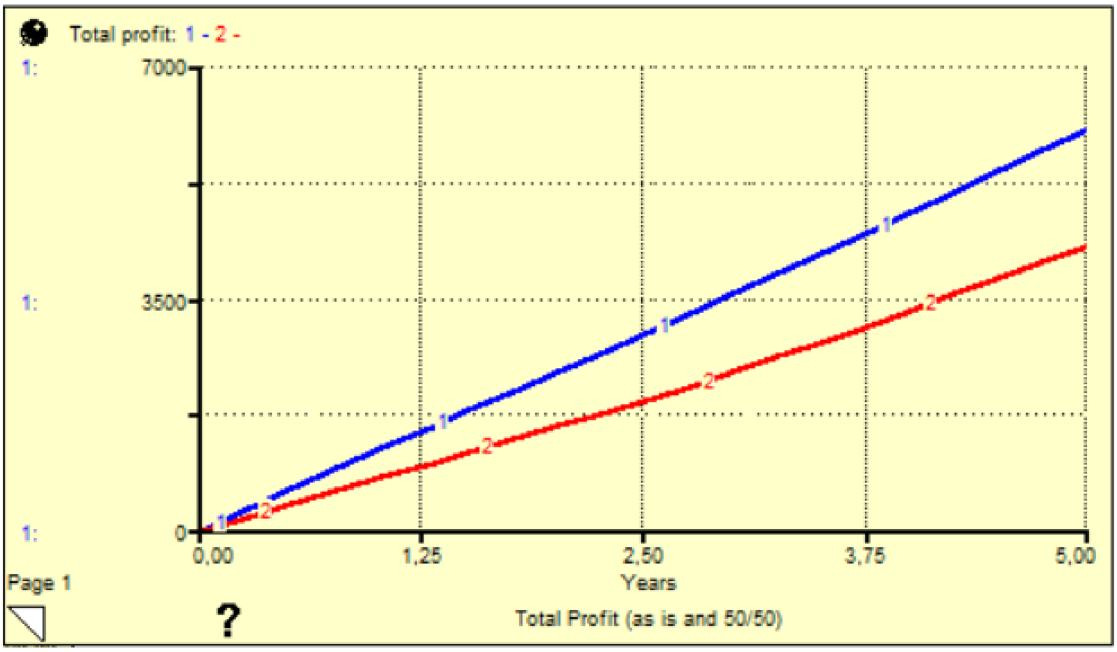

Figure 5.16 – Two scenarios of total profit accumulation: natural situation (blue curve) and artificial situation (red curve) (in 10^5 US dollars)

5.4.2 Assessment of unearned profit

Data input for RQ 4-2 is present in table 5.8.

Table 5.8 Data input for RQ 4-2

Element	Element type	Data input/initial value	Figure №
Rhodium losses generation	Flow	equation	Fig. 5.17
Unearned profit 1 generation	Flow	equation	Fig. 5.17
Rhodium price	Value	700 $/troy ounce	Fig. 5.17
Unearned profit 1	Stock	0	Fig. 5.17

Table 5.8 (continued)

Unearned profit 2 generation	Flow	equation	Fig. 5.17
Unearned profit 2	Stock	0	Fig. 5.17
Rhodium recycling costs per tonne	Value	equation	Fig. 5.17
Scrap collection costs	Value	Equation (explained in chapter 5.2)	Fig. 5.17
Scrap purchasing costs	Value	$42{,}8417 * 10^5$ \$/tonne	Fig. 5.17
Technological recycling costs	Value	equation	Fig. 5.17

Figure 5.17 shows the model's fragment, the purpose of which is the unearned profit (due to imperfect recycling technology) computation.

Generally, metal losses during recycling process result in profit loss which is called unearned profit. Two cases of unearned profit can take place and so relevant calculations will differ.

The first is when, if recycling would have been perfect and process's output was 100%, it would be possible to sell every unit of metal recovered. For instance, during pyrometallurgical process, 17% of rhodium is lost due to the imperfection of technology, which means a producer cannot sell that 17% to market. This type of unearned profit will be further called "unearned profit 1".

The second case is assuming that unearned profit is which could have been earned, if there was no necessity of purchasing and recycling that fraction of rhodium scrap which will be lost during the pyrometallurgical or hydrometallurgical process. For instance, if it is required to satisfy demand of 8 rhodium tonnes, then if rhodium recovery rate was 100%, only 8 tonnes of rhodium contained in scrap would be purchased from collector-companies However, in reality, RR is usually 83% and, so that secondary production could produce those 8 tonnes, it should purchase 8/0,83 tonnes. This results in additional costs, and thus profit gained is less.

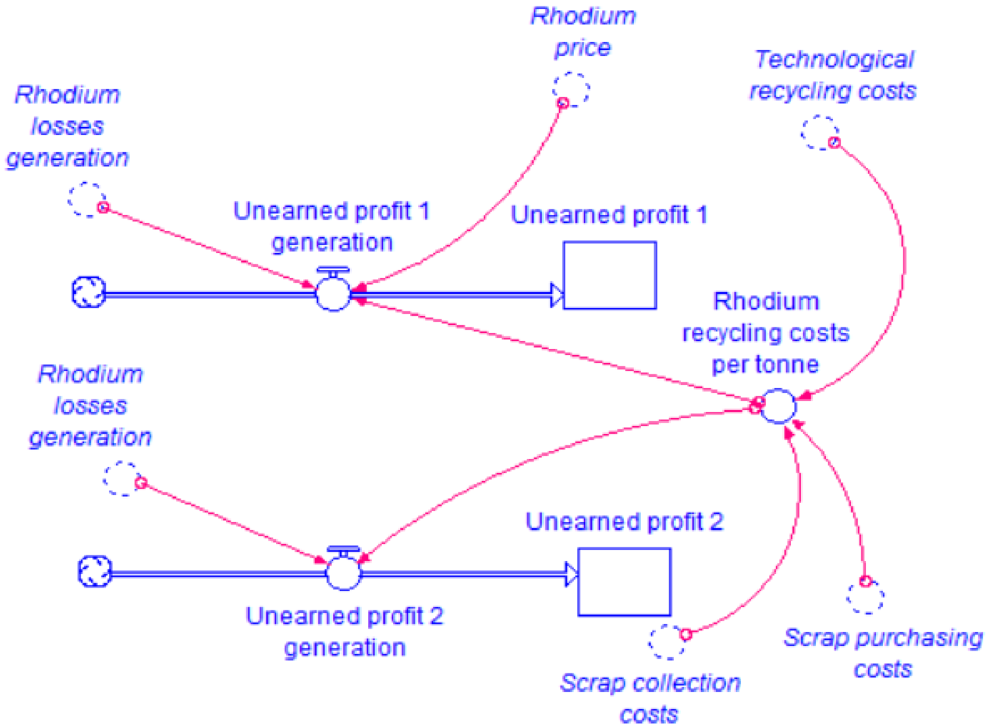

Figure 5.17 – The model's fragment, calculation unearned profit from recycling

"Unearned profit 1 generation" is a flow, which fills "Unearned profit 1" stock.

"Unearned profit 1 generation" = "Rhodium losses generation" * ("Rhodium price" – "Rhodium recycling costs per tonne")

"Recycling losses generation" = (1 - "Rhodium recovery rate") * "Secondary rhodium". The fraction of metal which is lost during the recycling process, the opposite amount is transferred to the customer. This flow is present on figure 5.7.

"Unearned profit 2 generation" = "Rhodium losses generation" * "Rhodium recycling costs per tonne"

"Unearned profit 2" is a stock similar to "Unearned profit 1". They represent accumulated unearned profit throughout the modeled time period.

Figure 5.18 illustrates a chart, demonstrating the flow "Unearned profit 1 generation" during five years. Two rhodium RR are considered: 83% and 84%. 84% is taken artificially to observe how an increase in 1% of RR can affect profit from recycling. Diminish returns effect is not taken into account, due to the absence of relevant data.

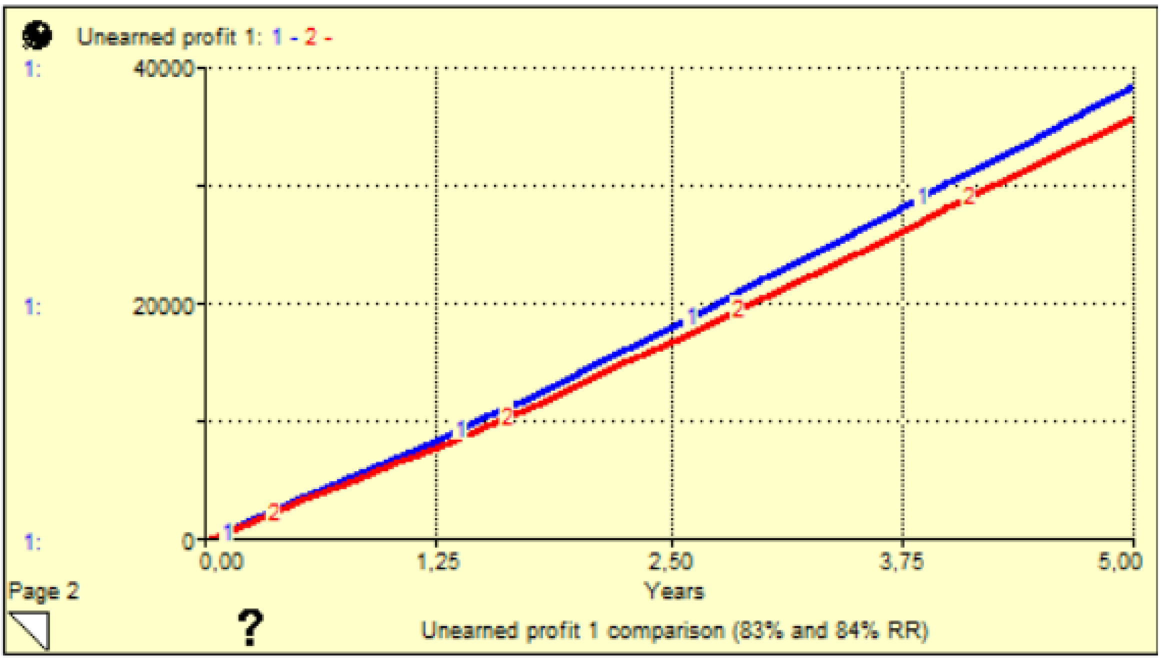

Figure 5.18 – "Unearned profit 1 generation". Blue curve – 83% RR, red -84% (in 10^5 US dollars)

The chart on figure 5.19 shows "Unearned profit 2 generation".

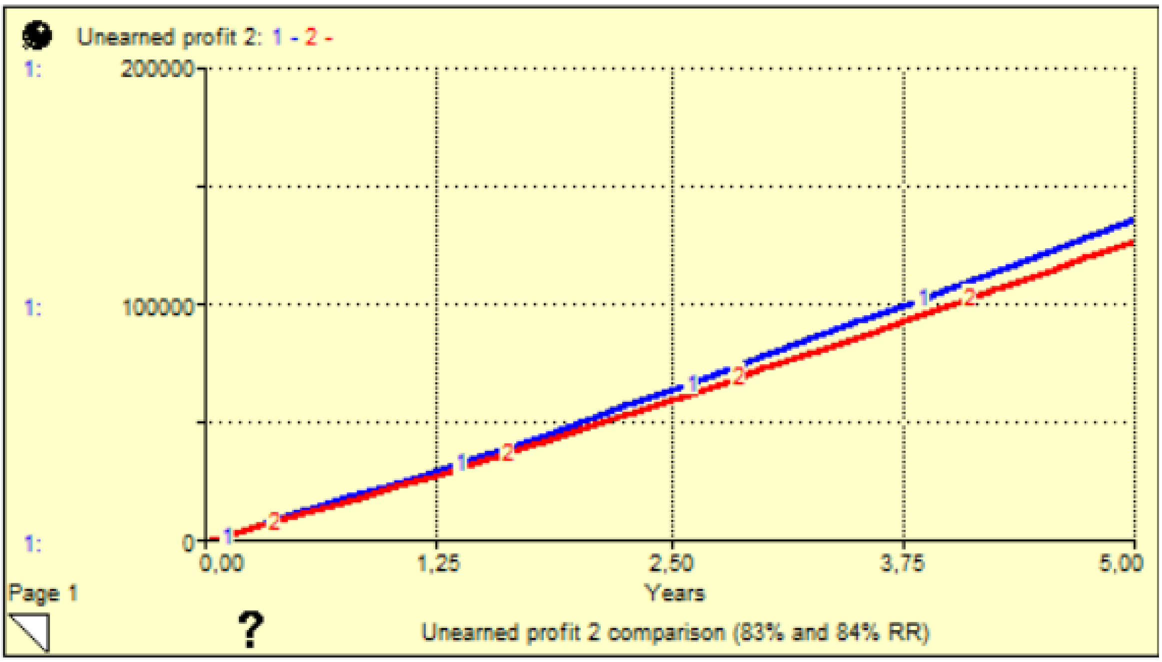

Figure 5.19– "Unearned profit 2 generation"; blue curve - 83%, red – 84% (in 10^5 US dollars)

5.4.3 Assessing the environmental impact of rhodium production

In *(IPA - environmental facts; Saurat and Bringezu 2008; Saurat and Bringezu 2009; EC framework)* it is suggested to assess the impact of platinum-group metals production on the environment based on two criteria:

- CO2 equivalent gases emissions;
- SO2 equivalent gases emissions.

CO2eq. Gases are also known as greenhouse gases (GHG) and mostly influences the environment by contributing to the global warming *(Anderson et al., 2016; Gillenwater, 2010)*. SO2eq. is known for harm caused to humans' health *(Air quality FS, 2005; Mabahwi, 2014)*. The model can calculate both criteria, yet results only for CO2eq. will be shown, since there are no specific differences in change of equivalent gases with production, both linearly increase as production increases. Also, *EC framework* mainly views CO2eq. as a priority group for reduction.

Another approach to recognizing environmental aspect could be through CO2 pricing costs evaluation. Such costs fall internally on an organization by externally set emission allowances cap (by legislating institution). There are different interpretations of CO2 pricing but most common would assume CO2 emissions allowances, where each allowance allows a company to emit one tonne of CO2 or equivalent gases.

Data for the RQ-3.

International Platinum Group Metals Association has assessed that approximately 30000 tonnes of CO2eq. gases are released to the atmosphere per production of a primary rhodium tonne, whereas only 735 tonnes per production of a secondary rhodium tonne *(IPA - environmental facts). Saurat and Bringezu (2008)* showed distribution of CO2eqv. emmision by countries mining PGM (see figure 5.20).

As for CO2 emmision allowance, price per tonne will greatly vary on country's legislation. For instnace, in the USA a research by *Luckow et al. (2015)* Showed that by 2020 CO2 price would vary from $15 to $25 per short ton. In the same time EU commision's allowance price averaged €5,34 in 2016 and €5,13 by 18th September in 2017 (data from *Investing.com*). EU prices will be taken as data input.

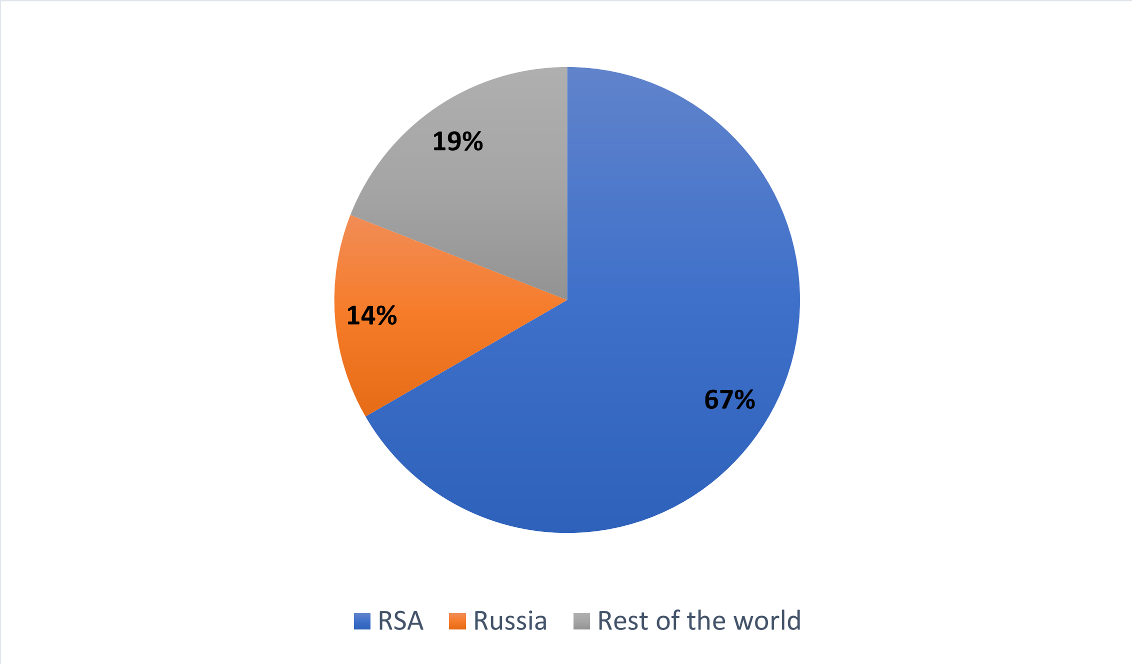

Figure 5.20 – Countries' contribution to CO2eq. emissions from PGM mining. Adapted from *Saurat and Bringezu (2008)*

Data input for the RQ 4-3 is present in table 5.9.

Table 5.9 Data input for the RQ 4-3

Element	**Element type**	**Data input/initial value**	**Figure №**
Primary production rate	Flow	Equation (explained in indirect parts of the model)	Fig. 5.21
CO2eq. generation by PP	Flow	equation	Fig. 5.21
South African CO2eq. contribution	Value	20 tonnes of CO2eq. per rhodium tonne	Fig. 5.21
Russian CO2eq. contribution	Value	4,286 tonnes of CO2eq. per rhodium tonne	Fig. 5.21

Table 5.9 (continued)

Others CO2eq. contribution	Value	5,714 tonnes of CO2eq. per rhodium tonne	Fig. 5.21
Carbon dioxide equivalent from PP	Stock	0	Fig. 5.21
CO2eq. generation by SP	Flow	equation	Fig. 5.21
Scrap collection rate	Flow	Equation (explained in previous chapters)	Fig. 5.21
Secondary production's contribution to COeq.	Value	0,735 tonnes of CO2eq. per rhodium tonne	Fig. 5.21
Carbon dioxide equivalent from PP	Stock	0	Fig. 5.21
CO2eq. generation by rhodium production	Flow	equation	Fig. 5.21
Total carbon dioxide equivalent amount from rhodium production	Stock	0	Fig. 5.21

Assumptions and constraints of the RQ 4-3.

Data in (*Saurat and Bringezu 2008)* for CO2eq. generation from PGM recycling is shown for European refineries. The model considers those values to be similar for the global scale.

Figure 5.21 reflects the model's fragment which calculates CO2eq. generation by primary and secondary rhodium production as well as cumulative gases generation and accumulation of CO2 pricing costs.

Comments on the functioning of the model's fragment and equations for the RQ 4-3.

For each mining rhodium tonne approximately 20000 CO2eq. tonnes are released in The Republic of South Africa, 4300 tonnes – in Russian Federation and 5700 tonnes – in the EU and other countries.

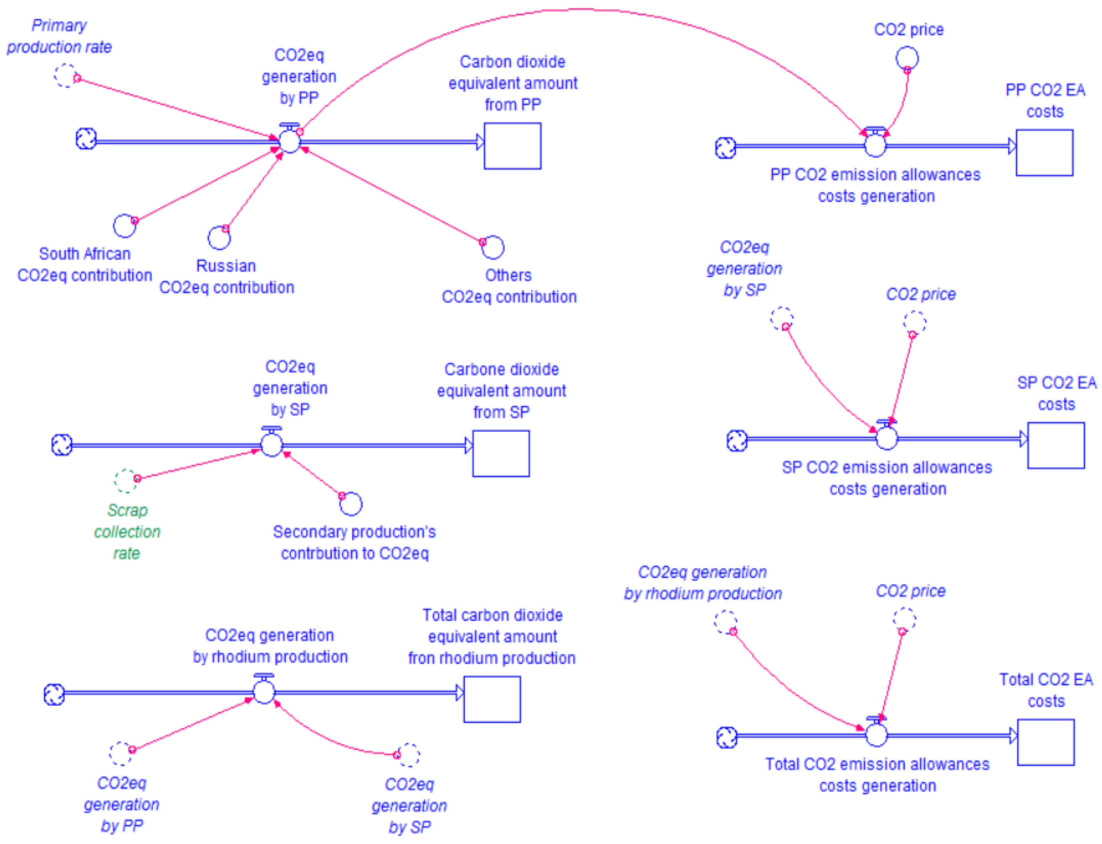

Figure 5.21 – CO2eq. gases generation and associated CO2 pricing costs calculations

"CO2eq. generation by PP" = "Primary production rate" * "South African contribution to CO2eq." + "Russian contribution to CO2eq." + "Others contribution to CO2eq.")

For each recycled rhodium tonne 735 CO2eq. tonnes are released into the atmosphere.

“CO2eq. generation by SP” = “Scrap collection rate” * “Secondary production’s contribution to CO2eq.”

Cumulative CO2eq. generation: “CO2eq. generation by rhodium production” = “CO2eq. Generation by PP” + “CO2eq. generation by SP”

“CO2 price” = IF TIME>=1 THEN 5,13 ELSE 5,34. This condition assumes that average CO2 price in 2016 was €5.34 per tonne and €5,13 per tonne in 2017 and onwards.

“PP CO2 emission allowance costs generation” = “CO2 price” * “CO2eq. generation by PP”. This flow calculates costs of primary production due to CO2 pricing. Similar equations are made for secondary and total (cumulative) rhodium production.

“PP CO2 EA costs” is a stock accumulated CO2 pricing costs of primary production. Similar equations are made for SP and total rhodium production.

The quantity of generated CO2eq. gases by PP and SP for five years is presented graphically on figure 5.22

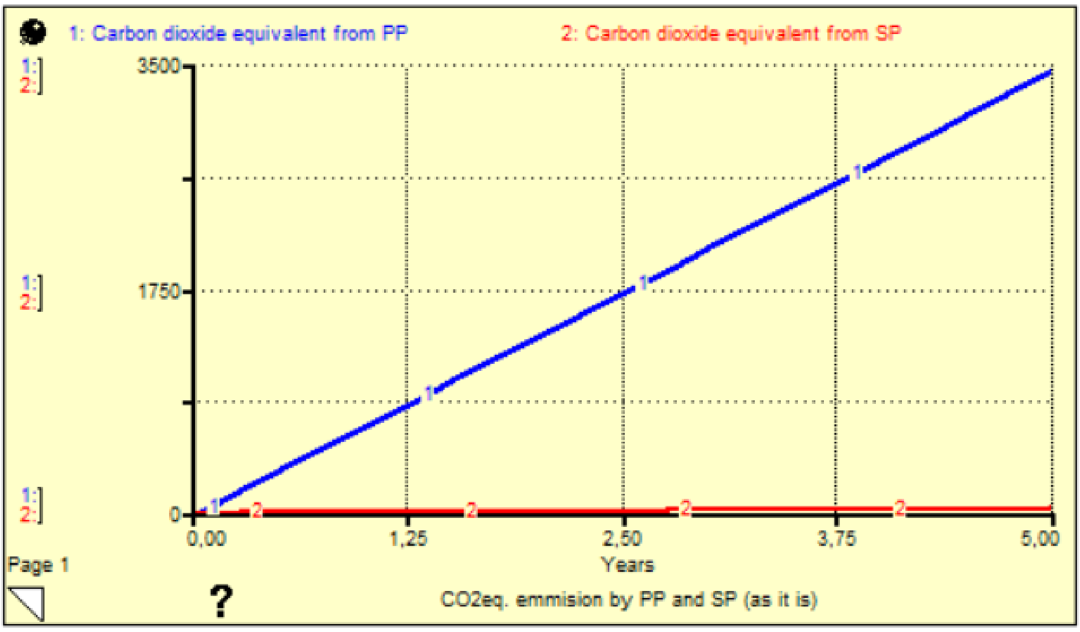

Figure 5.22 - CO2eq. generation by PP and SP (in 10^3 tonnes)

Figure 5.23 demonstrates a scenario of CO2eq. generation by PP and SP during five years if one-half of world’s rhodium was supplied by primary production and the other by secondary production (artificial scenario – to minimize realistic difference in production scales of PP and SP for comparison).

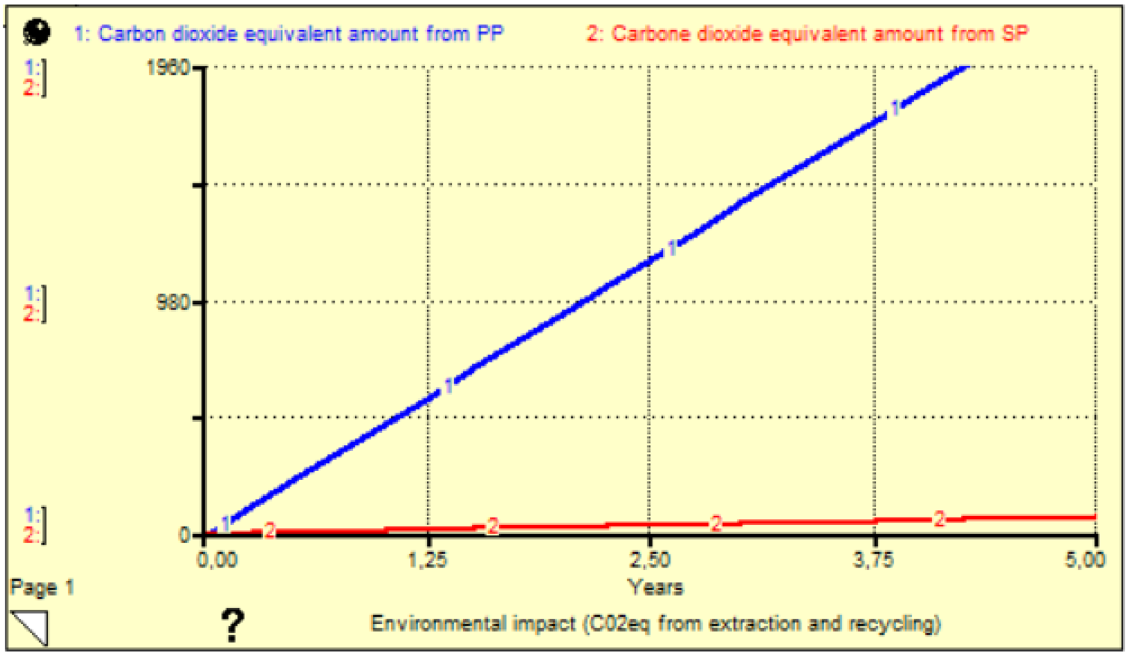

Figure 5.23 – CO2eq. generation; SP rate = PP rate (in 10^3 tonnes)

Figure 5.24 reflects rhodium productions costs associated with CO2 pricing.

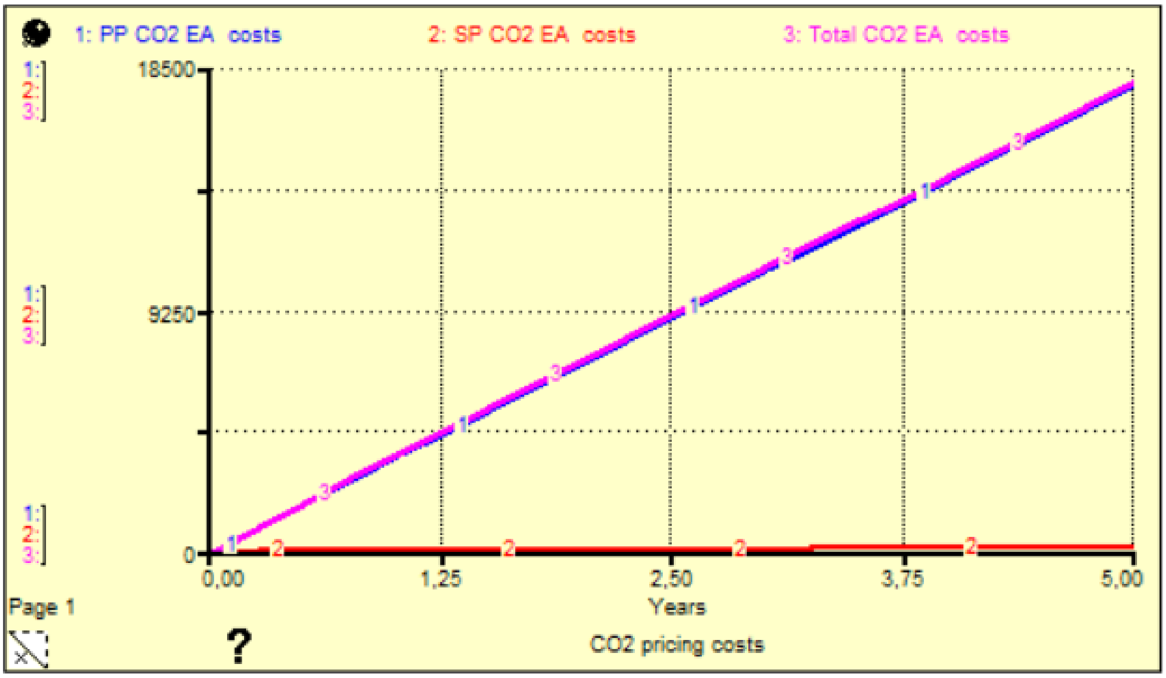

Figure 5.24 – CO2 pricing costs (in 10^3 euro)

5.4.4 Scrap stock depletion and systematic impact

EC framework states directive of the European Commission – "EU's 2020 strategy". In one of the strategic goals, it is assumed that GHG's level should be reduced by 20% by the year

In fact, the EU's directive is not a document, which has the legal power to regulate mining levels of metals, rather it has regulatory meaning for reduction of GHG through utilization of renewable source of energy and can serve as a recommendation in other fields. Nevertheless, the document presents realistic data on the desired CO2eq. levels and as one can see from the literature review, the majority of authors debate on the necessity of developing recycling systems to reduced negative impact of primary production on the environment.

With the dynamics model, it is possible to see the systematic impact caused by reduced primary rhodium production volumes on the economy, environment and scrap generation.

Data, the model's fragments and comments for the RQ 4-4.

No specific data required, the model's fragment and comments are the same as in previous chapters, but now RQ1, RQ3 and R4 are viewed as a system rather than separate objectives.

In truth answering RQs separately could be achieved without a dynamics model, but having a systemic view is what stirs great value in the model, to show how a change in one parameter (reduction in PP volume) leads to a change of the whole observe system (corresponding change in environmental criteria, profit and scrap generation level).

Assumption and constraints of the RQ 4-4.

Three scenarios are to be compared with each other:

1. Realistic – situation as it is, primary production levels are not reduced.
2. Primary production levels are artificially reduced by 10%.
3. Primary production levels are artificially reduced by 20%.

Time-period for scrap generation change from a short period (five years) to long period (hundred years), due to the first one being insufficiently short to demonstrate the impact of reduced primary production levels.

Based on these assumptions, three charts are built: environment assessment (figure 5.25), economic assessment (figure 5.26) and scrap levels assessment (figure 5.27).

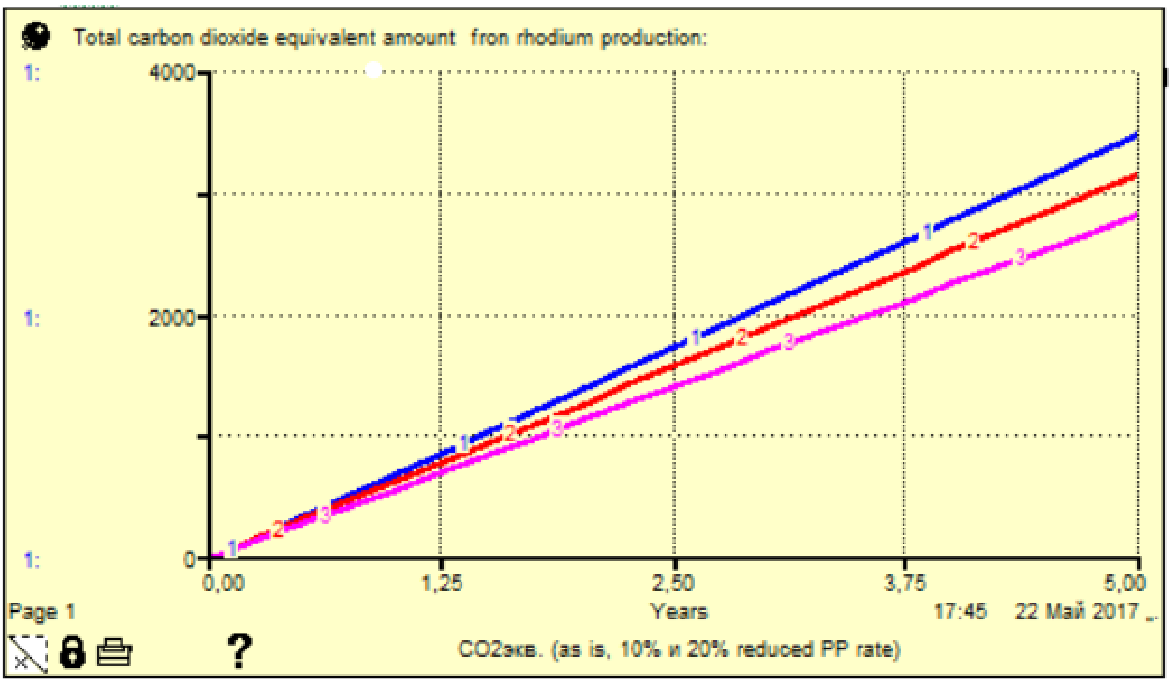

Figure 5.25 – CO2eq. generation comparison: blue curve – PP reduced by 0%; red curve- PP reduced by 10% and purple curve -PP reduced by 20% (in 10^3 tonnes)

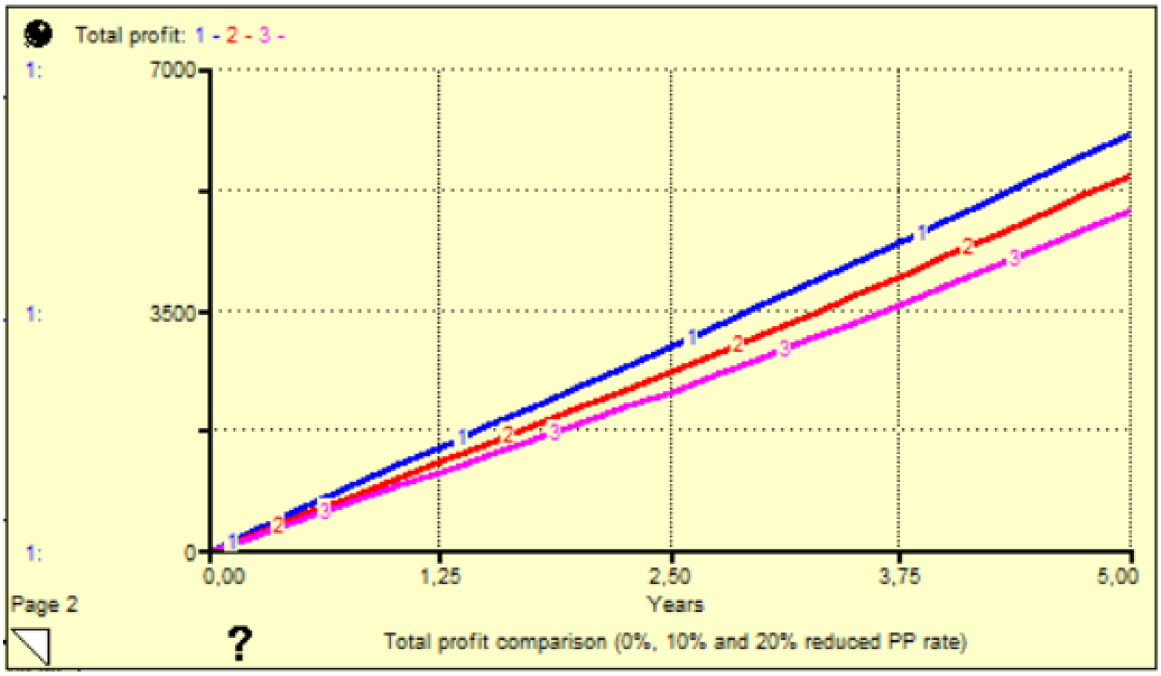

Figure 5.26 – Total profit: blue curve – PP reduced by 0%; red curve- PP reduced by 10% and purple curve -PP reduced by 20% (in 10^5 US dollars)

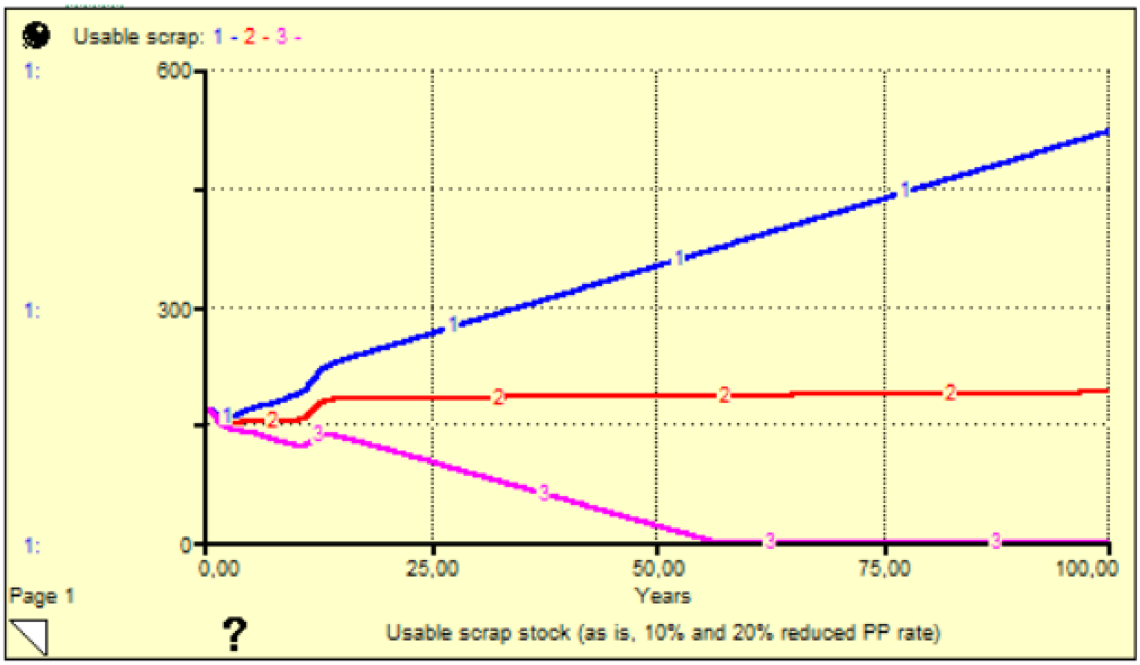

Figure 5.27 – Scrap generation levels: blue curve – PP reduced by 0%; red curve- PP reduced by 10% and purple curve -PP reduced by 20% (in tonnes)

Having analyzed the charts on CO2eq. gasses generation and total profit accumulation from rhodium production for five years, it is possible to come up with a table, which summarizes comparison of different reduced primary production volumes (see table 5.10).

Table 5.10 Comparing systematic impacts of reduced PP volumes (figure of profit and CO2eq are taken by the end of modeling year).

Reduction of primary production	CO2eq. emission (in 10^3 tonnes)	Total profit (in 10^5 US dollars)	Scrap generation
0 %	3500	6088	Surplus trend
10%	3164	5476	Stable trend
20%	2827	4948	Decline trend

5.4.5 Conclusion on the RQ 4

Result on fig. 5.16 showed, that economies of scale and time turn seemingly insignificant difference in primary and secondary production costs (as mentioned in chapter 5.2.) into rather noticeable. In a scenario, when PP and SP are equal, in five-years' time profit losses will reach approximately $219 million dollars in comparison to realistic scenarios.

Therefore, recycling is truly necessary in extent, to which it can supply rhodium quantities, which are unprovided by primary production, in order to meet rhodium demand. Profit earned by rhodium production resulted to be 30% less in the case of reduced mining volumes (and thus increased recycling volumes), which leads to understanding on the necessity of optimizing processes inherent to secondary production.

Result on fig. 5.19 demonstrates how the increase in rhodium recovery rate by 1% influences increase in profit generated by secondary production. With technology level of 83% RR, costs on 17% metal losses (such losses are also known as “waste” in Lean manufacturing, meaning something that does not bring value *(Mostafa. and Dumrak, 2015)*) during recycling process, reached $138 million dollars in five years. At the same time 84% rhodium RR could reduce extra costs by 7% (costs reached $126 million dollars, improvement of RR by 1%). In other words, improvement of rhodium RR by 1% for pyrometallurgical process leads to $9,5 million dollars increase. Or rephrase that. At 16% metal losses during PP it is possible to reduce recycling costs by 7%.

The chart on fig. 5.22 shows that through five years, primary rhodium production will generate approximately 3,5 million tonnes of CO2eq. gases, whereas secondary production – only 35 thousand tonnes. Thus, for five years, secondary production will generate similar CO2eq. amount to the amount generated by primary prod,uction of just one rhodium tonne.

Having rid of scale difference of SP and PP (chart on figure 5.23), it becomes visible that in five years, primary production will generate 2,3 million tonnes of CO2eq., which is just over 33 times more than CO2eq. emissions from secondary production (69 thousand tonnes).

Evaluation environmental impact from perspective of CO2 emission allowances (fig. 5.24) showed that while trend in CO2 price declined from €5,34 in 2016 to €5,14 in 2017 and assuming trends to be similar in next three years, total CO2 pricing cost from world rhodium production would reach €18 million by 2021. Surely this figure reflects in actual rhodium price, especially one can see that this contributes to primary rhodium’s price as primary production has a far greater impact on environment than secondary production.

Reduced primary rhodium production levels by 10% lead to reduced leads to the reduction of CO2eq. emissions by 9,6% and, in the same time, profit accumulated for five years will be 11% less with the loss of $61,2 million dollars.

If to consider, that scrap collection process and recycling process are optimized to an extent of secondary production costs being at least equal to primary production than SP substitute 10% loss in metal primary production, since as one can see on fig. 5.27, red curve show rather stable scrap generation through a hundred years' time. It is worth mentioning, that despite the stability, reducing of PP by 10% can be riskier than it seems, since the red curve shows scrap generation according to current demand trends and not taking into account the fact that demand can raise, more importantly, as noticed before world rhodium demand is highly dependent on South African suppliers (who represent 80% of total supply), which are known to have troubles with labour strikes leading to delays in supply, which, as shown in sub-chapter 5.1, leads to reduction of scrap generation levels.

Figure 5.27 demonstrates three scenarios development of used scrap levels change in a long-term period (hundred years). Having viewed only a short-term period (five years) it would seem that there are no issues with scrap generation levels for recycling, since on that short period, 20% reduced primary production levels cause no impact and after a delay one can even see an increase in scrap generation by the fifth year (purple curve on fig. 5.27). However, by extending the modeling time to a hundred years it become vividly visible how wrong the previous statement was: reduced PP volume by more than 10% used scrap levels will show tendency to decrease and reduced PP by 20% will result in rhodium scrap depletion in 56 years (there will be no more scrap to collect, considering scrap collection levels to be unchanged – 50%). This once again proves IPA's claims about the interdependence of primary and secondary production and despite, that last one being far eco-friendlier and, if to consider a situation where it becomes more economically justified, – less than 10% reduction of PP seems to be the tough border.

6. INDIRECT FRAGMENTS OF THE DYNAMICS MODEL

In this chapter comments, will be given on equations and functioning of the model's fragments, which have not directly solved research questions, however without which direct parts of the model would not operate correctly.

Data input for indirect parts of the model is present in table 6.1.

Table 6.1 Data input for indirect parts of the model

Element	Element type	Data input/initial value	Figure №
Autocatalysts demand level increase	Value	CGROWTH (5)	Fig. 6.1
Autocatalysts demand	Value	24,2 tonnes	Fig. 6.1
Autocatalysts demand change	Value	equation	Fig. 6.1
Glass demand level increase	Value	CGROWTH (5)	Fig. 6.1
Glass demand	Value	1,6 tonnes	Fig. 6.1
Glass demand change	Value	equation	Fig. 6.1
Others demand level increase	Value	CGROWTH (5)	Fig. 6.1
Others demand	Value	0,8 tonnes	Fig. 6.1
Others demand change	Value	equation	Fig. 6.1
Chemical demand level increase	Value	CGROWTH (5)	Fig. 6.1
Chemical demand	Value	3,1 tonnes	Fig. 6.1
Chemical demand change	Value	equation	Fig. 6.1

Table 6.1 (continued)

Electronics demand level increase	Value	CGROWTH (5)	Fig. 6.1
Electronics demand	Value	0,1 tonnes	Fig. 6.1
Electronics demand change	Value	equation	Fig. 6.1
Total demand	Value	equation	Fig. 6.1, 6.2
Primary production change fraction	Value	0	Fig. 6.2
Primary production rate	Value	Equation with initial value: 23,1 tonnes)	Fig. 6.2
Total demand and primary supply gap	Value	equation	Fig. 6.2
Secondary rhodium demand	Value	equation	Fig. 6.2
Primary rhodium flow	Flow	equation	Fig. 6.2
World rhodium stock	Stock	2,1 tonnes	Fig. 6.2
Autocatalysts production	Flow	equation	Fig. 6.3
Glass production	Flow	equation	Fig. 6.3
Others production	Flow	equation	Fig. 6.3
Chemical production	Flow	equation	Fig. 6.3
Electronics production	Flow	equation	Fig. 6.3
Glass	Stock	0	Fig. 6.3
Others	Stock	0	Fig. 6.3
Chemical	Stock	0	Fig. 6.3
Electronics	Stock	0	Fig. 6.3

Figure 6.1 illustrates the model's fragment, the purpose of which is to calculate total demand (cumulative demand from all rhodium-consuming industries).

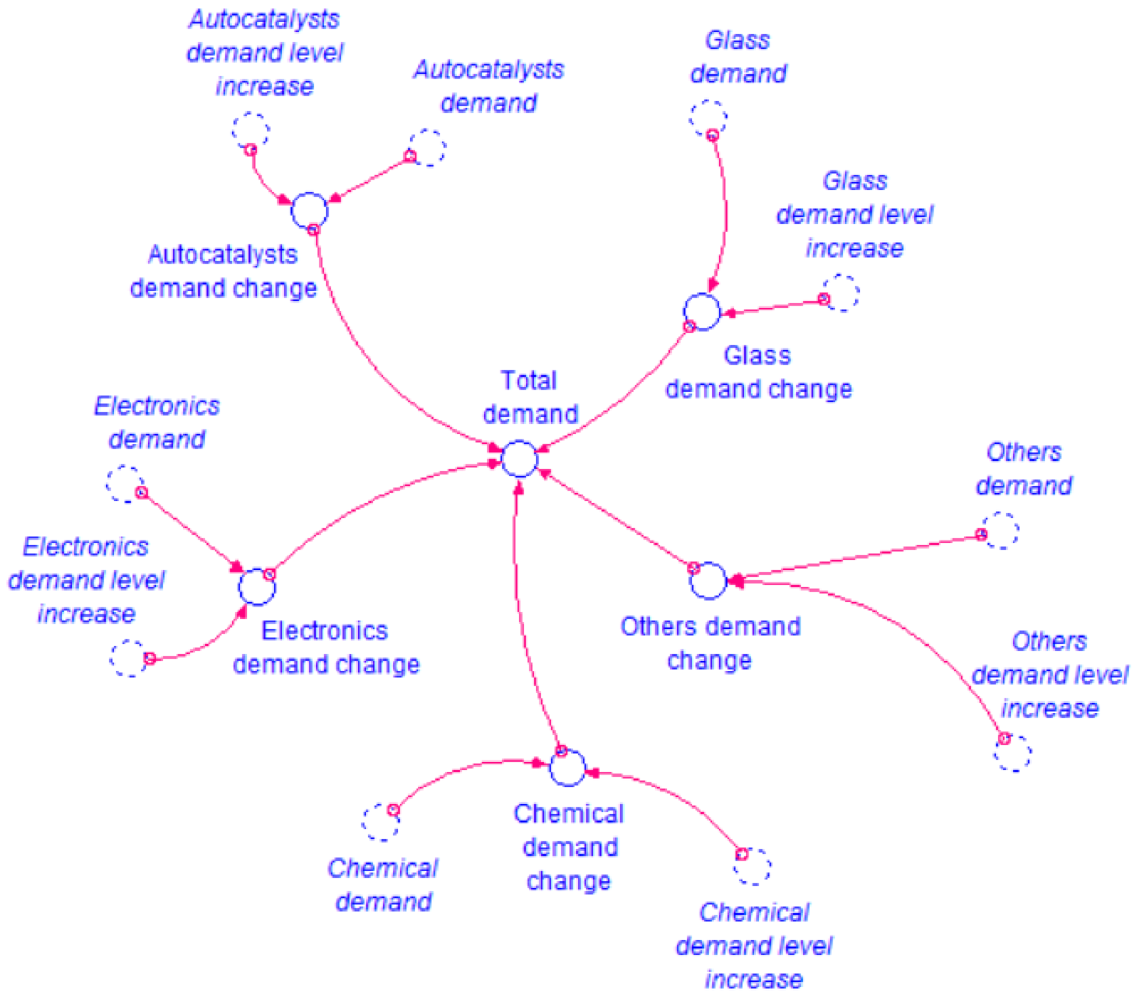

Figure 6.1 – The model's fragment – calculation of total demand

"Total demand" equals the sum of individual industries' demands:

"Total demand" = "Autocatalysts demand change" + "Glass demand change" + "Others demand change" + "Chemical demand change" + "Electronics demand change"

"Autocatalysts demand change" is a parameter which reflects the demand and corresponding change, if such is relevant. So, if a change of demand is known in each year than "Autocatalysts demand" will be altered in the specific year according to "Autocatalysts demand level increase".

"Autocatalysts demand" is initial demand level at the start of the modelling year (2016).

"Autocatalysts demand level increase" is a change fraction parameter. It says "increase", since based on *JM PGM (2016)* demand is likely to increase, but the actual change can be set as of decrease, if needed.

If "Autocatalysts demand level increase" is not set then "Autocatalysts demand change" equals "Autocatalysts demand", since no change is to happen.

"Autocatalysts demand" = 24,2 tonnes, which is the initial value for 2016.

"Autocatalysts demand level increase" = CGROWTH (5). CGROWTH function reflects demand increase by 5%.

"Autocatalysts demand change" = "Autocatalysts demand" + STEP ("Autocatalysts demand" * "Autocatalysts demand level increase",1), where STEP is a function directing the demand change in the year of change, more specifically in year "1", which would be 2017 since year "0" is 2016 for the model.

Translating the equation above, the meaning would be next: autocatalyst demand in 2017 will be 5% higher than in 2016.

Similar comments are relevant for other industries' demand.

As mentioned before, the model is based on the assumption that market is ideally balanced. For this matter fragment on figure 6.2 exists.

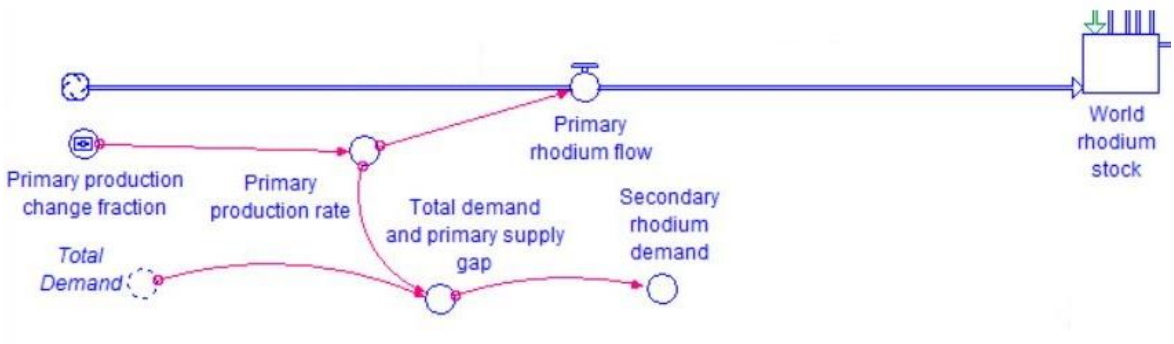

Figure 6.2 – The model's fragment controlling the change of primary and secondary production

"Primary production rate" = 23,1 – (23,1 * "Primary production change fraction"). Initially, change value is 0, yet it can be and is changed during the development of scenarios describing the impact of reduced primary production rates. In this case, “Primary production change fraction” will take value set by the decision maker.

“Total demand and primary supply gap” is reflecting the lack of primary rhodium supply and is described by the following equation: “Total demand” - “Primary production rate”.

The lack of primary rhodium is causing the demand in secondary recycled rhodium:

“Secondary rhodium demand” = “Total demand and primary supply gap”. Thus, recycling provides that rhodium supply which cannot be suggested by primary supply.

So, if it is required to reduce PP volume (for instance, to reduce pressure on the environment), then it is necessary to satisfy the demand with increased SP volumes. This fragment in conjunction with direct fragments allows comparing primary and secondary production economically and ecologically.

The model’s fragment, which describes rhodium outflows from the market, is present on figure 6.3.

“World rhodium stock” is a conceptual stock, which can be compared to market or warehouse to where all rhodium flows from primary and secondary production and further outflows to consuming industries. The initial value for this stock is set to 2.1 tonne due to rhodium overproduction (market balance is in surplus – *JM PGM (2016)*).

Stocks such as “Electronics”, “Glass”, “Others” and “Chemical catalysts” do not participate directly or indirectly in answering research questions; they are the remnants of the model in the publication about the potential for rhodium recycling *(Bessudnov et al. 2017)* and allowed to calculate rhodium mass quantity generated in specific products. These stocks were not removed, because they can still be useful in the development of particular scenarios.

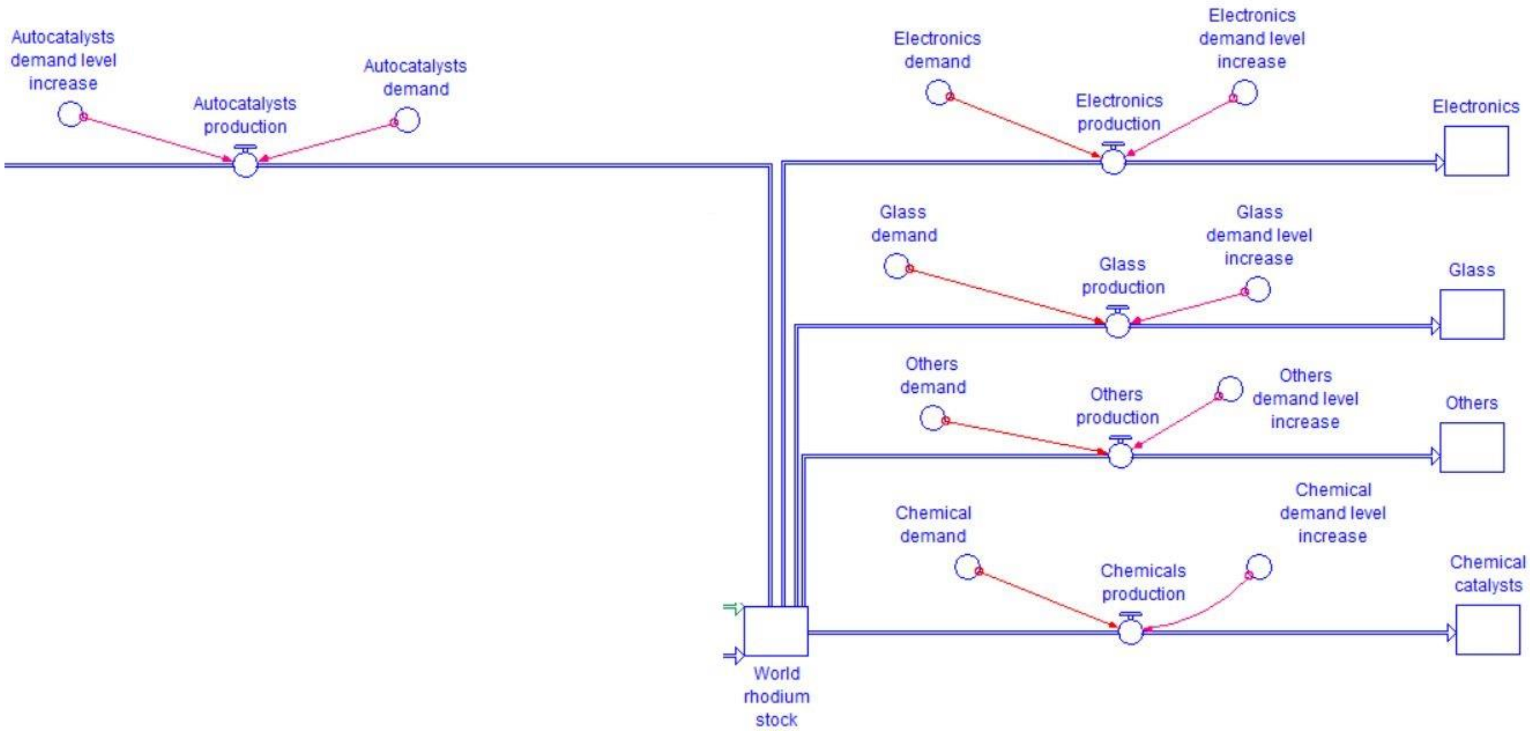

Figure 6.3 – The model’s fragment, calculating rhodium consumption

7. CONCLUSION

In the course of the master's thesis the material flow analysis was conducted based on the processes inherent to rhodium production as well as the dynamics model for rhodium flow was developed. In the result of answering research questions it was established that although secondary production is defiantly economically justified it is not more profitable than primary production and currently, recycling is necessary to fill in the gap caused by the deficit of primary rhodium supply.

In (*IPA on recycling*), International Platinum-Group Metals Association presents facts on platinum-group metals recycling and shares its concern for sufficiency of rhodium scrap for recycling, since as mentioned, fraction of scrap is not "harvested" by collector companies since the majority of secondary rhodium production locates in the EU, whereas significant fraction of automobiles, which are the only reliable source of rhodium scrap, is being exported to countries with less developed scrap collection and recycling process. According to the model's assumptions and results, scrap quantity will be sufficient for secondary rhodium production (see fig. 5.1), considering that supply and demand trends will not deviate dramatically.

Most scientific works, dedicated to critical raw materials (see the literature review), concluded about the necessity of the development of recycling technologies, from the perspective of increasing metal recovery rate, to reduce the risk of supply deficit and further possibly partly substitute primary production to reduce negative impacts on the environments caused by mining. Expanding the results on the environmental influence of PGM production, presented by IPA *(IPA on environmental impact)* and *Saurat and Bringezu (2008)* in dynamics and on parameter changes (such as demand change), it was shown that, indeed, recycling of rhodium is far eco-friendlier than primary production. For five years, quantity of CO2 equivalent gases is accumulated and geneared by secondary production, similar to the quantity of a one tonne primary production (see fig. 6.3). However, currently, PP is more profitable than SP (chapters 5.2 and 5.4). The development of technological process of rhodium recycling, can partly solve, issue with high secondary production costs (in comparison to PP).

Transition from 83% to 84% rhodium recovery rate leads to SP cost reduction by approximately 7%, but the model does not consider the diminishing returns effect, so in fact, for every extra percentage increase in recovery rate, additional costs for technological process wil be accumulated, altough scrap collection costs will be lower.

A transition from pyrometallurgical recycling process to hydrometallurgical seems very expensive, such even 98% recovery is not economically justified: despite savings on lower scrap collection costs, additional costs on technological process appear. Therefore, is more reasonable to focus on optimizing scrap collection process, what is suggested by *Ryan et al. (20*10*)* and *Hagelüken (2012)*.

If to imagine a situation, a specific scenario, under which rhodium recycling becomes more profitable than mining then it is only possible to substitute 10% of reduced primary production volumes. Since the reduction of PP by greater than 10% will cause supply deficit in less than a hundred years. For instance, PP reduction by 20% will lead to rhodium scrap depletion in 56 years, and thus, make recycling impossible, therefore, this confirms the concerns of IPA *(IPA on environmental impact; IPA on recycling)* and shows once again a high interdependence of PP and SP, described in (*IPA on recycling*; *Saurat and Bringezu 2008; Saurat and Bringezu 2009*).

The master's thesis is one of a few scientific works, which quantitatively analyze rhodium recycling. The most important scientific result is rhodium material flow dynamics model. The model allows conducting the metal's material flow analysis. With its help, it is possible to assess and company primary and secondary production economically and ecologically, and more importantly, make a decision based on systematic impacts on analyzed parameters.

Dynamics model is developed for rhodium MFA on a global scale, however, it is flexible and can be adapted for a specific country, region or for the needs of a company, producing not only rhodium but other metals as well. In this case, based on a more detailed data it will be possible to remove the majority of the assumptions presented in the work, making the model more precise and adequate.

It is considered relevant to conduct further studies based on the work to reach the following goals:

- The development of scenarios, which take into account spontaneous fall in primary production levels, caused by labour strikes (such as in South Africa in 2008 and 2012) as well as the economic assessment of the consequences;

- To link the model with autocatalysts and automobile production, to assess the impact of rhodium supply shortages or even surplus on those industries;
- The enhancement of model's precision based on updated data;
- The quantitative assessment of the diminishing returns effect with the increase of rhodium recovery rate.

REFERENCES

Air quality FS, 2005. Air quality fact sheet. 2005. Sulfur dioxide (SO2) *Department of the Environment and Heritage, Australian Government.* http://www.environment.gov.au/protection/publications/factsheet-sulfur-dioxide-so2

Anderson, T.R., Hawkins, E. and Jones, P.D. 2016. CO_2, the greenhouse effect and global warming: from the pioneering work of Arrhenius and Callendar to today's Earth System Models. *Endeavour*, vol. 40, pp. 178-187. DOI: https://doi.org/10.1016/j.endeavour.2016.07.002

Annual Report 2012. Chamber of Mines of South Africa http://www.chamberofmines.org.za/industry-news/publications/annual-reports

Bartak, D. 1996. Recovery of Platinum Group Metals from Spent Catalysts. Final Report for the RRTTCC 1996.

Bessudnov, A.A., Golroudbary, S., Saud, S., Mujkic, Z., Elwali, M. and Krehoveckii, N. 2017. The Potential for Rhodium Recycling. International conference in the topical issues of rational natural resources utilization, Saint-Petersburg, Russia, April 19 – April 21, pp. 6-9.

Bicanová, K., Wittlingerová, Z., Dvorák, J. and Zimová M. 2015. The material flows of lead in the Czech Republic. *Resources, Conservation and Recycling*, vol. 98, pp. 1-8.

BIO by Deloitte. 2015. Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW.

Bolinski, L. 1991. Platinum and Rhodium Recovery from Scrapped Automotive Catalyst by Oxidative Acid Chloride Leaching. McGill University, Department of Mining and Metallurgical Engineering.

Brunner, P.H. and Rechberger, H. 2004. Practical Handbook of Material Flow Analysis. London: CRC Press.

BV. Troy ounces. BullionVault ltd. - https://www.bullionvault.com/gold-guide/troy-ounces

Choi, C.H., Cao, J. and Zhao, F. 2016. System Dynamics Modeling of Indium Material Flows under Wide Deployment of Clean Energy Technologies. *Resources, Conservation and Recycling*, vol. 114 p. 59-71.

Davis, J., Geyer, R., Ley, J., He, J., Clift, R., Kwan, A., Sansom, M. and Jackson, T. 2007. Time-dependent material flow analysis of iron and steel in the UK: Part 2. Scrap generation and recycling. *Resources, Conservation and Recycling*, vol. 51, pp. 118-140. DOI: https://doi.org/10.1016/j.resconrec.2006.08.007

EAMA. European Automobile Manufacturers Association. Data on average vehicle age in the EU. http://www.acea.be/statistics/tag/category/average-vehicle-age

EC framework. European commision. “2020 strategy”. https://ec.europa.eu/info/strategy/european-semester/framework/europe-2020-strategy_en -

Ekvall, T., Fråne, A., Hallgren, F. and Holmgren K. 2014. Material Pinch Analysis: A pilot study on global steel flow. Report of Swedish Environmental Research Intitute number, vol. 111, № 6, pp. 359–367

Elwali, M., Krehoveckii, N.I., Bessudnov, A.A., Golroudbary, S., Saud, S., Mujkic, Z. and Kraslawski, A. System dynamics model for determining the recycled material level in usage stock. International conference in the topical issues of rational natural resources utilization, Saint-Petersburg, Russia, April 19 – April 21, pp. 20-22.

European Commission, DG Enterprise and Industry. 2010. Report of the Ad-hoc working group on and defining critical raw materials

Faisal, S.A., Golroudbary, S.R., Bessudnov, A., Elwali, M and Krekhovetckii, N. 2017. Investigating Growth Potentiality of Critical Materials towards Sustainable Supply Using System Dynamics (Case-Indium). International conference in the topical issues of rational natural resources utilization, Saint-Petersburg, Russia, April 19 – April 21, pp. 9-12.

Fornalczyk, A. and Saternus, M. 2013. The Possibilities of Reusing the Ceramic Carriers Coming from Used Auto Catalytic Converters. *Advances in Ceramic Science and Engineering*, vol. 2, pp.56-63.

Ghosh, A. and Ray, H.S. 1991. Principles of Extractive Metallurgy. *New Age International*.

Gillenwater, M. 2010. WHAT IS A GLOBAL WARMING POTENTIAL? AND WHICH ONE DO I USE? GHG Management Insitute. http://ghginstitute.org/2010/06/28/what-is-a-global-warming-potential/

Graedel, T. E., Allwood, J., Birat, J-P., Buchert, M., Hagelüken, C., Reck, B. K., Sibley, S. F. and Sonnemann, G. 2011. What Do We Know About Metal Recycling Rates? Journal of Industrial Ecology, vol. 15, pp. 355–366. Doi:10.1111/j.1530-9290.2011.00342.

Gregory, J. Lectures on the marerial flow analysis. Massachusetts Institute of Technology. Lectures slides - https://ocw.mit.edu/courses/engineering-systems-division/esd-123j-systems-perspectives-on-industrial-ecology-spring-2006/lecture-notes/lec14.pdf

Gsodam, P., Lassnig, M., Kreuzeder, A. and Mrotzek, M. 2014. The Austrian silver cycle: A material flow analysis. *Resources, Conservation and Recycling*, vol. 88, pp. 76-84.

Gupta, C. K. and Mukherjee, T. K. 1990. Hydrometallurgy in Extraction Processes: Volume 1. CRC Press.

Hagelüken, C. 2012. Recycling the Platinum Group Metals:A European Perspective, *Johnson Matthey*, vol. 56, №1, pp. 29–35. DOI:dx.doi.org/10.1595/147[106]712X611733

Hao, H., Liu, Z., Zhao, F., Geng, Y. and Sarkis, J. 2017. Material flow analysis of lithium in China. *Resources Policy*, vol. 51, pp. 100-106. DOI:10.1016/j.resourpol.2016.12.005

Haque, N., Bruckard, W. and Cuevas, J. 2012. A techno-economic comparison of pyrometallurgical and hydrometallurgical options for treating high-arsenic copper concentrates. The 26th International Mineral Processing Congress (IMPC 2012), New Delhi, India, September 24 – September 28, pp. 1908-1923.

Harjanto, S., Cao, Y., Shibayama, A., Naitoh, I., Nanami, T., Kasahara, K., Okumura, Y., Liu, K. and Fujita, T. 2006. Leaching of Pt, Pd and Rh from Automotive Catalyst Residue in Various Chloride Based Solutions. *Materials Transactions*, Vol. 47, No. 1, pp. 129 – 135. DOI:http://doi.org/10.2320/matertrans.47.129

Hatayama, H., Daigob, I., Matsunob Y., & Adachib Y. 2012. Evolution of aluminum recycling initiated by the introduction of next-generation vehicles and scrap sorting technology. *Resources, Conservation and Recycling*, vol.11, № 66, pp. 8–14

Infomine. Rhodium Investing - Rhodium Stocks, Mining Companies, Prices and News http://www.infomine.com/investment/rhodium/

International Platinum-group metal Association. PGM fact sheets - http://ipa-news.com/

Investing.com - https://www.investing.com/commodities/carbon-emissions-historical-data

IPA *on autocatalysts and PGMs*. (International Platinum Group Metals Association. Facts sheet – autocatalysts and platinum group metals. http://ipa-news.com/assets/sustainability/Autocatalyst%20Fact%20Sheet_LR.pdf?PHPSESSID=8f924aa0e30f81ba7fe97c7449665b58

IPA on environmental impact. International Platinum Group Metals Association. Facts sheet – The Environmental Profile of Platinum Group Metals - http://ipanews.com/assets/sustainability/Environmental%20Profile_LR.pdf?PHPSESSID=e0b3ea0e4d4c49af30a6edb4db2099dd

IPA on secondary production. International Platinum-Group Metal Association. PGM fact sheets. On secondary rhodium production - http://ipanews.com/assets/sustainability/Secondary%20Production%20Fact%20Sheet_LR.pdf?PHPSESSID=303a7741a1b2e8aea3f311818f5b9d00

Isee Systems company website - https://www.iseesystems.com/

JM PGM 2016. Johnson Matthey PGM market review for the November 2016 - http://www.matthey.com/investor/reports

Johnson Matthey annual reports -http://www.matthey.com/investor/reports

Johnson Matthey archive of data on rhodium supply and demand - http://www.matthey.com/investor/reports?parentFolderPiD=58c675d6aa66bb24cc0d064a –

Johnson Matthey. The period of the 1985-1999. Data on rhodium supply and demand. http://www.platinum.matthey.com/services/market-research/market-data-tables

Johnson Matthey. The period of the 2000-2004. Data on rhodium supply and demand. http://www.platinum.matthey.com/services/market-research/market-data-tables

Johnson Matthey. The period of the 2004-2013. Data on rhodium supply and demand. http://www.platinum.matthey.com/services/market-research/market-data-tables

Kim, J. G. 2013. Material flow and industrial demand for palladium in Korea. *Resources, Conservation and Recycling*, vol. 77, pp. 22-28.

Kolliopoulos, G. , Balomenos, E. , Giannopoulou, I. , Yakoumis, I. and Panias, D. 2014. Behavior of Platinum Group Metals during Their Pyrometallurgical Recovery from Spent Automotive Catalysts. Open Access Library Journal, vol. 1, pp. 1-9. doi: 10.4236/oalib.1100736.

Krekhovetckii, N., Golroudbary, S.N., Zlatan, M., Elwali, M., Saud, S., and Bessudnov, A.A. 2017. Modelling Material Flow of Niobium. International conference in the topical issues of rational natural resources utilization, Saint-Petersburg, Russia, April 19 – April 21, pp. 22-25.

Kriek, R.J., Engelbrecht, W.J. and Cruywagen, J.J. 1994. Separation and recovery of some platinum group metals (PGMs) by means of selective photocatalytic reduction. *The Joumal of The South African Institute of Mining and Metallurgy*, pp.75-82.

Krivenko, A.P and Glotov, A.I. 2000. Types of deposits, stocks, production and market of platinum-group metals. Moscow State Technical University, vol. 3 №2 pp. 211-224 (on Russian)

Leal-Ayala, D.R., Allwood, J.M., Petavratzi, E., Brown, T.J., Gunn, G. 2015. Mapping the global flow of tungsten to identify key material efficiency and supply security opportunities. *Resources, Conservation and Recycling*, vol. 103, pp. 19-28. DOI: https://doi.org/10.1016/j.resconrec.2015.07.003

Lillkung, K. and Aromaa, J. 2012. Hydrometallurgical recovery of platinum group metals. Alto University, Alto University publication series SCIENCE + TECHNOLOGY.

Lingyu, Y., Anjian, W., Qishen, C., Jianwu L. 2013. Dynamic material flow analysis of zinc resources in China. *Resources, Conservation and Recycling*, vol.75, pp. 23-31

Luckow, P., Stanton, E.A., Fields, S., Biewald, B., Jackson, S., Fisher, J. and Wilson, R. 2015. 2015 Carbon Dioxide Price Forecast. *Synapse Energy Economics, Inc. Cambridge, Massachusetts.*

Mabahwi, N.A.B., Leh, O.L.H and Omar, D. 2014. Human Health and Wellbeing: Human Health Effect of Air Pollution. *Procedia - Social and Behavioral Sciences*, vol. 153, pp. 221-229. DOI: https://doi.org/10.1016/j.sbspro.2014.10.056

Manser, A.G.R. and Keeling, A. 1996. Practical Handbook of Processing and Recycling Municipal Waste. CRC Press.

Monat, J.P., and Gannon T.F. 2015. What is Systems Thinking? A Review of Selected Literature Plus Recommendations. *American Journal of Systems Science* , vol. 4(1), pp. 11-26. DOI: 10.5923/j.ajss.20150401.02

Mostafa, S. and Dumrak, J. 2015. Waste Elimination for Manufacturing Sustainability. *Procedia Manufacturing*, vol. 2, pp. 11-16.

Neuwirth, C., Peck, A. and Simonović, S.P. 2015. Modeling structural change in spatial system dynamics: A Daisyworld example. Environmental Modelling & Software, vol. 65, pp. 30-40. DOI: http://dx.doi.org/10.1016/j.envsoft.2014.11.026.

Park, J-a., Hong, SJ., Kim I., Lee, J-y. and Hur T. 2011. Dynamic material flow analysis of steel resources in Korea. *Resources, Conservation and Recycling*, vol. 55, pp. 456-462. DOI: https://doi.org/10.1016/j.resconrec.2010.12.007

Platt, B., Doherty, C., Broughton, A.C. and D. Morris D. 1991. Beyond 40%: Record-Setting Recycling And Composting Programs. Institute for Local Self-Reliance.

Porter, J.W. 1997. Too much recycling can be a waste of resources. Atlanta Journal-Constitution. https://sites.google.com/site/winporttest/environmental-strategies-2/op-eds/too-much-recycling

Ray, H.S. 2012. Non-Ferrous Extractive Metallurgy. Department of Metallurgical & Materials Engineering. Indian Institute of Technology, Kharagpur. Lecture No. # 07 Principles of Hydrometalling https://www.edutry.com/Course/M-Sc-Sociology/44887/Videos

Rich, M. 1995. The International Lead Trade Vincent Rich. Woodhead Publishing Limited.

Riddle, M., Macal, C. M., Conzelmann, G., Combs, T. E., Bauer, D. and Fields F. 2015. Global critical materials markets: An agent-based modeling approach. *Resources Policy*, vol. 45, pp. 307-321. DOI: http://dx.doi.org/10.1016/j.resourpol.2015.01. 002.

Rumpold, R. and Antrekowitsch, J. 2012. Recycling of Platinum Group Metals from Automotive Catalysts by an Acidic Leaching Process. The 5th International Platinum Conference “A Catalyst for Change”, Sun City, South Africa, September 18 – September 21, pp. 695-714.

Ryan, A., Clarke, B., Atilan, O., Watts, J. and Trickey, S. 2010. Recycling: volume, momentum and consequences for PGMs. The 4th International Platinum Conference, Platinum in transition ‘Boom or Bust’, October 11 – October 14, Johannesburg, the Republic of South Africa.

Saunders, M., Lewis, P. and Thornhill, A. 2009. Research Methods for Business Students. Pearson Eduction.

Saurat, M. and Bringezu, S. 2008. Platinum Group Metal Flows of Europe, Part 1. *Journal of Industrial Ecology*, vol. 12, pp. 754–767. doi:10.1111/j.1530-9290.2008.00087.x

Saurat, M. and Bringezu, S. 2009. Platinum Group Metal Flows of Europe, Part II. *Journal of Industrial Ecology*, vol. 13, pp. 406–421. doi:10.1111/j.1530-9290.2008.00106.x

Singhvi, A., Shenoy, U.V. 2002. Aggregate Planning in Supply Chains by Pinch Analysis. *Chemical Engineering Research and Design* , vol. 80, № 6, pp. 597-605

SMC. 2015. Annual Financial Report of the Stillwater Mining Company. http://www.annualreports.com/Company/stillwater-mining-company

Spatari, S., Bertram, M., Gordon, RB., Henderson, K. and Graedel, T.E. 2005. Twentieth century copper stocks and flows in North America: a dynamic analysis. *Ecological Economics*, vol. 54, pp. 37-51.

Stanković, V. and Comninellis, C. 2011. RHODIUM RECOVERY AND RECYCLING FROM SPENT MATERIALS. The 9th European Symposium on Electrochemical Engineering, June 19 – June 23, Chania, Greece.

Sterman, J.D. 2000. Business dynamics: systems thinking. Irwin/McGrow-Hill

Stringer, E. 2014. Action Research. 4th Addition. Sage Publications Inc.

Sverdrup, H. U. and Ragnarsdottir, K. V. 2016. A system dynamics model for platinum group metal supply, market price, depletion of extractable amounts, ore grade, recycling and stocks-in-use. *Resources, Conservation and Recycling*, vol. 114, pp. 130-152. DOI: http://dx.doi.org/10.1016/j.resconrec.2016.07.011.

Swain, B., Kang L., Chinmayee, Mishra, C., Ahn, JW. and Hong,, H.S. 2015. Materials flow analysis of neodymium, status of rare earth metal in the Republic of Korea. *Waste Management*, vol. 45, pp. 351-360. DOI: https://doi.org/10.1016/j.wasman.2015.07.020

Thakker, R., Sarkani, S. and Mazzuchi, T. 2012. A system dynamics approach to demand and allocation of wireless spectrum for mobile communication. Procedia - Computer Science, vol. 8, pp. 118-123. DOI: http://dx.doi.org/10.1016/j.procs.2012.01.023.

UNEP. 2009. Critical Metals for Future Sustainable Technologies and their Recycling Potential. Sustainable Innovation and Technology TransferIndustrial Sector Studies

UNEP. 2011. Recycling Rates of Metals – A Status Report, A Report of the Working Group on the Global Metal Flows to the International Resource Panel.

USGS, USA database on raw materials. https://minerals.usgs.gov/minerals/pubs/commodity/platinum/stat/

WS. 2009. Making business on secondary automotive catalysts.The Waste Recycling. 2009, vol.1, pp. 6-7. (on russian)

Ziemann, S., Weil, M. and Schebek, L. 2012. Tracing the fate of lithium—The development of a material flow model. *Resources, Conservation and Recycling*, vol. 63, pp. 26-34.

APPENDICES

Appendix A

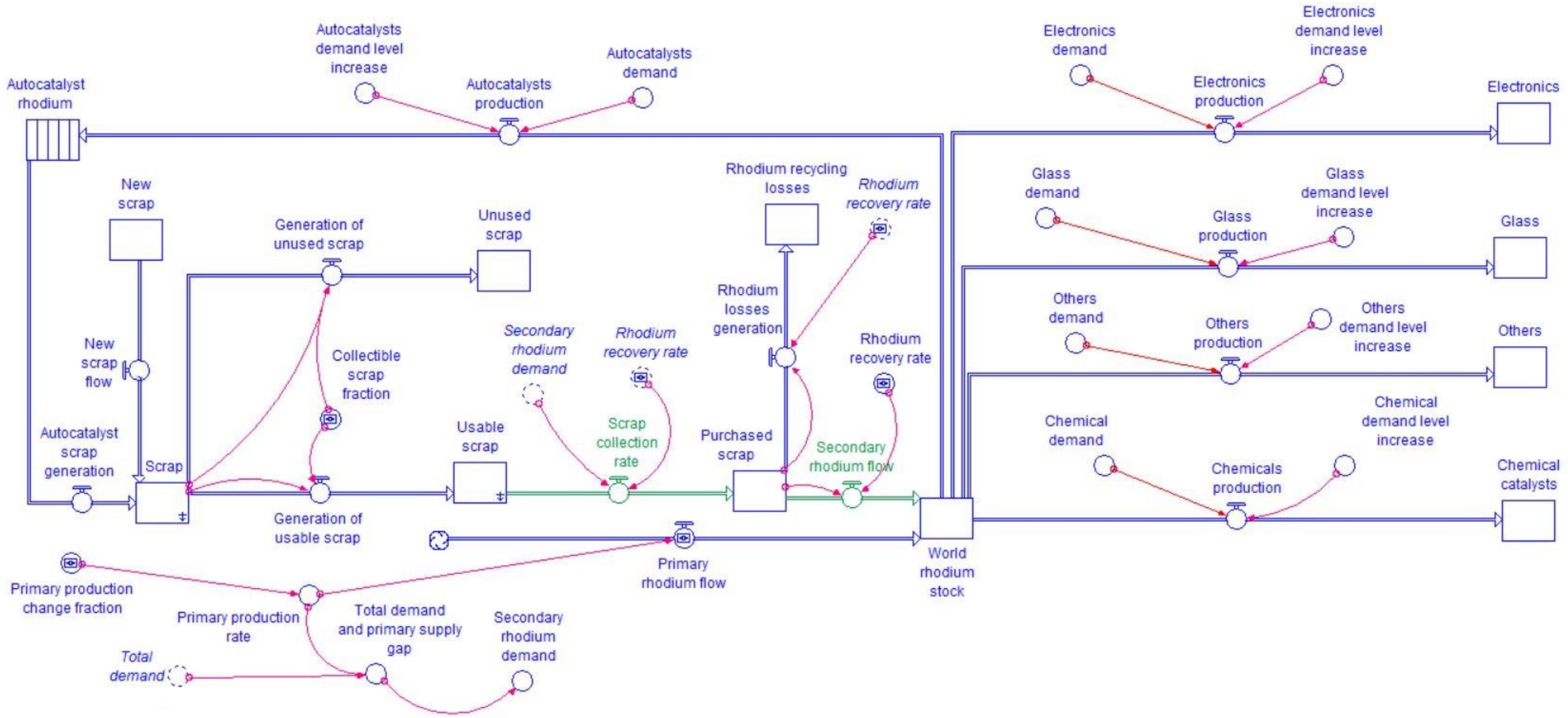

Figure A.1.1 – Dynamics material flow model

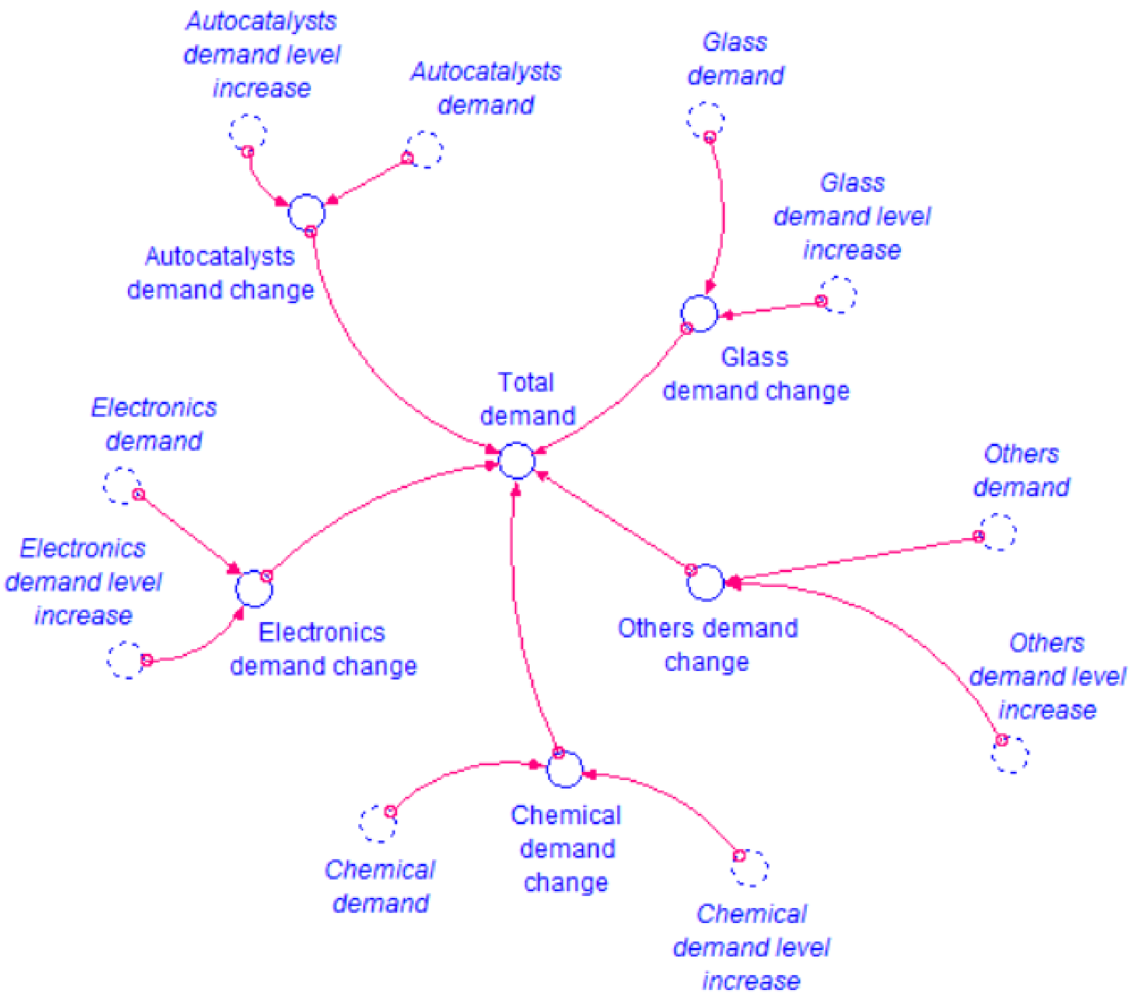

Figure A.1.2 – Dynamics material flow model (continued)

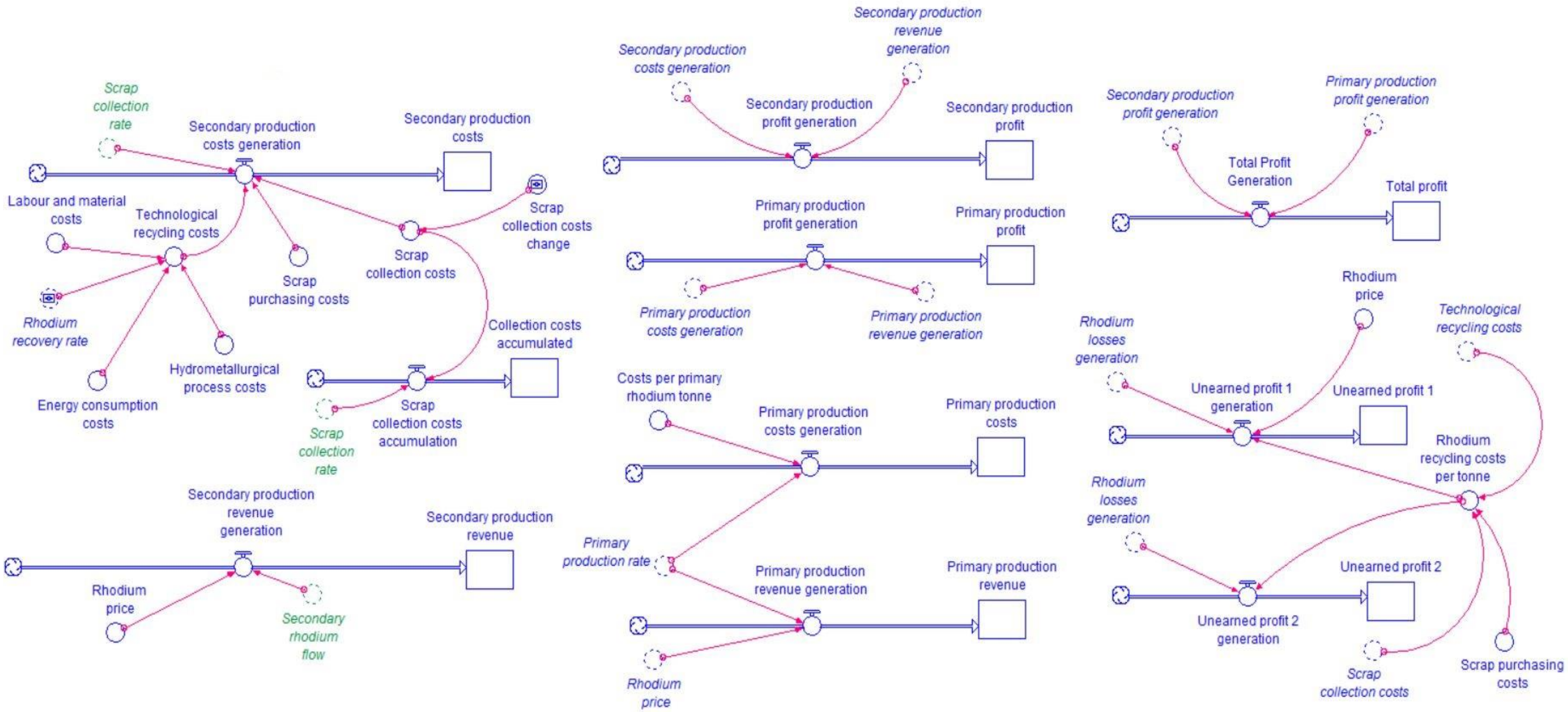

Figure A.1.3 – Dynamics material flow model (continued)

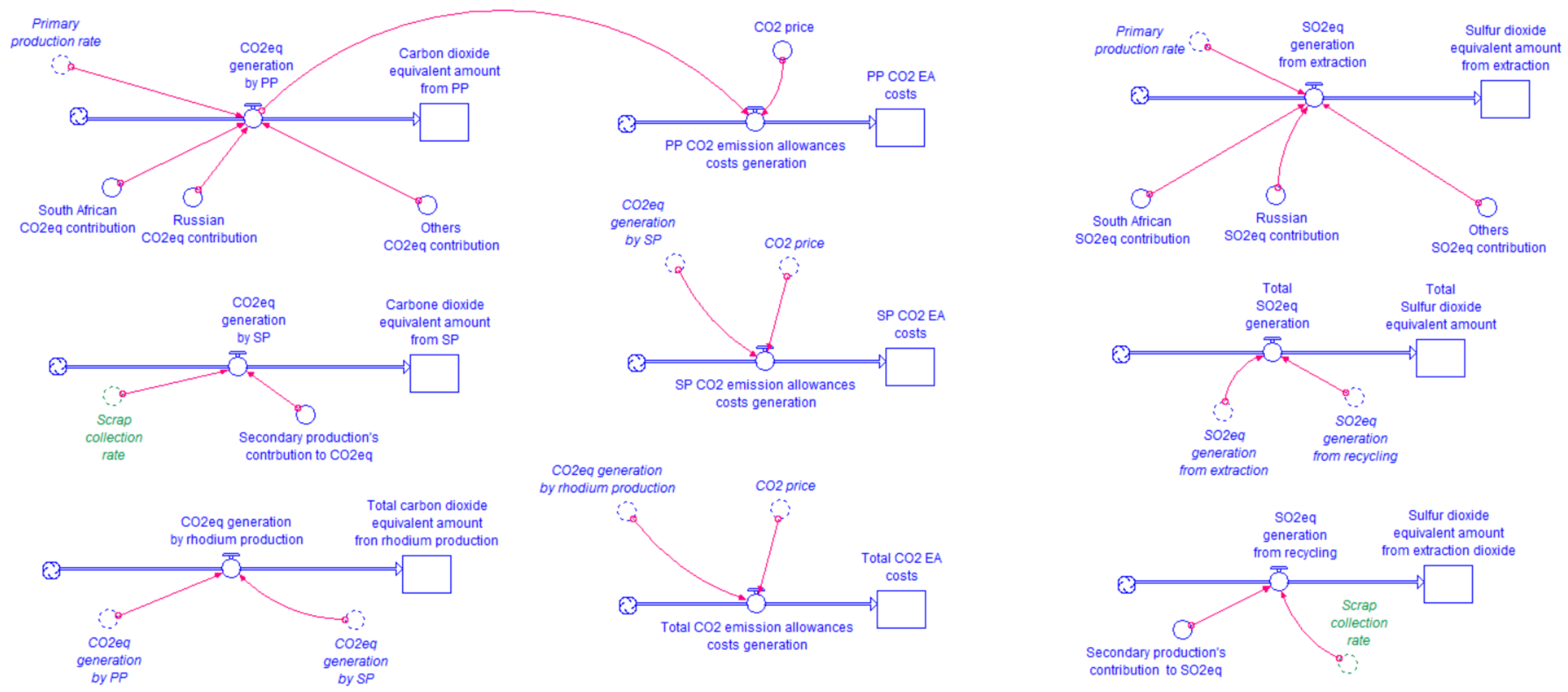

Figure A.1.4 – Dynamics material flow model (continued)