Deliverable D4.3

Case Studies

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Notice

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PURPOSE

Deliverable 4.3 *Case Studies* details case studies that use some of the methods outlined in D4.2 *Mapping of MICA methods to stakeholder questions*. This is in order to demonstrate how these methods can be applied to answer stakeholder questions as identified in D2.1 *Stakeholder report: identification & analysis*.

EXECUTIVE SUMMARY

The Mineral Capacity Intelligence Analysis (MICA) project and the MICA EU Raw Materials Intelligence Capacity Platform (EU-RMICP) aim to provide decision-making support and information for stakeholders in the raw materials field. For MICA work package 4 (WP4), the aim is to identify and describe methods and tools for answering stakeholder questions. Deliverable 4.1 *Factsheets of Methods for Raw Material Intelligence* includes a description and information about selected MICA methods and D4.2 *Mapping of MICA methods to stakeholder questions* analyses the appropriateness of the methods for addressing various stakeholder questions. In this report, D4.3 *Case Studies*, case studies are presented that illustrate the use of selected MICA methods to address common stakeholder questions. The case studies include the following 7 methods/stakeholder topics: (1) Dynamic material flow analysis, (2) Scenario development, (3) Trade, (4) Uncertainties, (5) Urban mining, (6) Computable general equilibrium models and (7) Criticality.

Case study 1: Dynamic material flow analysis (dMFA) demonstrates how this tool can be used for strategic decision-making for raw materials within both i) policy and ii) industry, using aluminum as a case. To illustrate the benefits of dMFA for industry, the first section of this case study showed how dMFA can be used to estimate future scrap amounts by alloy and type to identify the potential of current applications and identify effective interventions to open up new recycling pathways. This case study can answer stakeholder questions about forecasting of material flows, anticipating potential challenges, and evaluating strategies for addressing these challenges under different contexts.

Case study 2: Scenario development illustrates how scenarios can be developed for forecasting metal futures and estimating their associated environmental impacts. In this study, Life Cycle Sustainability Assessment (LCSA) was used to forecast how the impacts of 7 major metals, including aluminum, iron, copper, zinc, lead, nickel and manganese, will develop in the future and the magnitude of these impacts at a global level. This case study demonstrated how LCSA can be used to answer stakeholder questions about the environmental impacts of metals and the related future global consequences.

Case study 3: Trade describes the importance of tracking the movement of materials across borders for better understanding the flows of any one metal and the accumulation of in-use stocks in different regions. Because trade data are generally unavailable, this information has to be estimated. This study describes methods for estimating these data using copper as a case and answers stakeholder questions related to methods for geopolitics and supply chains.

Case study 4: Uncertainty recognizes the presence of uncertainty in any aspect of mineral intelligence and illustrates how uncertainty can be quantitatively dealt with, in particular, for material flow analysis. This study uses the rare earths in the EU-28 as a case and details two data reconciliation methods, their respective caveats and the preferable method depending on the specific case. This case study answers stakeholder questions related to the robustness of model results and data quality.

Case study 5: Urban mining shows how data and methods included in the MICA raw materials intelligence system can be used to answer stakeholder questions related to i) estimating the size of urban mines, ii) assessing the availability of these materials for secondary metal production and iii) determining how urban mines can be accessed. This study uses the urban mine of residential buildings in Amsterdam as a case and a combination of methods to detail the potentials and obstacles of analyzing urban mines. This case study answers stakeholder questions related to methods for assessing amounts, qualities, and accessibility of secondary resources of the future.

Case study 6: Computable General Equilibrium (CGE) models deal with the economic modelling of materials and, in particular, provide details on how CGE models can be modified to allow greater consideration of specific resources and can then be used to consider specific policies on resource efficiency and the circular economy. This study uses steel as a case and analyses the future of steel in China and how this will impact the EU. This case study answers questions related to the use of economic models for calculating material stocks and flows and related energy use and greenhouse gas (GHG) emissions.

Case study 7: Criticality, a common stakeholder topic, explores some key features of criticality assessments and discusses issues associated with undertaking such assessments. The current list of critical raw materials for the EU is used as an illustrative example. This case study answers stakeholder questions regarding the usefulness and limitations of different approaches to criticality assessments.

While the case studies presented in this report showcase the benefits of the MICA methods and how they can be used to answer stakeholder questions, they also illustrate that there are common challenges shared by all methodologies when applying them to raw materials. These challenges relate to: data availability/data quality, developing consistent system definitions, uncertainty within scenario development and modeling and stakeholder communication.

DELIVERABLE REPORT

1. Introduction

The supply of raw materials is essential for global prosperity and fulfilling the fundamental needs of humans. As raw material consumption grows and begins to outstrip supply, several challenges must be overcome in order to ensure equitable resource access for the global population. Resource challenges are often complex, multi-faceted and, thus, involve and require a variety of stakeholders for devising solutions. For stakeholders to solve these challenges in a sustainable manner, access to robust and comprehensive information and methods is essential. The aim of MICA is to provide an intelligence platform for answering questions and guiding stakeholders towards appropriate methods and information for addressing stakeholder needs.

Deliverable 4.1 *Factsheets of Methods for Raw Material Intelligence* has identified methods that can provide essential information for answering stakeholder questions and D4.2 *Mapping of MICA methods to stakeholder questions* have mapped these methods to the stakeholder questions identified in D2.1 *Stakeholder report: identification & analysis*. In this deliverable, a collection of case studies are presented that detail how select methods outlined in D4.2 have been applied to various raw material challenges. These case studies demonstrate how the methods can be used to answer several stakeholder questions.

This report, D4.3 *Case Studies*, identifies the following 7 case study topics, which include both identified MICA methods as well as common stakeholder challenges:

- Dynamic Material Flow Analysis
- Scenario Development
- Trade
- Uncertainties
- Urban Mining
- Computable General Equilibrium Models
- Criticality

In chapter 2, a combination of ongoing and completed research on these different methods/topics is presented in the form of case studies. Chapter 3 identifies common challenges met by practitioners when applying these methods and also presents conclusions and recommendations.

2. Case Studies

2.1. Dynamic Material Flow Analysis (dMFA) Case Study: Aluminum as an example

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2.1.1. Introduction

Material flow analysis (MFA) is a common tool used to map and quantify the metabolism of metals in the anthroposphere (Brunner and Rechberger 2004; Pauliuk and Müller 2013). MFA analyses have been conducted on a wide range of metals, e.g. silver (Johnson et al. 2005), chromium (Johnson, Schewel, and Graedel 2006), zinc (Graedel et al. 2005), iron (Rauch and Pacyna 2009) and nickel (Rauch and Pacyna 2009), and use a static approach that usually covers one year. Such assessments provide insight into the sources, sinks, consumption, recycling and losses of various metals. However, because of the complexity of metal stocks in the environment and anthroposphere, their long lifetimes and influence on metal flows, static MFA's provide little insight into the full dynamics of resource use. Dynamic material flow analysis (dMFA) is a method that was developed in recognition of the importance of in-use stocks and their long-term changes on material cycles. Stock dynamics are modeled in dMFA by including exogenous assumptions regarding the magnitude of in-use stocks, their lifetimes and composition, as well as the population and the population's lifestyle. Dynamic material flow analyses allow us to better understand the relationship between services, in-use stocks, emissions and the material and energy requirements of society (Müller 2006), which is essential to i) anticipate challenges regarding resource scarcity and environmental protection, ii) forecast energy and material use, and iii) estimate the availability, demand and quality of post-consumer scrap for recycling. Here, we describe two case studies that use dMFA for metals to elucidate on the aforementioned challenges: 1. Aluminum recycling from automotives and 2. Forecasting greenhouse gas (GHG) emission from the global aluminum stock.

2.1.2. Aluminum recycling from automotives: The cascading effect

The large diversity of aluminum alloys reaching end-of-life processes poses a significant challenge for recycling. This is due to the variable quality of secondary aluminum and the limited number applications for post-consumer scrap. In the case of automotive aluminum, research has shown that, by approximately 2020, the supply of automotive aluminum scrap will likely exceed the demand by the same sector due to the majority of aluminum recycling pathways favoring the lowest quality application (Modaresi and Müller 2012). However, automotive aluminum scrap contains a variety of alloys that could be used in alternative, higher-quality applications and these new recycling pathways would help to mitigate scrap surplus. In order to address this and identify promising aluminum recycling strategies for vehicles under the constraints of alloys, Løvik, Modaresi, and Müller (2014) developed a stock-driven dynamic MFA with a component, alloy, and elemental-level resolution. This model forecasted future scrap amounts by alloy and type to identify the potential current applications and effective interventions to open up new recycling pathways.

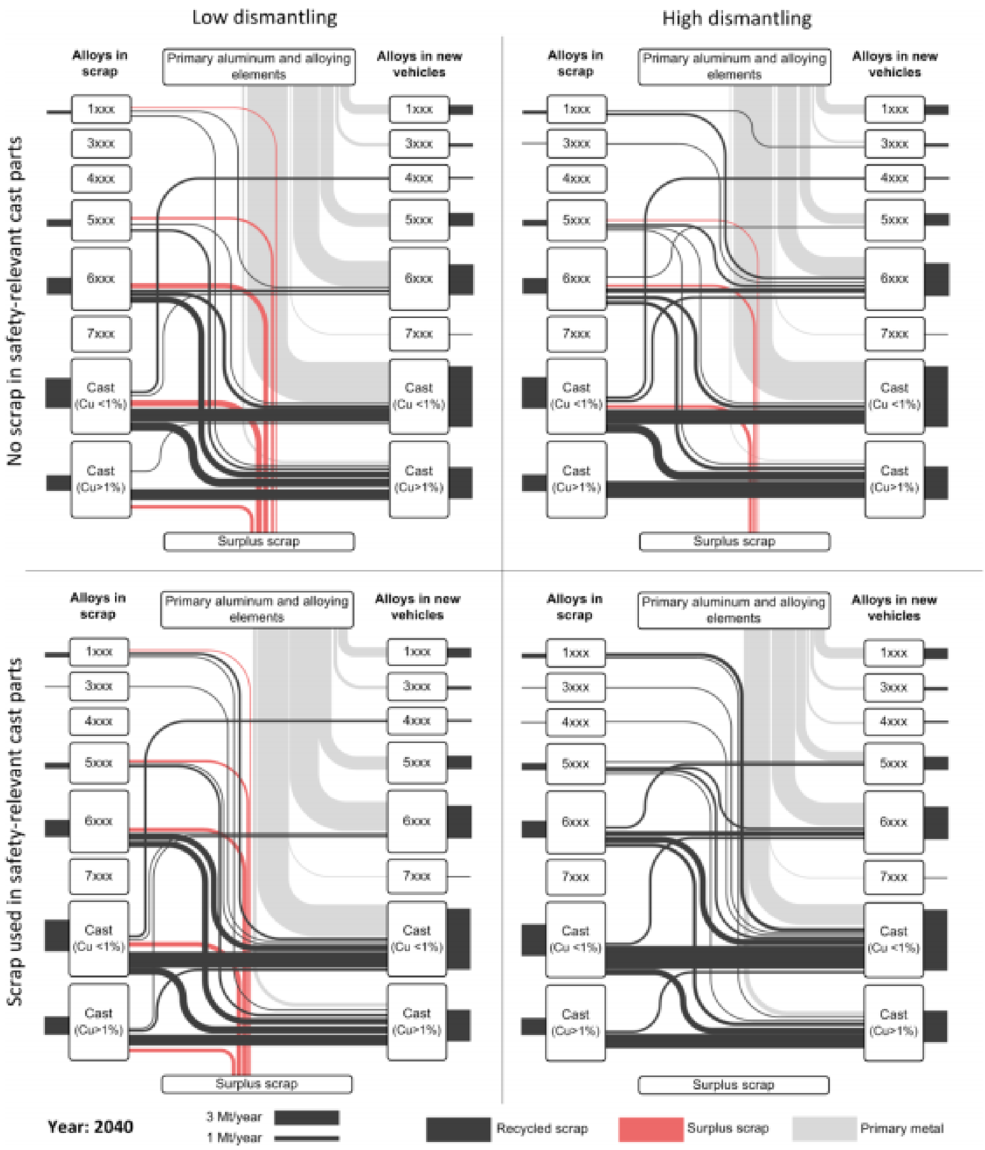


Figure 1 The automotive recycling cascade scenarios, where alloys are recycled into new alloys in 2040 (Løvik, Modaresi, and Müller 2014).

The findings from this study showed that recycling from end-of-life aluminum processes occurs via a cascading effect, where most scrap is utilized to produce a handful of alloys that have limited applications (Figure 1). This is primarily due to material mixing, which prevents closed-loop recycling due to the need for high quality aluminum with little contamination in other applications. As shown in the upper half of Figure 1, component dismantling and scrap sorting could help to decrease the amount of alloy blending and introduction of impurities and, thus, delay the onset of automotive aluminum scrap surpluses. However, the limitation of using secondary aluminum in safety cast parts, such as wheels, is a key development that, without, makes it difficult to avoid scrap surpluses. Therefore, the authors identified the following priorities that should be considered in order to efficiently increase automotive aluminum recycling: i) component dismantling before shredding, ii) closed-loop recycling of safety cast parts, and iii) technologies that automate scrap sorting (Løvik, Modaresi, and Müller 2014).

2.1.3. Forecasting future global GHG emissions based on aluminum stocks

Humanities currently face the dual challenge of satisfying the rapid growth of global material demand while, simultaneously, reducing carbon emissions. A particularly large factor in successfully meeting these two targets is navigating the path dependency of the built environment stocks, the long-term scrap availability due to the decommissioning of these stocks and the resulting emission pathways. Using a stock-driven dMFA approach, Liu, Bangs and Müller (2012) aimed to assess this challenge for the global aluminum cycle in order to i) determine how the aluminum industry could achieve, by 2050, a 50% decrease in emissions relative to 2000 values and ii) identify the most efficient mitigation strategies considering aluminum stock patterns.

The authors found that current aluminum recycling is dominated by pre-consumer scrap (Figure 2). This is an inefficiency in the manufacturing process that leads to increased emissions and an overall higher aluminum demand. While this allows manufacturers to boast high recycling rates, post-consumer scrap recycling [primarily in the form of beverage cans and vehicles] is the only method that can significantly reduce energy consumption and emissions. Furthermore, this study found that GHG emissions caused by the current global aluminum cycle are primarily due to primary production, e.g. smelting, mining and refining. Therefore, the above manufacturing inefficiency is a large driver of aluminum associated GHG emissions.

In-use aluminum stocks and their patterns of development set fundamental limitations to future GHG emission pathways. Figure 3 shows that the level at which aluminum stocks saturate and when, determines future material demand and the associated emissions. According to the results of this study, mitigation options should focus on reducing the aluminum emission intensities and decarbonizing electricity. However, in the long-term, reduction potentials are expected to be dominated by recycling, due to stock saturation and the related post-consumer scrap generation. Because, today, strategies tend to focus on the former, it is essential that technologies are developed quickly to meet the narrow window of opportunity during stock development and saturation (where electricity really counts). Nonetheless, meeting the emission target of a 50% reduction in the aluminum industry compared to 2000 levels by 2050 can only be achieved by a combination of rapid technological development, high recycling rates and a low per capita stock saturation amount. Therefore, to mitigate the global aluminum cycle's GHG emissions, it is essential to focus on material efficiency in addition to traditional energy efficiency strategies.

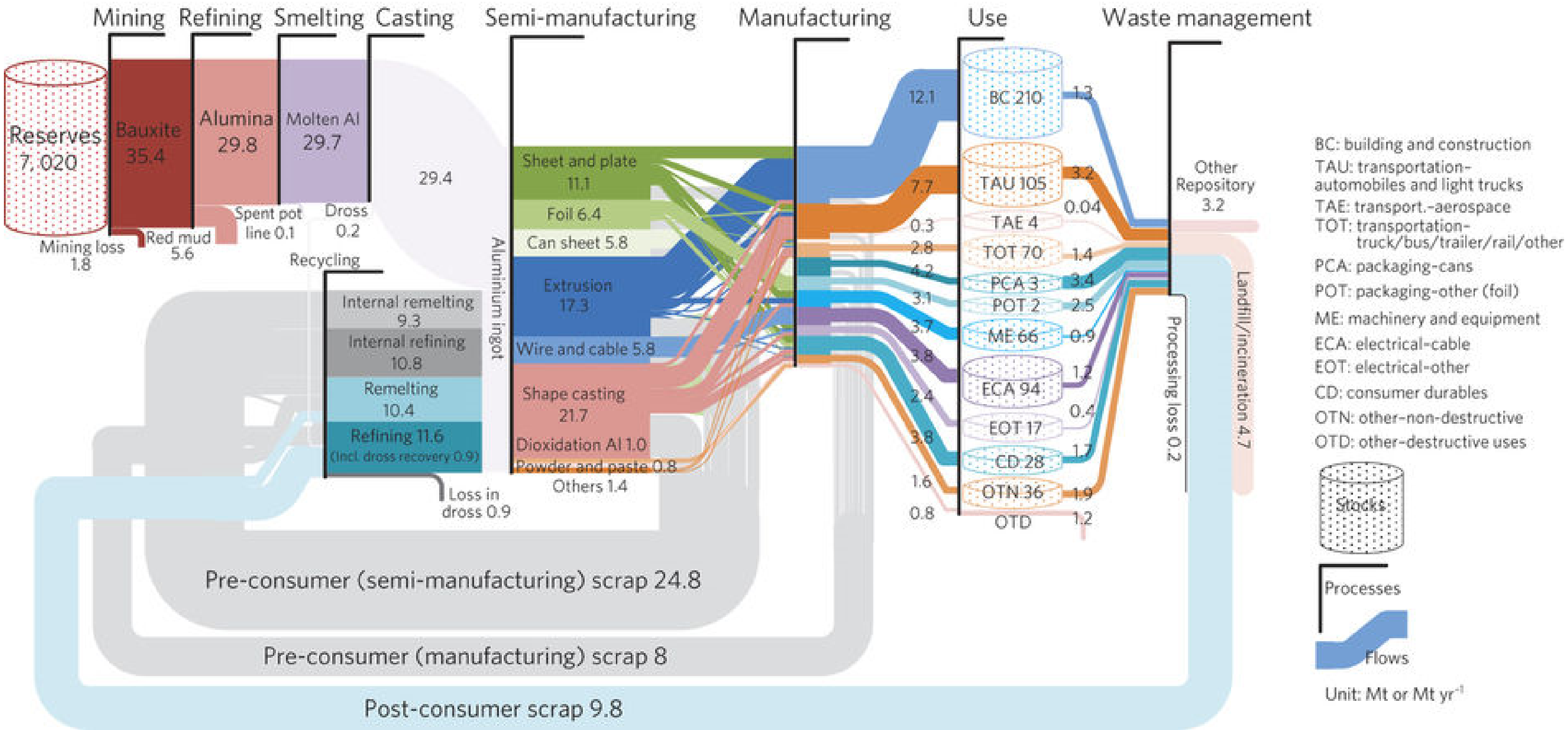
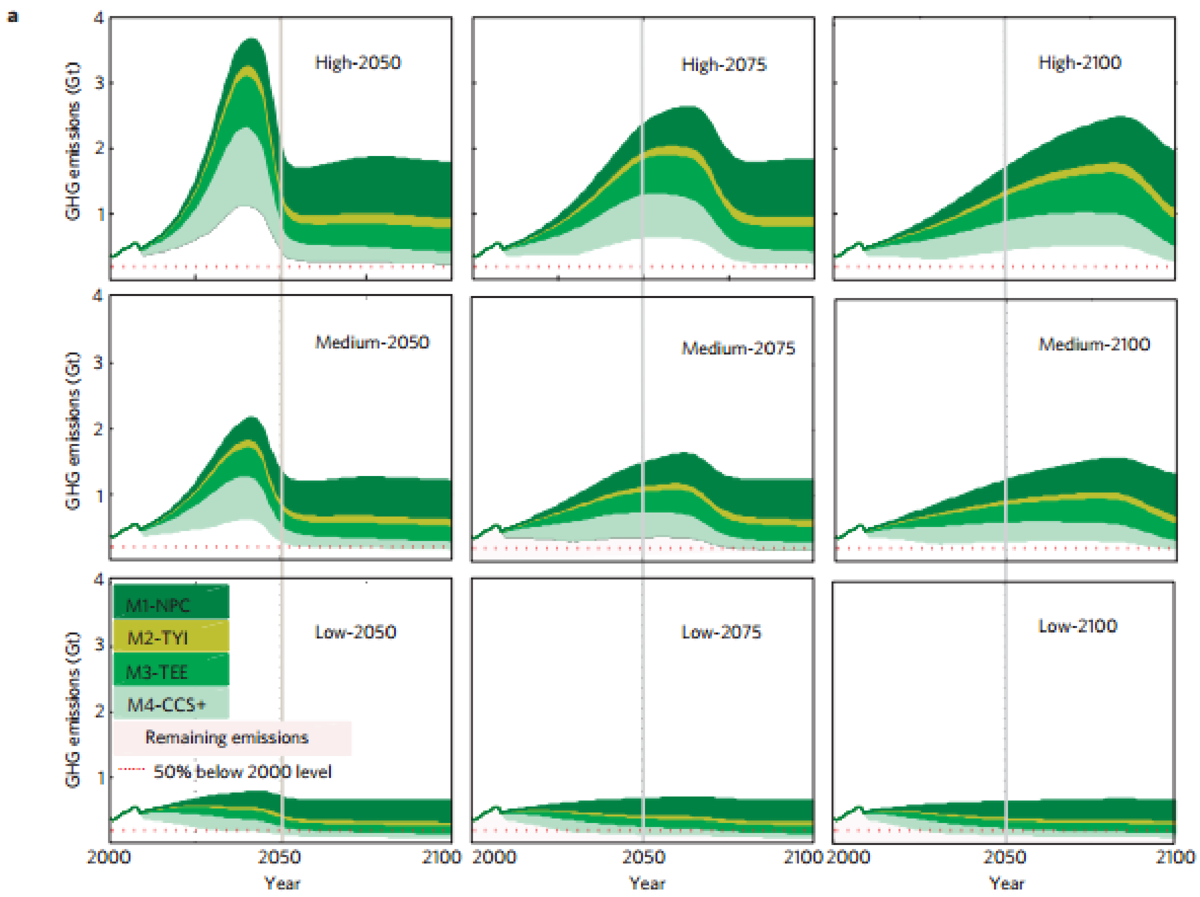


Figure 2 The global anthropogenic metallurgical aluminum cycle, 2009, in megatonnes or metatonnes per year of aluminum equivalents (Liu, Bangs, and Müller 2012).



b

	Emissions (2050/2000)			Acc. emissions (Gt, 2010–2050)			Max. reduction (%, 2000–2050)		
	S-2050	S-2075	S-2100	S-2050	S-2075	S-2100	S-2050	S-2075	S-2100
S-High	5.7	6.5	4.7	86.0	52.5	41.9	27%	77%	22%
S-Medium	3.8	4.1	3.4	56.6	39.9	35.1	-21%	2%	-17%
S-Low	2.0	1.9	1.7	27.6	24.3	23.3	-63%	-64%	-65%

Figure 3 Emission pathways for the global aluminum cycle under 9 dynamic stock scenarios, low, medium and high stock saturation levels (a.) and their associated emissions (b.)

2.1.4. Discussion and Conclusions

Dynamic material flow analysis is a powerful tool that can be used for strategy development for i) mitigating pollution, ii) anticipating resource challenges and iii) improving resource recycling. While this case study illustrated the use of dMFA for strategy development for aluminum, this method can be applied to any mineral, particularly for estimating the future availability of secondary materials. Nonetheless, the robustness of dMFA results is dependent on the availability of high quality raw data. Therefore, in order to develop reliable strategies based on this method, availability to robust data is key. Data can be obtained from industry statistics (e.g. the International Aluminium Institute), statistical offices (e.g. the Food and Agriculture Organization and the United Nations Environmental Programme) as well as government/industry reports. However, this data is rarely reported using a systems context and, therefore, substantial efforts are required to interpret and appropriately include data in dMFA models.

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2.2. Scenario Development Case Study: Environmental impacts of metal scenarios

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This work has been accepted by the Journal of Industrial Ecology.

2.2.1. Introduction/motivation

This case study refers to stakeholder questions related to the environmental impacts related to metal production and how these may develop in future.

The case study shows how data and methods included in the MICA raw materials knowledge system can be used to answer the following questions:

1. What are the cradle-to-gate environmental impacts of metal production, per kg metal?
2. How may these impacts develop in the future?
3. What are cradle-to-gate impacts of metal production at the global level, as a result of both changes in demand and supply, and in per kg impacts?

2.2.2. Methods and data

The method used to answer these questions is Life Cycle Sustainability Assessment (LCSA). Life Cycle Sustainability Assessment is a framework method, i.e. it outlines a procedure rather than pointing at one specific methodology (Guinée, 2016). It is, however, life cycle based. It builds on the LCA methodology but expands to cover higher scale levels, larger time horizons and other impacts besides environmental ones. In this case, we limit the scope to cover environmental impacts, but upscale to the global level and expand towards 2050.

The method is described in Van der Voet et al. (2017). It contains the following elements:

- Demand scenarios of seven major metals: iron, aluminium, copper, zinc, lead, nickel and manganese, for 2010-2050. These demand scenarios are provided by Elshkaki et al. (2016, 2017) and are obtained by dMFA. They were taken as the starting point for this case study.
- Supply scenarios of these seven metals. In order to assess environmental impacts it is important to know via what technologies these metals are produced. A distinction between primary and secondary production is essential, but also between the various routes of primary production. The translation from demand scenarios into supply scenarios has been made based on past trends projected into the future (Kuipers, 2016; Verboon, 2016).
- Assessment of the environmental impacts of the production of 1 kg metal in the present situation. This was done with the LCA method, performed using the CMLCA[1] software (Heijungs, 2012) and using the CML-IA[2] impact assessment (Guinée et al., 2002).
- Adapted environmental impacts of 1 kg of metal for a series of future years, still using LCA. For that, we accounted for changes in the foreground system (energy efficiency improvements and ore grade decline), changes in the ratio primary / secondary production, and changes in the background system, especially the energy system, under different assumptions of progress on the road of the transition towards a renewable energy system.
- Environmental impacts of global metal supply, obtained by simple multiplication.

Databases used were the following:

- Past time series primary production data for the seven metals: the British Geological Survey (BGS) database on metal production and trade;

[1] CMLCA is scientific software for LCA, IOA, EIOA, and more, it is developed by the Institute of Environmental Sciences, Leiden University

[2] CML-IA is a database that contains characterisation factors for life cycle impact assessment and is easily read by the CMLCA software program

- Secondary production data we took from Elshkaki et al. (2017) as they provided these with the demand scenarios;
- Information on the different production routes: this was taken from various literature sources (Kuipers, 2016; Verboon 2016);
- Unit process data for the background system, and in some cases the foreground system as well, was taken from Ecoinvent v2.2;
- Data on the global energy mix have been taken from International Energy Agency (IEA). We used the World Energy Outlook (WEO) energy scenarios for time series 2010-2035, and extrapolated linearly into the future to cover the period until 2050;
- Impact assessment data were taken from the CMLIA database v4.8 (2016);
- Time series data on the efficiency of production processes have been taken from Worldsteel (2016) and World Aluminium (2016). The past curve has been assumed to continue into the future unchanged. For the other metals, we have not included this aspect due to lack of data.
- Time series data on ore grades for copper, zinc, lead and nickel have been taken from various publications (Crowson, 2012; Mudd et al., 2013; Mudd & Jowitt, 2013; Mudd, 2010), and again the developments have been extrapolated into the future (Northey et al., 2014).
- The relation between ore grade and energy use have been taken from literature sources as well (Norgate & Haque, 2010; Norgate & Jahanshahi, 2006; Valero et al., 2011). For iron, aluminium and manganese we could not find evidence of declining ore grades.

We are aware of the large uncertainties. Time series data on metal primary production are fairly well available. The same can be concluded with regard to energy. However, much of the additional information, essential for the calculation of environmental impacts, is lacking or only available in a haphazard manner.

We are also aware of the wealth of information available at the metal production branch organisations and research institutions. Some have made these available, others haven't. This refers to efficiency and ore grade data, but also to unit process data for purposes of LCA studies.

2.2.3. Results

Despite uncertainties and missing data, the results of this case study are still interesting and relevant. A sample of the results is shown in Figure 4. As an indicator, GHG emissions are shown, but in fact a variety of impacts have been assessed using these methods and databases.

Figure 4 shows the difference in GHG per kg metal for the seven metals, as well as the difference between primary and secondary production. In Figure 5 we show the changes over time due to the assumptions made for two different demand scenarios: Markets First (a Business as Usual scenario) and Equitability First (a scenario including rapid economic development of developing countries, and advancing energy transition).

The differences in GHG emissions/kg between the two scenarios are considerable and again show most markedly for aluminium and manganese. In the Equitability First scenario, the energy transformation appears to have clear benefits for the more electricity intensive metals. For iron, there is not much change in any of the scenarios.

Figure 6 shows what happens if these per kg impacts are multiplied with demand.

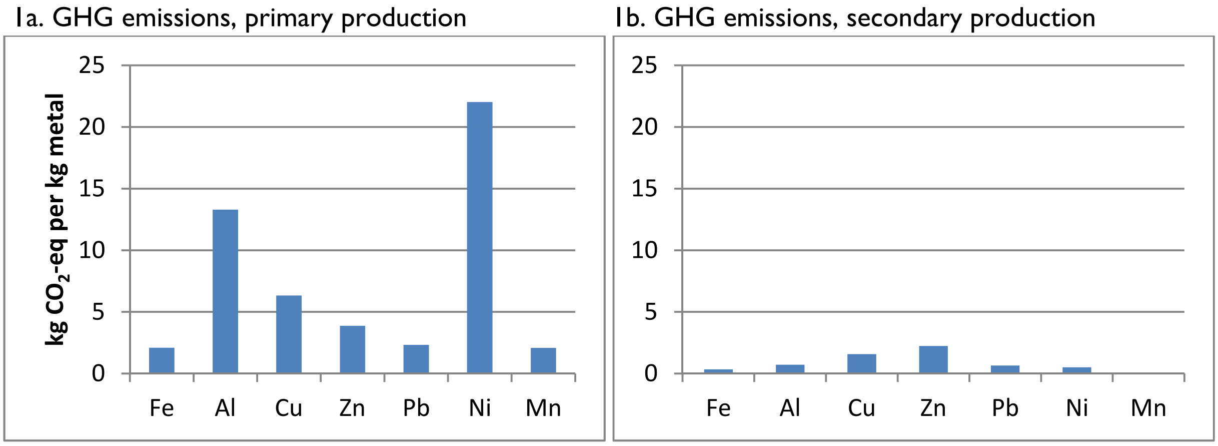

Figure 4 GHG emissions per kg produced metal in 2010 (numbers for iron, nickel and manganese include steelmaking).

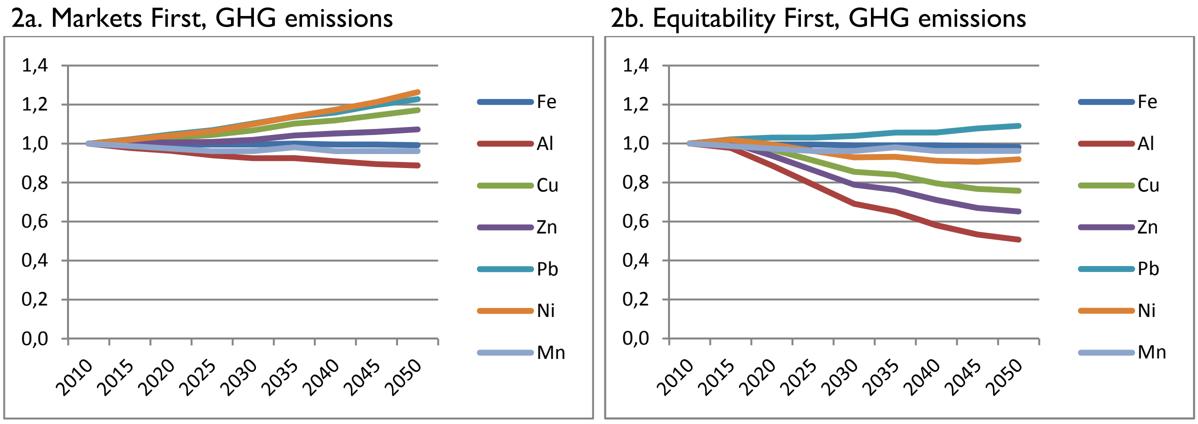

Figure 5 Relative changes over time in per kg GHG emissions of primary produced metals.

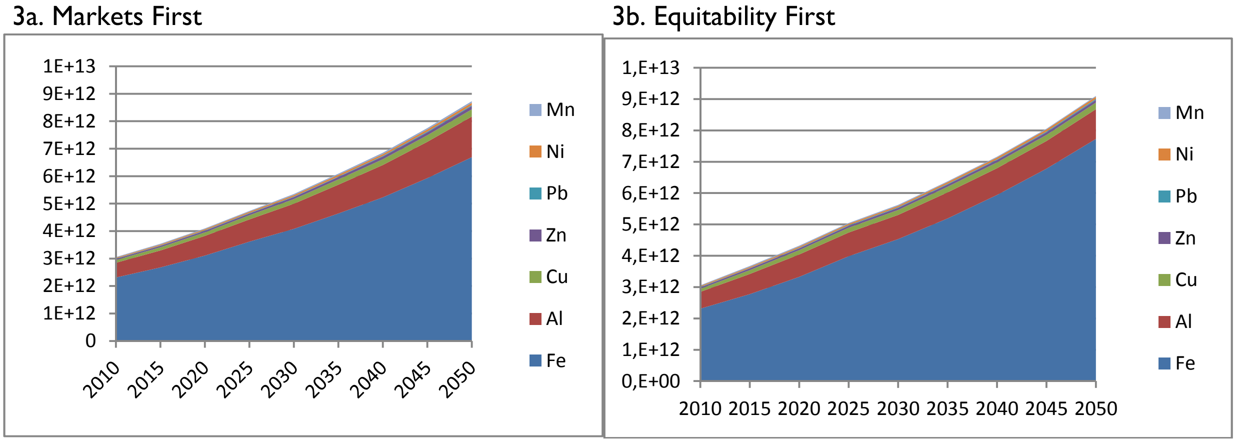

Figure 6 Greenhouse gas emissions related to the production of seven metals under Markets First and Equitability First scenarios, 2010-2050.

Comparing these results with the demand scenarios, we see that GHG emissions rise together with production. The Equitability First scenario with the highest demand growth also has the highest level of emissions. It appears that the considerable improvements in the per kg impacts under the Equitability First scenario are more than offset by the demand increase.

Despite the relatively very low per kg impact of iron, the sheer production size compared to all other metals makes iron dominant even in GHG emissions. Due to the fact that the transition towards a renewable electricity system has relatively little benefits for iron, the demand growth trend is only slightly mitigated by the reduced emissions per kg. Leaving iron out, we see that for the other metals the increase in GHG emissions is considerably less than the increase in demand.

The conclusion of this case study is that if metal use is not explicitly addressed in resource policies and strategies, it will rise considerably over the next decades. Environmental impacts will rise as well. The energy transition will bring benefits with regard to GHG mitigation, but those benefits will have little influence on GHG emissions from metal production. For the dominating metal iron, these emissions are process inherent and will change only when novel, carbon free steelmaking processes are developed, or when demand is to a large extent fulfilled by secondary production. This is not expected to happen before 2050, but may occur after that.

2.2.4. Interpretation/discussion

To answer the questions stated in Section 2.2.1, it has been necessary to use a number of methods and a variety of data. We conclude the following:

- Not just data on metal production, but also data on production processes, their efficiency, their emissions and the developments in those processes over time is required to answer these stakeholder questions. Such data are not standardly available.
- Data on ore grades and ore grade decline are becoming available slowly but the database is still incomplete.
- Data on secondary production are only sparsely available.

- Consistent data on the urban mines, the source of future secondary material, are missing altogether.

The MICA platform does not create data, but guide towards such data. It seems to be essential in this rapidly developing field that the MICA platform is not just a repository for data but also for published literature, in the scientific journals as well as in the grey literature. Many of the data for this case study were taken from literature, not from established databases.
For the background system, data on energy should be a part of the MICA platform, as this appears to be essential for a variety of reasons. There may be more of such data, not directly minerals related but important for the interpretation and framing of mineral related questions. It may be beneficial for the MICA project to pay some dedicated attention to this issue.

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2.3. Trade Case Study: Estimation of metal flows embedded in international trade

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References to other case studies/other areas of the MICA platform are colored blue

2.3.1. Introduction/motivation

The mining of raw materials, their transformation into useful products and the use of those products does not usually happen all within the borders of one country. Instead, mining is linked to the availability of ore deposits for a particular raw material, the transformation of mined ores into metals may or may not take place on site, and the use of those metals, either as metals or embedded in end-use products, is generally distributed globally. Therefore, it is important to track the movement of materials across borders in order to better understand flows of any one metal and the accumulation of in-use stocks in different regions.

Unfortunately, for this purpose, these data are generally not directly available beyond a certain life-cycle stage and must be estimated indirectly (→ Method: Material Flow Analysis/Substance Flow Analysis; Case Studies: dMFA, Parameter uncertainty in MFA, Urban Mining Inventory). This note discusses such an estimation based on reported trade statistics.

2.3.2. Methods and data

Trade across borders is recorded by customs offices and reported using well-defined goods classification schemes. Examples of these classification schemes include the Combined Nomenclature (CN, used by EUROSTAT), the Standard International Trade Classification (SITC) and the Harmonised System (HS). Both the HS and CN (which follows the structure of the HS) are more detailed than SITC. Though none of these classifications are detailed enough to trace all metals (e.g. some specialty metals are classified together), they are useful in many cases. These classifications are periodically revised and updated in order to keep up with the changing nature of traded goods, with new codes being added, obsolete codes being deleted, and codes being merged or split. Moreover, there are correspondence tables published to translate data reported using one classification into other classifications or into earlier/later versions of the same classification (e.g. UN 2010a). Trade data reported as described above are available from national customs offices, from EUROSTAT and from the United Nations, often free of charge but sometimes with certain limitations (see e.g. Eurostat 2016; UN 2015).

There are some important decisions to make when estimating flows of metals across borders based on these data. First, the geographical focus of the investigation must be defined. For example, the interest may be on trade relationships of individual countries such as Australia, Italy or Japan, or trade within a group of countries such as OECD members, or between EU-28 countries and the rest of the world. Secondly, a primary data source needs to be selected fitting this geographical focus. If the EU is the focus of the investigation, EUROSTAT data (Eurostat 2016) is probably a good choice whereas data directly from the General Administration of Customs (GACC 2016) may be preferable if China is the focus. The UN Commodity Trade Statistics Database (Comtrade, UN 2015) is a commonly used data source as it receives and harmonizes data from almost 200 countries and areas (UN 2010b). Having chosen the geographical focus of the investigation and a suitable data source, a decision must be made as to which classification of goods and which version of it to use when extracting the data – this will determine the time coverage and time resolution of the data as well as the degree of detail available in terms of number of different trade codes.

As trade figures are reported both for imports and exports, there is in theory a built-in consistency check. However, there are often misalignments between the reported figures such that users are forced to decide which figures to trust (imports vs. exports) or whether to use an average of both. In addition, there may be delays in reporting, such as when a shipment leaves a country in one year but arrives at its destination the following year, or when the origin/destination of trade flows is obscured by intermediary countries. In some cases, it may be necessary to correct the figures in other ways, such as when obvious input errors find their way into the data tables (usually factors of 10, in this case trade between two countries/regions suddenly appears to be 10-1000 times larger/smaller, cf. discussion in Tercero Espinoza & Soulier 2016).

Finally, a decision has to be made as to which commodities to include in the analysis and how to account for their metal content. For example, trade figures might account for "Motor vehicles for transport of persons (excluding buses)" without further distinction. It is clear that the material content of a small, two-seat vehicle is different from that of an SUV. Other differences in material content might include the use of batteries and electric motors compared with the use of internal combustion engines in hybrid vehicles. Thus, it becomes necessary to define "a statistical car" with an estimate of its raw material content of interest (e.g. magnesium, steel, lithium or neodymium), and these estimates may be different depending on the year and trade flow (i.e. imports vs. exports). Considerable effort including stakeholder consultation is invested when preparing such tables of metal content for different trade codes, and these remain a major source of uncertainty.

To exemplify the use of trade data to follow metal flows across borders, we use the UN Commodity Trade Statistics Database (UN 2015) and copper as an example. The analysis and results shown follow Tercero Espinoza et al. (2016) and Tercero Espinoza & Soulier (2016).

2.3.3. Results

Taking the appropriate steps as outlined above, it are possible to trace flows of copper across borders distinguishing between concentrates (the result of mining and beneficiation), copper metal, semi-finished products (e.g. copper tube) and finished products (e.g. air conditioning units). The results for the year 2010, between six arbitrarily defined world regions, are shown in Figure 7.

Since trade data are available for a series of months or years, it is also possible to explore trends of individual commodities or groups of commodities (e.g. "semi-finished products"). Figure 8 shows this for copper concentrate from 1992 to 2014. In addition, summary figures could be constructed using the same data for copper in all trade flows, i.e. the sum of arrows in Figure 7 and the flows of copper scrap (not shown).

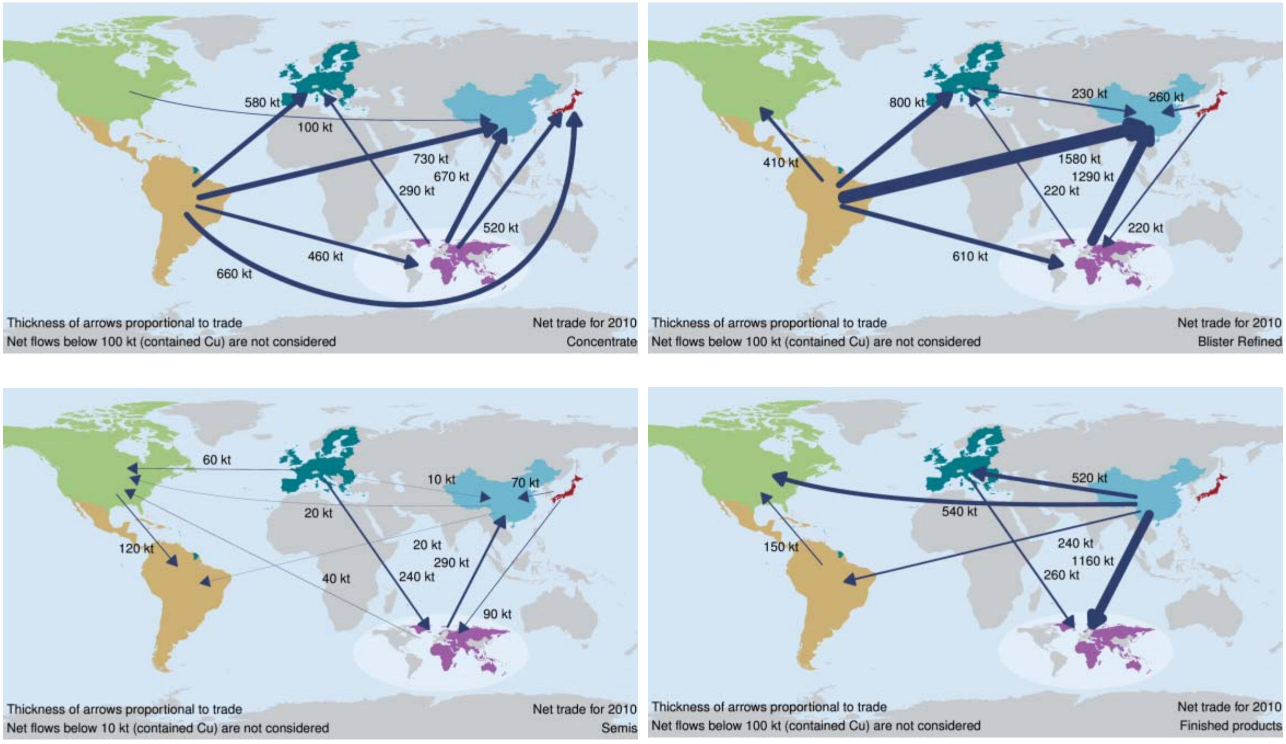

Figure 7 Global net flows of copper in concentrates (top-left), as metal (top-right), in semi-finished products (bottom-left) and in finished products (bottom-right) between North America, Latin America, Europe (EU-28), China, Japan and the Rest of the World in the year 2010. Note that the arrows depict net trade flows (the sum of imports and exports) between each pair of regions in thousands of metric tons (kt) contained copper. The arrows are scaled in the same way and are therefore directly comparable between figures. See similar figures for other years in Tercero Espinoza & Soulier (2016).

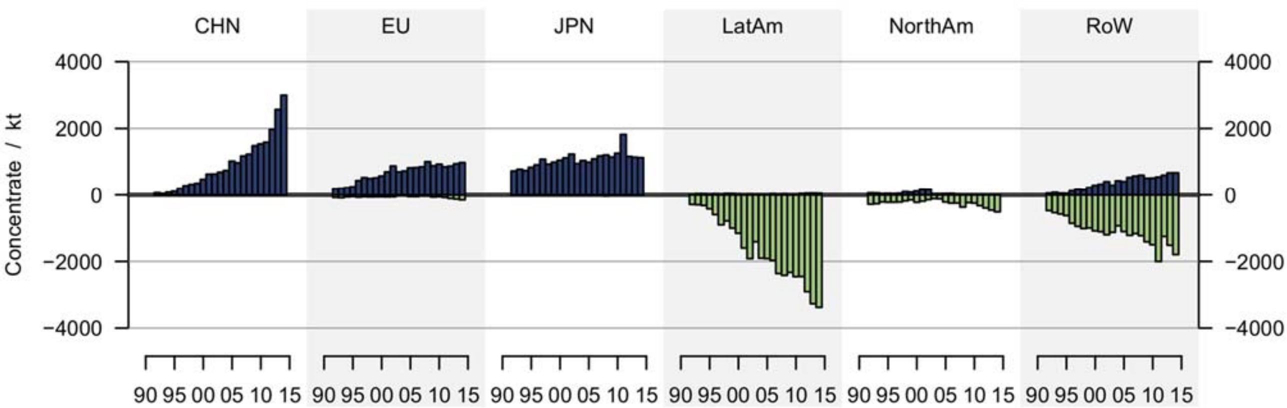

Figure 8 Trends in imports and exports of copper concentrates in the six world regions are defined graphically in Figure 7. Imports are depicted as positive and coded dark blue; exports are depicted as negative and colored green. The vertical axes are in thousands of metric tons (kt). Figure modified from Tercero Espinoza & Soulier (2016).

2.3.4. Interpretation/discussion

The visualization of copper flows shown in Figure 7 provides an overview of the global sources of copper and copper-containing products. It is immediately evident that Latin America and, to a lesser extent, the Rest of the World (RoW) are the most significant global sources of copper concentrates and metal. A difference in the pattern of trade flows (concentrate vs. metal) is also apparent. For example, the arrows for concentrate are more evenly distributed than those for metal (Figure 7 top-left vs. top-right). Latin America was a net exporter of copper concentrates (in the order of several hundred thousand metric tons) to the EU-28, China, Japan and the Rest of the World in 2010. In contrast, net exports of copper metal from Latin America were concentrated towards China (over one-and-a-half million vs. several hundred thousand metric tons). In a similar fashion, metal exports from the Rest of the World were also mostly directed towards China. North America mostly imported copper as metal but only imported minor quantities of copper in concentrate; in fact it was a minor exporter of this.

Also apparent from Figure 7 is that international trade in copper semi-finished products (bottom-left) is less pronounced than concentrates, metal and finished products. This highlights the importance of regional markets for these goods.

The picture is essentially reversed when considering copper contained in finished goods (Figure 7, bottom-right). Here, China is the main exporter to all other regions considered.

The data also allow an examination of each region and its position in the copper and copper-containing value chains. For example, Europe imported concentrates and metal, mostly from Latin America. Together with mined copper and recycled copper in Europe, this is used to make semi-finished and finished products. Europe is a major net exporter of copper semi-finished goods, albeit at the low-levels characteristic of this stage in the value chain. At the same time, Europe is a net importer of finished goods, which come mostly from China. Combining the arrows shown in Figure 7, and considering European copper mining (→ pointer to mining data) and recycling (→ pointer to recycling data), it is evident that Europe continues to "accumulate copper". A similar analysis could be made for each of the regions shown in Figure 7, or for any region defined any other way provided similar data are available.

Since raw material markets, like most other markets, change with time, it is instructive to examine trends over longer time periods. Figure 8 shows imports and exports of copper concentrate from 1992 to 2014 for the same regions described above. The numbers shown in Figure 7 are but a snapshot of Figure 8 and also do not show that there may be imports and exports between regions (cf. RoW). Conversely, the visualization in Figure 8 does not differentiate between trade partners. However, the underlying data are in principle available (cf. Methods and data) and tailored analyses may be performed depending on the questions being asked.

The time series shown in Figure 8 reveals that Latin America was not always the principal world supplier of copper concentrates, nor was China always the largest importer. Instead, in the early 1990s, Japan was the largest importer of copper concentrates and the Rest of the World was the main supplier, with Latin and North America also contributing substantially. The picture has changed drastically since then. China became the largest importer of copper concentrates at the beginning of the current decade and growth in imports continues to surpass that of the next two largest importers (i.e. Europe and Japan) combined. Europe has also increased its imports to similar levels to Japan, but at a much slower pace than China. At the same time, Latin America has emerged as the largest exporter of copper concentrates, now surpassing exports from North America and the Rest of the World combined. While exports from North America have remained essentially stable, exports from the Rest of the World have increased substantially, but then so have imports.

Equivalent analyses may be made for copper metal, semi-finished products and finished products (cf. Tercero Espinoza & Soulier 2016), or for other metals provided appropriate estimates of metal content for the relevant trade codes are available.

In summary, flows of metals across national borders are recorded directly only at certain stages of the supply and value chains (e.g. unwrought metal or metal semi-fabricated goods such as tubes and plates) but not explicitly for finished products (e.g. TV sets and vehicles). Nevertheless, reasonable estimates of these figures are accessible through a combination of trade data; decisions and assumptions (cf. Methods and data). The generated cross-border metal flow estimates may be used in the preparation of regional MFA (→ Method: MFA/SFA; Case Studies: dMFA, Parameter uncertainty in MFA) and top-down estimates of anthropogenic stocks (cf. Case Study on Urban Mining Inventory), or "resources" for future recycling. In addition, valuable insights on global markets and competitiveness as well as dependencies in raw material supply at different stages of the respective value chains might be gained from examination of international trade data alone, or in combination with other information.

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2.4. Uncertainties Case Study: Parameter Uncertainty in Material Flow Analysis

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2.4.1. Introduction

As emphasized in the MICA factSheet on "*Parameter uncertainty in mineral intelligence analysis*", uncertainty is an unavoidable aspect of mineral intelligence. The case study herein addresses the particular issue of parameter uncertainty treatment in material flow analysis (MFA), with a particular focus on rare earths in the EU-28. The methodology of MFA (see factSheet "*Material and Substance Flow Analysis*") was largely developed in the sixties to study the "urban metabolism" (Wolfman, 1965) and later applied by e.g. Ayres (1989, 2001) to industrial metabolism. Baccini and Brunner (1991) extended the domain of application to the anthroposphere; i.e., the portion of the geosphere that is influenced by human activity. More recently, the Yale group (Graedel and co-workers) have extensively applied MFA to mineral raw materials and in particular to so-called critical metals (e.g., rare earths, cobalt, tungsten, etc., see Chen and Graedel, 2012 for a review). Laner et al. (2014) present an overview of uncertainty treatment in MFA. In this factsheet, the issue is addressed with particular reference to the two fundamentally distinct types of uncertainty; i.e., random variability versus epistemic uncertainty (Ferson and Ginzburg, 1996).

It is reminded that an essential basis for MFA is the principle of conservation of mass. The sum of flows entering a system must equal the sum of flows leaving this system, plus variations of stock within the system:

$$\sum_{i=1}^{n} IN_i = \sum_{j=1}^{m} OUT_j + \Delta S \qquad \textit{Equation 1}$$

where:
IN_i is inflow i (mass per unit time);
OUT_j is outlow j (mass per unit time);
ΔS is variation of stock (mass).

In general, by convention, if the sum of outflows exceeds the sum of inflows, the variation of stock is negative (the system has released mass). In the opposite case the variation of stock is positive (the system has stocked mass).

2.4.2. Reconciliation in MFA

The most important (and time-consuming) step in MFA is data collection (see MICA factSheet "*Material and Substance Flow Analysis*") regarding the various flows in the system. In most situations, estimated inflows, outflows and stocks do not initially satisfy Eq. (1) (conservation of mass), in which case the analysist uses some form of data reconciliation. The traditional approach to data reconciliation (Narasimhan and Jordache, 2000) assumes that data come from measurements and that measurement errors follow a Gaussian distribution with zero average and a diagonal covariance matrix. The precision of each measurement *F* (understood as a mean value) is characterized by its standard deviation ($\square_i$). Data reconciliation is then performed by minimizing an objective function. Considering the simple case of a process with *m* entering flows and *n* exiting flows (with respective averages F_i and standard deviations $\square_i$; i=1..m+n) and designating initial estimators for the reconciled flows as F_i*, reconciliation is obtained by minimizing the following objective function:

$$\chi^2 = \sum_{i=1}^{m+n} \left[\frac{1}{\sigma_i} \left(F_i - F_i^* \right) \right]^2 \qquad \textit{Equation 2}$$

under the constraint that the sum of flows entering the process equals the sum of flows exiting the process (mass conservation):

$$\sum_{j=1}^{m} F_j^* = \sum_{k=m+1}^{m+n} F_k^* \qquad \textit{Equation 3}$$

Several MFA tools (e.g. *STAN*; Brunner and Rechberger, 2004) perform this type of calculation. A drawback of the methodology in the context of MFA is related to the fact that in practical situations of MFA projects, available information often does not justify a representation of flows using single Gaussian distributions. Information is typically incomplete and/or imprecise and therefore other tools for representing uncertainty may be preferred to single probability distributions. The MICA factSheet "*Parameter uncertainty in mineral intelligence analysis*" presents such alternative tools.

A practical tool for representing incomplete/imprecise information, especially coming from experts, is the well-known min-max interval. But as shown in the uncertainty factsheet, an expert may have information that allows him/her to express preferences within the interval. This yields the so-called possibility distributions (or fuzzy numbers) that are illustrated in Figure 5 of the uncertainty factsheet. Assuming information on flows and stocks in MFA are represented by possibility distributions, reconciliation under fuzzy constraints can be performed using the method of Dubois et al. (2014).

To illustrate this method, Figure 9 shows the simple case of a single process with one inflow, one outflow and no stock. As seen in Figure 9, the inflow and outflow are affected by uncertainty. There are two ways of viewing this uncertainty:

(i) the indicated values are preferred values within the intervals, resp., [45; 55] and [50;70]

(ii) the indicated values are the mean values of Gaussian distributions with standard deviation, resp., 5 and 10.

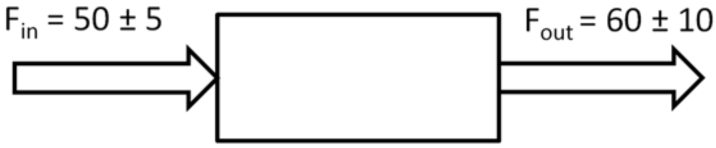

Figure 9 Single process with one inflow, one outflow and no stock.

Assuming the first interpretation, reconciliation is obtained by identifying the values that satisfy mass conservation and flow membership information (see Dubois et al., 2014). As illustrated in Figure 10, these conditions are satisfied for all values located within the intersection between the two possibility distributions: i.e. the interval [50; 55] with a "preferred" (most possible) value of 53.3. A value of e.g. 48 is not possible, as it does not lie within this intersection.

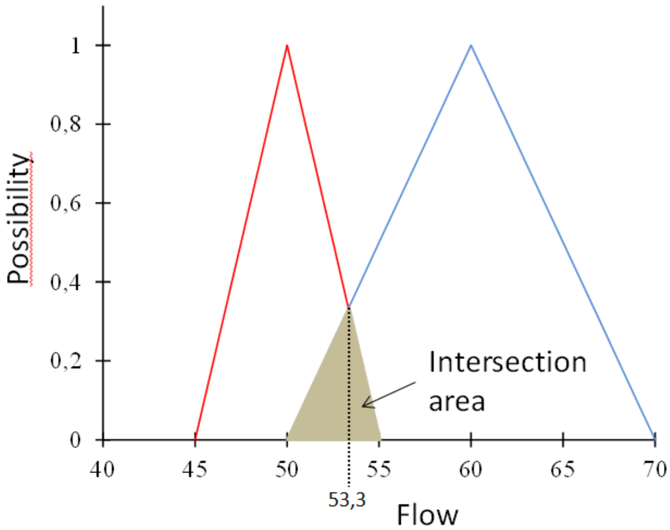

Figure 10 Schematic illustration of reconciliation under fuzzy constraints.

Considering now the second interpretation and applying equation (2) and (3) yields a reconciled flow of mean 52 and standard deviation 4.5. In this simple example, the two interpretations of uncertainty and their ensuing treatment yield very similar results, but this is not always the case. In particular if there were large discrepancies between estimates of inflow and outflow, the first method might indicate that it is not possible to find an intersection: either the model or the flow estimates are erroneous. On the other hand the second method will always yield a result because Gaussian probability distributions are defined over the interval [-∞; +∞]: a solution will be found albeit in areas of very low probability. This may be a problem in the case of outliers (erratic values) and therefore tools such as *STAN* incorporate checks to verify that the reconciled "solution" is not too remote from initial estimates.

2.4.3. Application: rare earths in the EU-28

From 2011 through 2015, the ASTER project on rare earth flows and stocks in the EU-28 (see Guyonnet et al., 2015) was led by BRGM in partnership with Solvay, BIO by Deloitte and the University of Toulouse, with the support of the French Research Agency (ANR). Consistent with the standard MFA procedure, the system under investigation was first defined and then information regarding individual flows was collected. For the case of neodymium in magnet applications, the defined system is depicted in Figure 11.

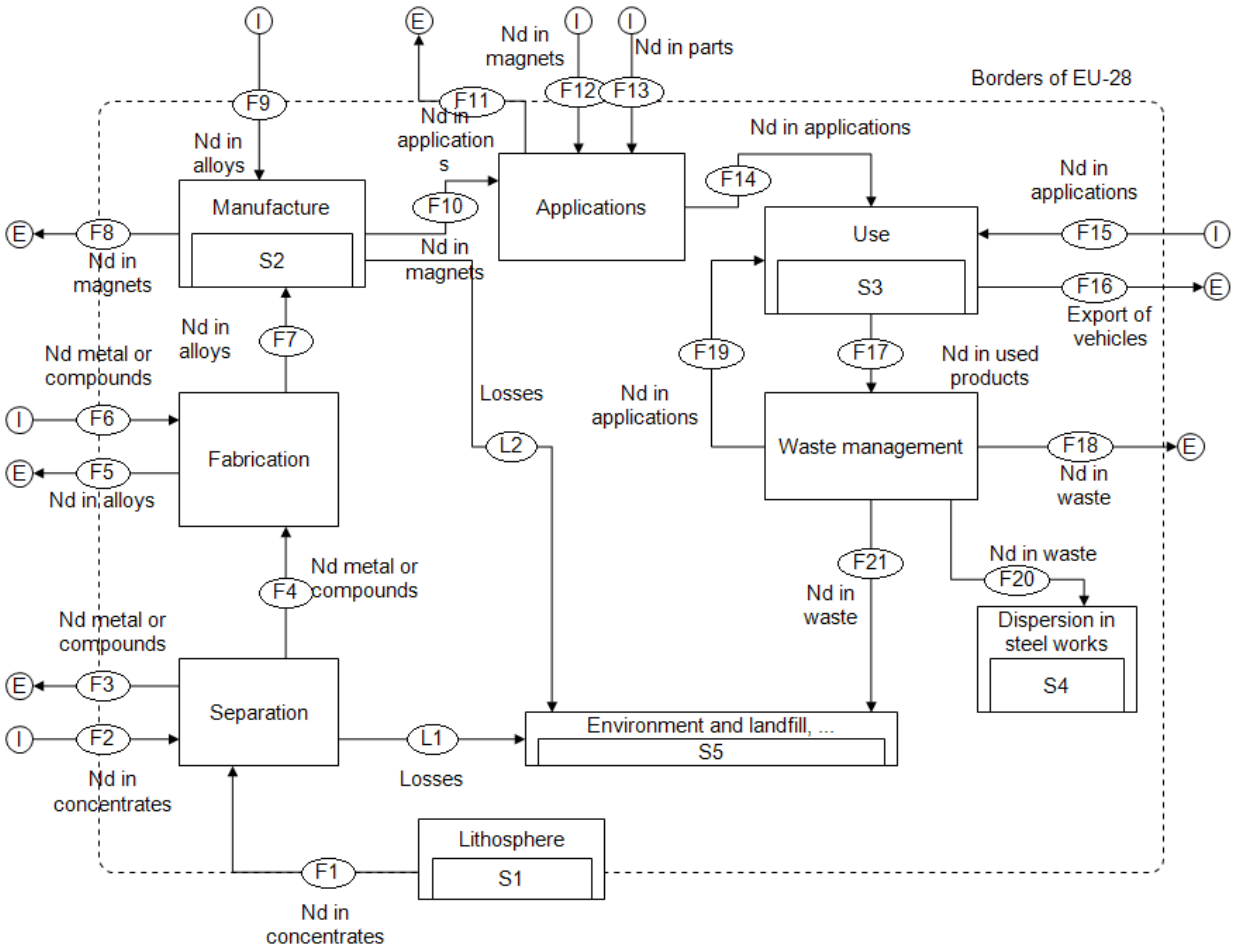

Figure 11 System investigated for the case of Neodymium in magnet applications. Notes: F = flow; L = loss; I = import; E = export; S = stock variation.

The applications considered in the analysis can be seen in Table 1.

Data sources included statistical databases (e.g. import, export and production data from EUROSTAT, World Trade Atlas, USGS, BGS, …), specialized reports (e.g., ROSKILL, company reports, …), data published in the literature regarding (i) quantities of rare earth elements (REEs) in components used in applications, (ii) weights of these components in applications and (iii) quantities of applications sold or used per year as reported by manufacturers, expert information, etc. An invaluable source of information in this study was Solvay's knowledge of the REE markets. The experts participating in the project were asked to provide estimates for flows, not as single values, but instead to:

- provide an interval which, based on their analysis, must include the actual flow value;
- express a preference within this interval.

Table 1 Neodymium-containing applications considered in this study.

Applications using NdFeB permanent magnets	Applications using NiMH batteries
Electric and Non electric vehicles	Portable batteries (rechargeable batteries):
Hard drives	- Cameras
Cell phones	- Electric shavers
Laptops and desktops	- Cell phones and cordless phones
Wind turbine generators (REE magnet-based)	- Laptops
MRI machines	- Handheld tools
Refrigerators	- Remote-controlled toys
Washing machines	- Emergency lighting equipment
Air conditioners	Industrial batteries:
Cameras	- Hybrid vehicles (HEV)
Headphones and earphones	- Electrical aircraft systems
CD player	- Satellite pinpointing systems
Fax, printers, scanner	
Shavers and electric epilators	

While the experts provided estimates for flow intervals, they expressed the preferred values at the center of the intervals. The resulting data are presented in Table 2. The year investigated is 2010.

Table 2 Values from the data mining with experts (tons Nd metal, year 2010).

Flow/Stock	Min value	Max value	Preferred value	Flow/Stock	Min value	Max value	Preferred value
F1	100	300	200	F15	300	400	350
F2	2	10	6	F16	250	450	350
F3	150	250	200	F17	500	650	575
F4	5	25	15	F18	12	20	16
F5	40	70	55	F19	3	5	4
F6	150	250	200	F20	350	450	400
F7	120	220	170	F21	150	190	170
F8	2	10	6	S1	-100	-300	-200
F9	150	200	175	S2	70	120	87
F10	150	250	200	S3	180	400	290
F11	220	350	285	S4	300	500	400
F12	550	650	600	S5	150	260	205
F13	200	450	325	L1	5	15	10
F14	750	1000	875	L2	25	40	32.5

Notes : F = Flow ; S = stock ; L = losses; Data from Guyonnet et al. (2015).

The reconciliation of this data is presented below using the two methods illustrated above. It is reminded that each method corresponds to a distinct interpretation of the indicated uncertainty: imprecision in the first method, and random variability in the second method. For the second method, values were defined by considering that:

- the preferred value in Table 2 is a “mean” value;

- the ranges between the mean and the min values (or max values) represent 3 standard deviations (i.e., 99,7% of the data in a normal distribution).

2.4.4. Reconciliation

Results of the reconciliation under fuzzy constraints (Dubois et al., 2014) yields the values shown in Table 3.

Table 3 Flows and stocks of Nd in the EU-28: results of reconciliation under fuzzy constraints (tons Nd metal, year 2010).

Flow/Stock	Support		Optimal core	Flow/Stock	Support		Optimal core
	min	max			min	max	
F1	150	288	215.8	F15	300	400	351.3
F2	2	10	6.4	F16	250	450	358.5
F3	150	250	198.7	F17	515	650	579.8
F4	5	25	14.5	F18	12	20	16.1
F5	40	70	55.7	F19	3	5	3.9
F6	150	250	202.8	F20	350	450	393.2
F7	120	220	161.8	F21	150	190	166.6
F8	2	10	6.6	S1	-150	-288	-215.8
F9	150	200	173.3	S2	70	120	88.3
F10	150	250	208.0	S3	180	400	282.3
F11	220	350	285.0	S4	350	450	393.2
F12	550	650	605.0	S5	180	245	207.6
F13	200	450	337.6	L1	5	15	9.0
F14	750	1000	865.6	L2	25	40	32.0

Notes : F = Flow ; S = stock ; L = losses

The optimal core values are represented in the Sankey diagram below, that can be seen in Figure 12.

The input data for reconciliation using the second method is shown in Table 4. It is reminded that "mean" values are the same as the "preferred" values of Table 2.

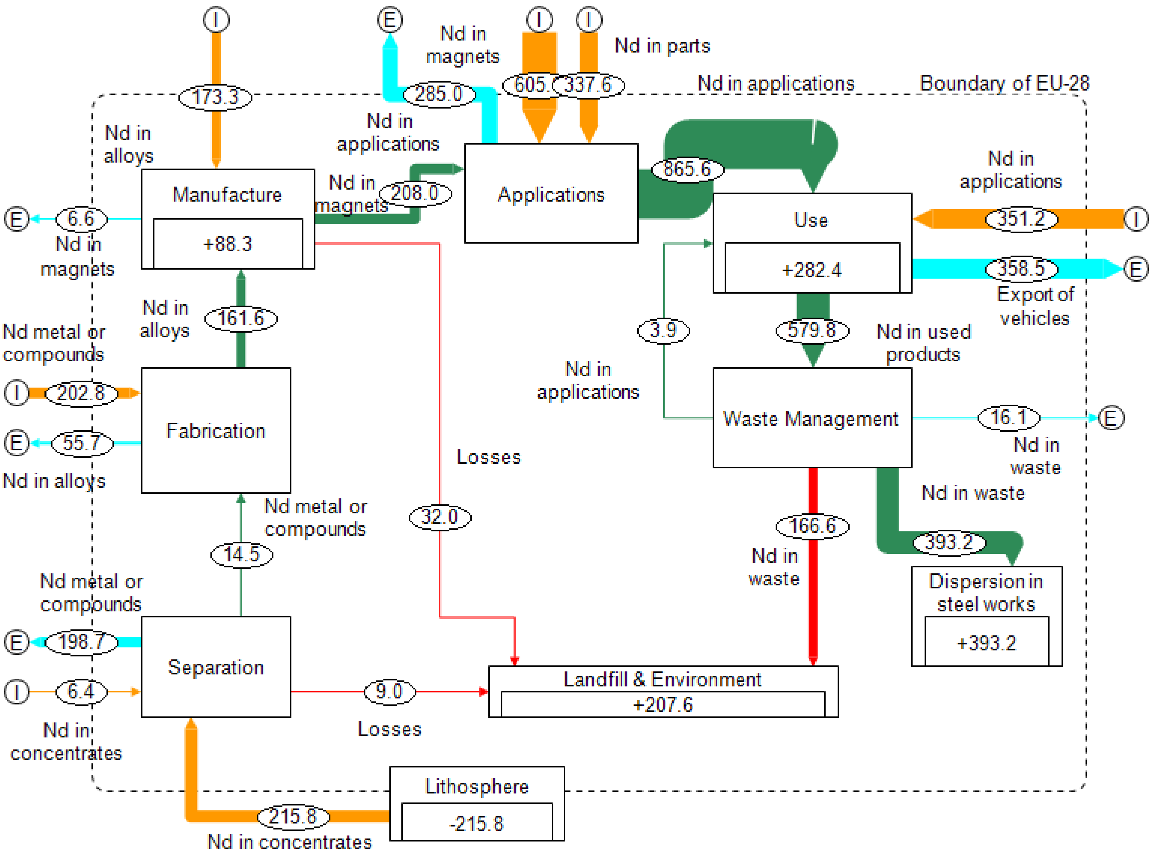

Figure 12 Sankey diagram with values from reconciliation under fuzzy constraints (tons Nd metal, year 2010, diagram built with STAN).

Table 4 Input for least-squares reconciliation.

Flow/Stock	Mean	Sigma	Flow/Stock	Mean	Sigma
F1	200	33.3	F15	350	16.7
F2	6	1.3	F16	350	33.3
F3	200	16.7	F17	575	25.0
F4	15	3.3	F18	16	1.3
F5	55	5.0	F19	4	0.3
F6	200	16.7	F20	400	16.7
F7	170	16.7	F21	170	6.7
F8	6	1.3	S1	-200	33.3
F9	175	8.3	S2	87	5.7
F10	200	16.7	S3	290	36.7
F11	285	21.7	S4	400	33.3
F12	600	16.7	S5	205	18.3
F13	325	41.7	L1	10	1.7
F14	875	41.7	L2	32.5	2.5

Notes : F = Flow ; S = stock ; L = losses

Results of the reconciliation are presented in Table 5 and graphically in the Sankey diagram of Figure 13.

Table 5 Results of least-squares reconciliation.

Flow/Stock	Mean	Sigma	Flow/Stock	Mean	Sigma
F1	215.2	15.2	F15	350.0	16.7
F2	6.0	1.3	F16	350.0	33.3
F3	196.2	14.9	F17	584.9	14.6
F4	15.0	3.3	F18	16.0	1.3
F5	54.6	4.9	F19	4.0	0.3
F6	204.8	12.2	F20	395.6	14.0
F7	165.2	12.2	F21	169.3	6.5
F8	6.0	1.3	S1	-215.2	15.2
F9	175.0	8.3	S2	99.6	22.1
F10	202.2	16.2	S3	280.6	51.7
F11	281.3	20.5	S4	395.6	14.0
F12	602.2	16.2	S5	211.8	7.2
F13	338.5	32.7	L1	10.0	1.7
F14	861.5	32.7	L2	32.5	2.5

Notes : F = Flow ; S = stock ; L = losses

2.4.5. Conclusions

In this specific example, the two reconciliation methods yield very similar results. As seen in Table 6 values differ by 0.3 to 12.8%. A basic question that should be addressed by the investigator at the data mining stage is: "*does the uncertainty in this data arise from random variability or from the incomplete/imprecise character of my knowledge regarding these parameters?*" If the answer is the latter, then representing the information using intervals (with or without preferences) may seem more "natural" than using means and standard deviations; hence the method of reconciliation under fuzzy constraints proposed by Dubois et al. (2014) can be applied.

As mentioned previously, the least-squares reconciliation method will always yield an answer and in some cases this may be misleading because the reconciled values may have very low levels of probability. The fuzzy-constraint method is less "robust" in the sense that it may fail to provide an answer. But this is an indication of inconsistency in the flow values or in the system structure and therefore the investigator needs to reexamine the data further.

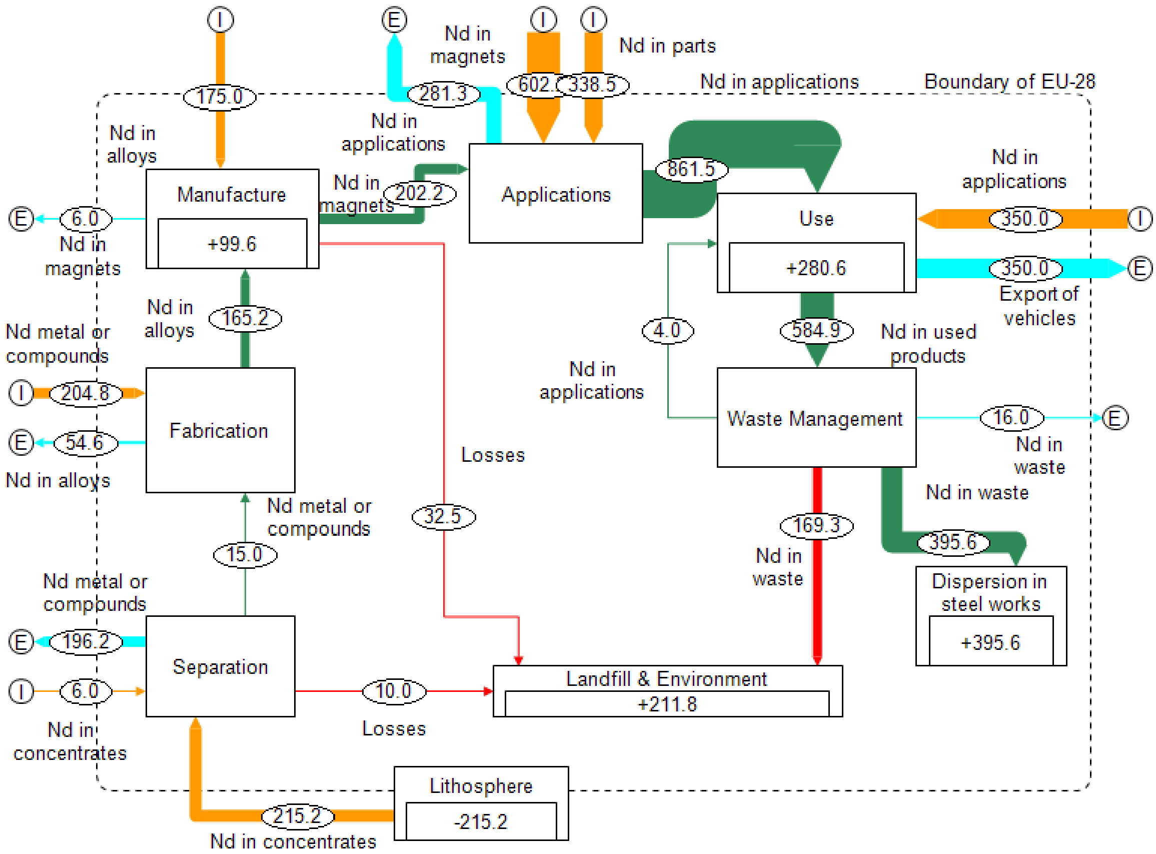

Figure 13 Sankey diagram for values from least-squares reconciliation (tons Nd metal, year 2010, diagram built with STAN).

Table 6 Percent differences between results from the two methods.

Flow/Stock	% difference	Flow /Stock	% difference
F1	0.3%	F15	0.4%
F2	6.3%	F16	2.4%
F3	1.3%	F17	0.9%
F4	3.4%	F18	0.6%
F5	2.0%	F19	2.6%
F6	1.0%	F20	0.6%
F7	2.1%	F21	1.6%
F8	9.1%	S1	0.3%
F9	1.0%	S2	12.8%
F10	2.8%	S3	0.6%
F11	1.3%	S4	0.6%
F12	0.5%	S5	2.0%
F13	0.3%	L1	11.1%
F14	0.5%	L2	1.6%

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2.5. Urban Mining Case Study: Prospecting the urban mine of Amsterdam

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2.5.1. Introduction/motivation

This case study refers to stakeholder questions related to urban mining and the circular economy. It has been conducted by a consortium including Leiden University, Delft University of Technology, De Waag Society and Metabolic. It was one of the projects of the AMS organisations, called PUMA: Prospecting the Urban Mine of Amsterdam. The report of this study (Van der Voet et al., 2017) is available from the AMS website.

This case study shows how data and methods included in the MICA raw materials intelligence system can be used to answer the following questions:

1. How large is the urban mine of residential buildings in Amsterdam with regard to copper and steel?
2. When will these materials be available for secondary metal production?
3. How can the urban mine be accessed?

2.5.2. Methods and data

The PUMA project had two distinct parts, conducted separately and in sequence. The first part was the quantification of the urban mine. The second part involved the potential future use of this urban mine. They are described below.

Quantification of the urban mine

The quantification of the urban mine has been an exercise of inventory. The method used to store the data and generate maps was GIS. Two types of information were necessary:

- Information on residential buildings
- Information on the metal content of those buildings.

Different, highly standardized databases are available on the built environment. The main database we used was the BAG database (Basisregistratie Adressen en Gebouwen). In the BAG, basic data on all buildings and addresses of the Netherlands is stored (www.basisregistratiesienm.nl/basisregistraties/adressen-en-gebouwen). This database contains the following for each address:

- Address and postal code
- Year of building
- Function of building
- Floor surface area
- Status (in use or not)

Additional data on the buildings are also available via the BAG, such as: the surface outline/footprint of the building (which can be computed based on the contours that are available as a shapefile as a whole and the number of stories it contains ("pandcontouren")), and the surface of the plot it stands on. The BAG is maintained and published by The Netherlands' Cadastre, Land Registry and Mapping Agency – in short Kadaster. Information on the height of the buildings is available from the Actueel Hoogtebestand Nederland (AHN), maintained and published by Waterschappen, Rijkswaterstaat en Provincies. Both are accessible via www.pdok.nl/.

Data from BAG and AHN are combined by the company ESRI, producer of the ArcGIS software, to a BAG-3D information system. Analysis and visualisation of the data is done in ArcGIS 10.2, QGis and Python. The BAG-3D database is accessible only with ArcGIS. However, the two uncombined databases are accessible for all.

The BGT (Basisregistratie Grootschalige Topografie) contains information on many different topics in a spatial grid. Rails, pipes, cables, street furniture etc. can be visualised in maps for the Netherlands, at a very detailed level. This information can be found at www.digitaleoverheid.nl/onderwerpen/stelselinformatiepunt/stelsel-van-basisregistraties/basisregistratie-grootschalige-topografie. It can also be accessed again via https://www.pdok.nl/. It can be combined with the other information in ArcGIS.

In addition, the municipality of Amsterdam produces maps of spatial data, published at https://maps.amsterdam.nl. Maps are shown based on data of land use, spatial planning, nature objects, and many others. These maps contain valuable data when expanding the urban mine database beyond residential buildings.

Information on the metal content of the building is more difficult to obtain. Ideally this type of information would be stored in building passports, or something similar. Although this will be standard practice in future, no such database is available for buildings constructed in the past. In view of the urban mining studies presently being conducted, there are a limited number of publications on metals in buildings. A literature survey was conducted and based on that a classification was made in three categories of metal content in kg/m^2. The literature survey revealed a wide variety in metal content, depending on the country, the scope and the level of detail of the study. No harmonized data format exists: some studies report in kg metal/m^2, some report in kg/dwelling, and some in kg/m^3. Some distinguish between the different applications; others just report one number which includes all.

In the PUMA project, a classification has been developed based on housing characteristics, such as height of building and age of building, number of dwellings and floor area of dwellings. The reporting in the PUMA project was extremely cautious, with the situation in mind that the report and maps will be accessed by a wide variety of interested, mostly non-expert people. The results of that literature survey are reported in Koutamanis et al. (2016), also available at the AMS website. In fact it would be possible to have a little more transparency on the metal contents per house.

Based on the abovementioned data, De Waag Society produced maps in ArcGIS, to be viewed at http://code.waag.org/puma/. The Dutch consultancy company 'Metabolic' performed a ground truth check by visiting a number of buildings to assess whether assumptions were reasonable. This report is downloadable from the AMS website as well (Blok & Roemers, 2017).

Drafting an urban mining plan

For this second part of the PUMA project, we used the method of Scenario Development, creating narratives of scenarios to envisage a future urban mining system. This work was kicked off by a workshop with stakeholders, among others the municipality of Amsterdam (that has expressed a great interest in becoming "circular"), the Amsterdam economic board, construction companies, housing corporations, recycling companies, the Amsterdam waste management company, various consultancies, and researchers. These we asked to explore what an urban mining system could look like under different external conditions, without any attempt at quantification. We defined four scenarios based on two axes:

- Scale level: local to global
- Driving force: markets or governments

The scenarios are shown in Table 7.

Table 7 Characteristics of four scenarios of implementation of urban mining in Amsterdam

Scenario Local Government Government is dominant over market: policy is driving force Most important level of decision making is local	**Scenario Global Government** Government is dominant over market: policy is driving force Most important level of decision making is national / supranational / global
Scenario Local Markets Market is dominant over government: market is driving force Most important level of decision making is local	**Scenario Global Markets** Market is dominant over government: market is driving force Most important level of decision making is national / supranational / global

2.5.3. Results

The results of the quantification of the urban mine is a database in GIS, linking metal contents to dwellings on a per dwelling basis. This GIS system can be displayed in maps. A sample is shown in Figure 14.

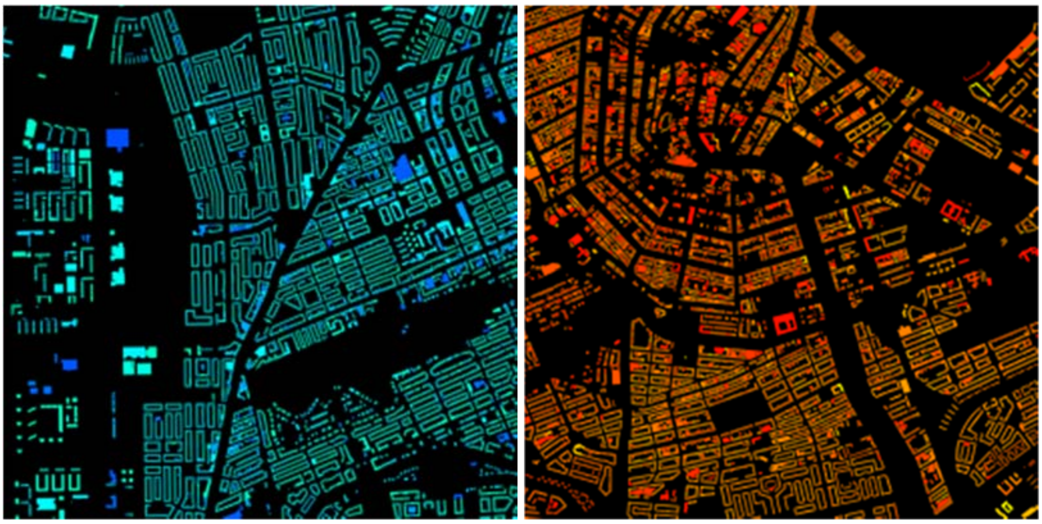

Figure 14 Fragments of the maps representing the urban mine for copper (blue) and steel (red). Lighter colors represent higher metal contents.

It was concluded that stocks in the built environment are large, but that recycling of these stocks already happens to a large extent. For other stocks, the actual gain of moving from recycling to urban mining may be larger.

The second part, including the scenario development, has resulted in a number of relevant insights. In the different scenarios, different actors have been identified as the most relevant ones either to set up and maintain the necessary information system, or to develop and implement policies. In all scenarios it was agreed that the present lack of systematic information is prohibitive for an effective urban mining system. Various options were identified to fill this gap. Likewise, in all scenarios it was agreed that without creating incentives, urban mining may not come off the ground. Incentives could be regulatory or market based. A new insight for many was that such an urban mining system cannot be a local-only affair. Present "circular" initiatives are often oriented towards local small scale businesses. There are local aspects to urban mining, but also global aspects and both must be accommodated to be effective and efficient.

2.5.4. Interpretation/discussion

To answer the questions stated in Section 2.5.1, we used different methods and a variety of data. We conclude the following:

- The databases on buildings and infrastructure in the Netherlands are well organized and very usable. They are available in GIS format and therefore can be used to create maps.
- GIS is not a method described in the MICA platform. This should be added.
- Data on metal content of buildings are available only through several isolated publications. No standard data collection happens at present, no comprehensive database is available. This may change in the future, e.g. through the creation of building passports.
- The Scenario Development method is a very useful tool in a new field, which is not well established and not well exercised, but might become very important. It helps visualise the options and leads to relevant insights. It does not require data but it does help if main stakeholders are interested and available.

As mentioned the MICA platform doesn't create data, but only guide towards such data. It seems to be essential in this rapidly developing field that the MICA platform is not just a repository for data but also for published literature, in the scientific journals as well as in the grey literature. Many of the data for this case study were taken from literature, not from established databases.

Urban mining is a relatively new topic that is now becoming of interest to various stakeholders. Definitions, methods and databases are not at all well established. The topic is now cautiously embraced by municipalities and various local stakeholders, and seems to be approached from the point of view of waste management. It might be worthwhile if geologists and other stakeholders of primary production could be engaged. Their expertise is additional, and will with no doubt lead to an enrichment of the field. One could imagine mining companies to be powerful stakeholders in urban mining.

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2.6. CGE models Case Study: The new CGE model UCL ENGAGE and a case study on the future of steel in China and worldwide, with implications for the EU

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2.6.1. Introduction/motivation

Case study 6 concerns the economic modelling of materials and in particular provides details on how Computable General Equilibrium (CGE) models can be modified to allow greater consideration of specific resources and then used to consider specific policies on resource efficiency and the circular economy, e.g. extraction taxation or targets on recycling rates.

A number of recent economic modelling studies have attempted to analyse resource efficiency and the circular economy (Ellen MacArthur Foundation, 2015; CE and BioIS, 2015). However, modelling analysis in this area is relatively underdeveloped. In particular, those models which do not represent explicitly key economic sectors are able to say little given the aggregated sectoral coverage in the original GTAP database.

Therefore, we have developed the ENvironmental Global Applied General Equilibrium (ENGAGE) materials model at UCL ISR to consider the economic and sectoral effects of potential policies on a circular economy and resource efficiency, which affect materials and resources at the stages of extraction, production and recycling.

We undertake a case study on the future of steel in China and worldwide, with implications for the EU. This case is of relevance for the contemporary debates about international economic policies, climate policies and a circular economy. Our new model and this case study are to complement other studies looking at steel (Morfeldt et al. 2015; Pauliuk et al. 2017), and we expect new insights into the dynamics of international trade, new projections for a baseline scenario, and tentative impact assessments for a range of policies.

2.6.2. Methods and data

The method used in this case study is a global CGE model. Computable General Equilibrium models are a neoclassical macroeconomic equilibrium model used to study policies through changes in relative prices.
The underlying database is a global set of monetary data in the form of Social Accounting Matrixes and trade data taken from the GTAP9-Power database for 2007. The 17 ENGAGE model regions are given in Table 8 below and are considered the major steel producers and consumers for both primary and secondary steel.

Table 8 ENGAGE-materials regions.

Regions (17)	
China	CHN
Japan	JPN
India	IND
USA	USA
Russia	RUS
South Korea	KOR
Brazil	BRA
Mexico	MEX
Canada	CAN
Australia	ANZ
Indonesia	IDN
Germany	DEU
Western Europe	WEU
Eastern Europe	EEU
Asia and Oceania	ASO
Latin America	LAM
Africa	AFR

However, in order to allow analysis of policies which can focus on the circular economy we were required to develop the model further beyond the standard model and database. Here we outline how the ENGAGE-materials model has been constructed through the following steps.

2.6.2.a. Extraction

Firstly, we disaggregate the material extraction sector 'Other mining' (OMN - GTAP sector) in each region in order to capture the flows of different key materials throughout the world economy. To our best knowledge, this has not yet been done in global CGE models before and is necessary for industry-focussed analysis on resource efficiency and a circular economy using a life-cycle approach of materials. Using shares and cost structures from the EXIOBASE dataset (Tucker et al., 2014) as well as a variety of national accounts databases, and employing the SPLITCOM programme for GTAP, we split the single 'Other mining' sector into: (1) mining of iron ore, (2) non-ferrous mining and (3) other mining.[3]

Physical data seems consistent between EXIOBASE and our estimates from USGS (likely same data).

However, value (price x quantity) monetary data from EXIOBASE seems inconsistent for some large mining producers, e.g. iron ore mining in China are relatively small in value terms. This requires independent estimation and potential re-estimation of OMN split. Table 9 summarizes our revised data for relevant countries and relevant areas.

[3] More disaggregated splits are faced with data restrictions and may become possible over time.

Therefore, where full data on mining sectors is available we use the national accounts to split these regions (AUS, BRA, CHN, CAN, IND, USA) and detail the relevant size of the iron mining sector, the iron ore mining sector's cost structure, and to what other economic sectors iron ore is sold.

Where data is available for only one or two sectors, e.g. only iron mining is given for AUS but all other mining is aggregated together, we use the data for this sector and then split the others based on other estimates/assumptions.

For Russia no national data has been available, so we re-calculate EXIOBASE data that we consider inconsistent here from bottom-up using average world prices (please note the red highlights in the table, column 'country', row six).
All other small iron ore producing model regions use the original EXIOBASE data source for splits.

Table 9 EXIOBASE vs ENGAGE shares of iron mining.

Source	Country	Iron ore		Other mining		GTAP OMN TVOM $m 2007
		EXIOBASE	ENGAGE	EXIOBASE	ENGAGE	
National Accounts 2007	Australia	4%	39%	96%	61%	53,609
National Accounts 2005	Brazil	45%	66%	55%	34%	32,390
National Accounts 2007	Canada	2%	9%	99%	91%	19,065
National Accounts 2007	China	7%	36%	93%	64%	121,248
National Accounts 2005	India	26%	25%	74%	75%	16,365
USGS and price estimates	Russia	2%	44%	98%	56%	15,576
National Accounts 2007	USA	0.3%	5%	99.7%	95%	48,041

2.6.2.b Primary and secondary production

Secondly, the production sector 'Iron and Steel' (I_M - GTAP sector) is further disaggregated to distinguish between primary and secondary production technologies. Table 10 below gives an overview on the relevant mining-related sectors and other sectors in our model UCL ENGAGE. Again, to our best knowledge, this has not yet been done before in global CGE modelling and is necessary for the scope of our study and follow-up research on resource efficiency and a circular economy. For secondary production we distinguish between the treatment of secondary steel (which utilises recycling services) and reprocessing of secondary steel into new steel which produces the final output. While primary steel production is based on the Blast Oxygen Furnace (BOF) technology, secondary steel production uses the Electric Arc Furnace (EAF) technology. Both technologies are explicitly modelled in our framework. The World Steel Association data was used for the calibration of primary and secondary production levels.

Table 10 ENAGE-materials sectors.

Mining related Sectors (16)		**Energy related (13)**	
Iron mining	I_M	Coal	COA
Non-ferrous mining	N_M	Crude oil	OIL
Other minerals mining	O_M	Gas	GAS
Iron and steel primary production	ISP	Petroleum & Coke	P_C
Re-procesing of secondary steel into new steel	RSS	Transmission and distribution	TnD
Secondary steel for treatment	SST	Nuclear power	NUP
Non-ferrous primary production	NFP	Coal-fired power	CFP
Non-ferrous secondary production	NFS	Gas-fired power	GFP
Non-metallic minerals	NMM	Wind power	WIP
Metal products	MTP	Hydroelectric power	HYP
Motor vehicles and transport equipment	MVT	Oil-fired power	OFP
Electronic equipment	ELE	Other power	OTP
Machinary and other equipment	MAE	Solar power	SOP
Recycling	RCY		
Construction	CNS		
Transport	TRA		
Other sectors (6)			
Agriculture and food	AGR		
Wood products	WOP		
Paper products publishing	PPP		
Chemical rubberplastic prods	CRP		
Other manufacture	OMA		
Service	SER		

Using EXIOBASE we split the total iron and steel production sector (I_S in GTAP) into two – Iron and Steel Primary (ISP) and Iron and Steel Secondary (ISS). Then, as stated above, secondary steel production sector ISS is split further, using some technological and economic assumptions, into (1) Secondary steel for treatment (SST) – which uses only recycling and the value of scrap as inputs, and (2) Reprocessing of secondary steel (RSS) – which is where we model the production of secondary steel through the EAF method. All output of SST sector is sold on to the RSS sector.

We also altered the production structure of these newly constructed primary and secondary production structures in order to capture a more realistic production process in these sectors. In Figure 15 below, we show the nested production structures for these three sectors which capture greater technological detail than previously where only one single iron and steel production sector existed.

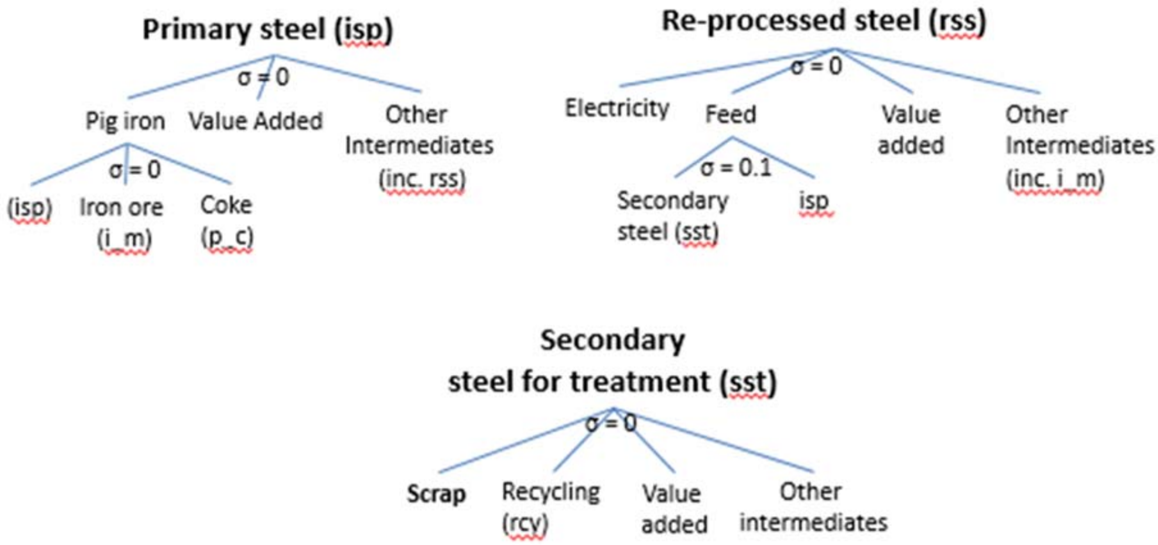


Figure 15 Production structure of ISP, RSS and SST sectors.

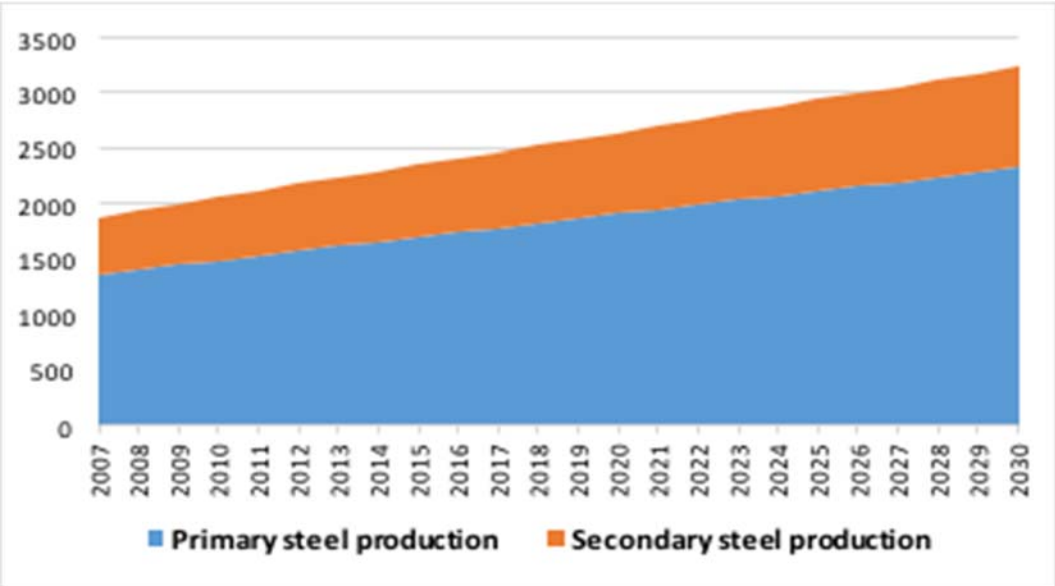
In the primary steel *(ISP)* sector the pig iron composite is created from a Leontief input of *ISP* (i.e. purchases from itself), iron ore, and coke. The Reprocessed steel (*RSS*) sector has electricity as a distinct input at the top level of the production function in order to replicate the production process used in Electric Arc Furnace. The Secondary steel for treatment (*SST*) sector combines with *ISP* in the second nest of the *RSS* sector with a very low elasticity of substitution between them. The *SST* sector only has one nesting level which has scrap, recycling, value added and other intermediates. The scrap is assumed to be the value of capital in the *SST* sector.

To summarise:

- all own-demand in the *ISS* sector is the output of the *SST* activity
- All recycling costs of *ISS* are attributed to *SST*
- All treatment outputs *SST* go into reprocessing *RSS*
- Secondary steel - the value of scrap is derived from that of Capital– the capital investment in steel treatment reflect the shadow value of steel scrap
- Substitution of steel coming from *ISP* and *RSS* can be industry specific
- Scenario opportunity for scrap availability – boost in overall or sector-specific recycling rates/quotas – through EXIOBASE supply and use data

2.6.3. Results

For the purposes of this case we have implemented an initial baseline and a test scenario using the newly constructed database and model structure. Here we provide a sample of the initial results. The model baseline is given in Figure 16a and Figure 16b. Figure 16a shows the increase in global steel production and how this is split between primary and secondary production. In the baseline we keep the share of primary and secondary in 2030 the same as in the calibration year of 2007. Overall production increases by about 50% over the time period which are taken from the World Steel Association (2015) global steel outlook.



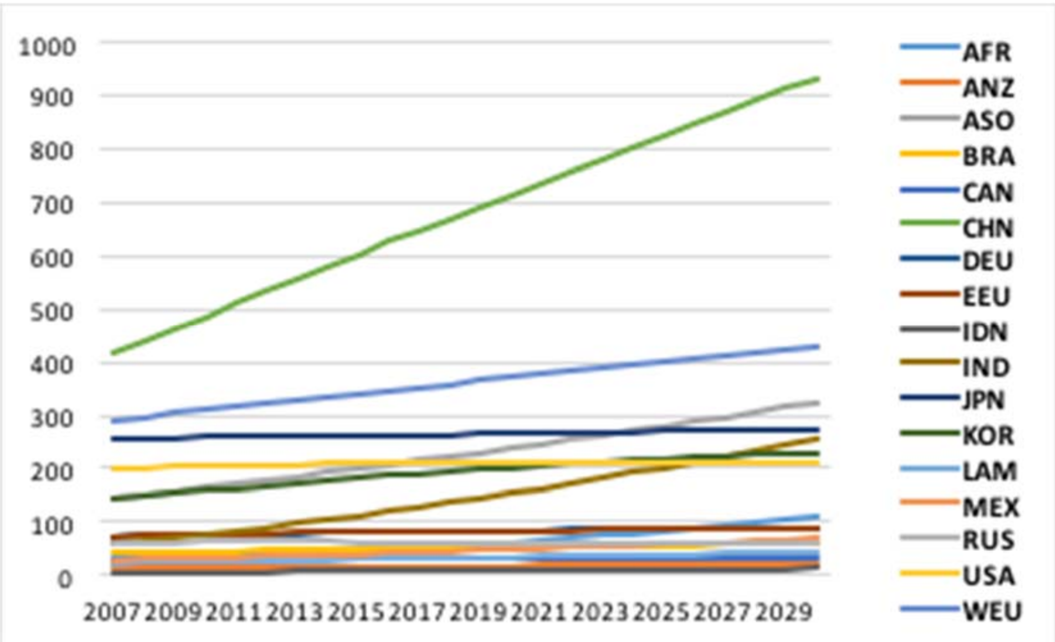


Figure 16 Global steel production to 2030 (a - upper) and Regional steel production to 2030 (b - lower)

In Figure 16b the initial results on regional iron and steel production baseline increases are shown. They appear to roughly match the World Steel Associations (2015) estimations, which seems to confirm the set-up of our model as described above. Indeed, the rationale here goes beyond meeting World Steel Association as we will seek to apply the model in future research. For instance, both baselines show Chinese production accelerating in the future, and we intend to amend the baseline to incorporate a saturation effect for steel (Bleischwitz and Nechifor, 2017) – an analysis of obvious relevance for both policy and industry, which does not yet seem to be part of e.g. UNEPs International Resource Panel trends analysis (UNEP 2017; Hatfield-Dodds et al. 2017: 408). We also underline this as an advantage of a macro-economic model and thus look forward to further analysis.

Figure 17 shows the initial regional shares in the baseline of primary vs. secondary production. Almost 85% of Chinese production comes from primary steel production showing that there is considerable potential to implement and gain improvements from policies aimed at increasing scrap rates. Mexico, Latin America and the USA all produce around 40% of their steel through secondary production. The two regions with the highest secondary production are Indonesia and Asia & Oceania which produce around 50% and 65% of their steel from secondary production, respectively.

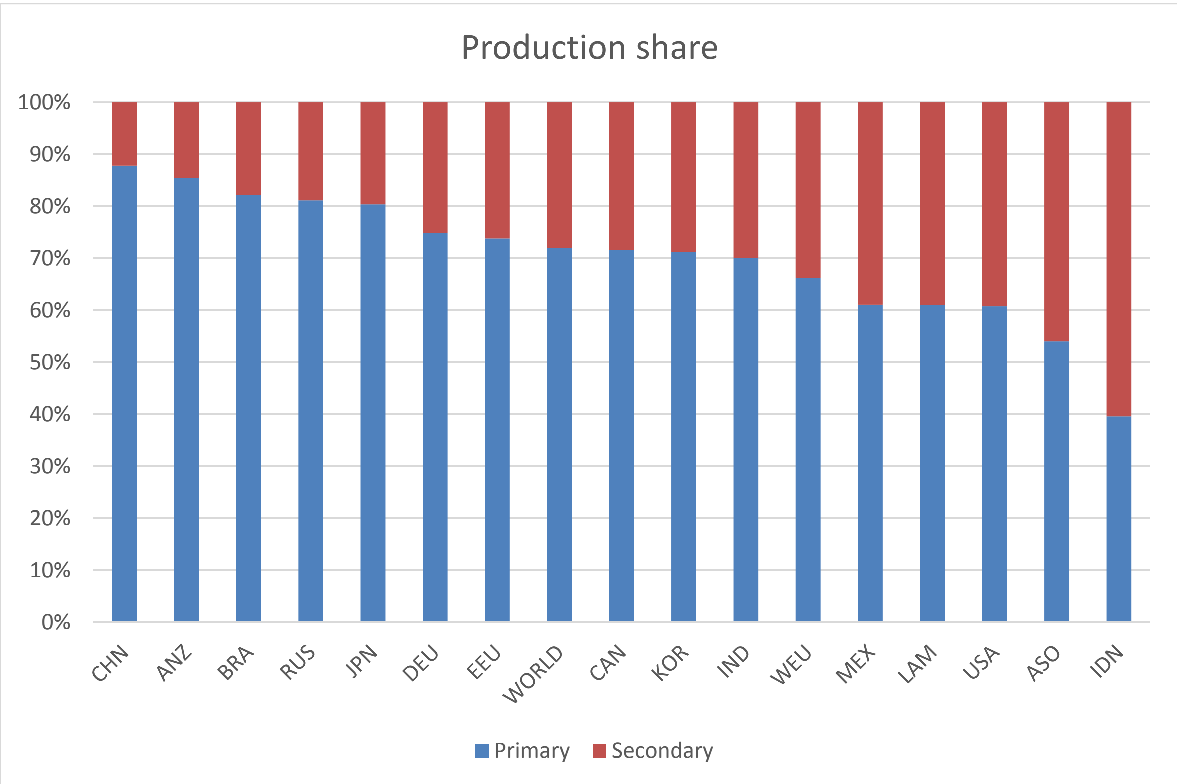


Figure 17 Production share in Baseline.

For the purposes of this case on steel within D4.3 we also have implemented a policy in the model which increases the output of the *SST* sector from 2018 to 2030 for each region. This can be interpreted as a doubling of the scrap availability in all modelled regions over this time period. Indeed, such policies will be refined throughout the remainder of this project and beyond.

The results in Table 11 show that doubling of scrap availability leads to secondary steel production increasing by around 7% in 2030 compared to the baseline. Global primary steel production reduces somewhat as there is a shift towards secondary production, however, there is an overall increase in total production by just under 2%. It appears that the rigidities in the production process modelled here mean that substantial increases in scrap availability may only lead to relatively small improvements in overall economic terms; this is up for further analysis over the next months and beyond the duration of MICA.

Table 11 Global iron and steel production by type 2017-2030 against BAU.

	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Scrap	0.00%	4.98%	10.30%	15.99%	22.08%	28.59%	35.56%	43.02%	50.98%	59.49%	68.60%	78.35%	88.79%	100.00%
Secondary production	0.00%	0.35%	0.74%	1.12%	1.56%	2.03%	2.53%	3.07%	3.62%	4.28%	4.89%	5.57%	6.34%	7.16%
Primary production	0.00%	-0.01%	-0.01%	-0.02%	-0.03%	-0.03%	-0.04%	-0.05%	-0.05%	-0.06%	-0.07%	-0.08%	-0.09%	-0.09%
Total production	0.00%	0.09%	0.19%	0.30%	0.41%	0.54%	0.67%	0.82%	0.97%	1.15%	1.31%	1.50%	1.71%	1.94%

Global GDP is given below in Figure 18a and shows that the majority of regions benefit from the exogenous increase to scrap availability. Those regions which are most negatively affected are South Korea and Africa which see reduction in GDP of 0.7% and 0.6% respectively in 2030 against the baseline. There is also a small reduction of GDP in Asia and Oceania region as well as Mexico. It appears that these four regions (AFR, ASO, MEX, KOR) lose out from a reduction in their primary production which outweighs the benefits of any increases in secondary production. The only region having a fall in both primary and secondary is ASO. All other regions incur increases in both primary and secondary steel production.

The environmental effect of doubling the scrap sector is given in Figure 19 and shows an overall reduction in the emissions from fossil producing sectors. In particular oil production decreases most given its input into primary steel production (further analysis is required here). Other decreases in coal and gas are partially offset by increased use of electricity in secondary production and associated rise in fossil fuel electricity production.

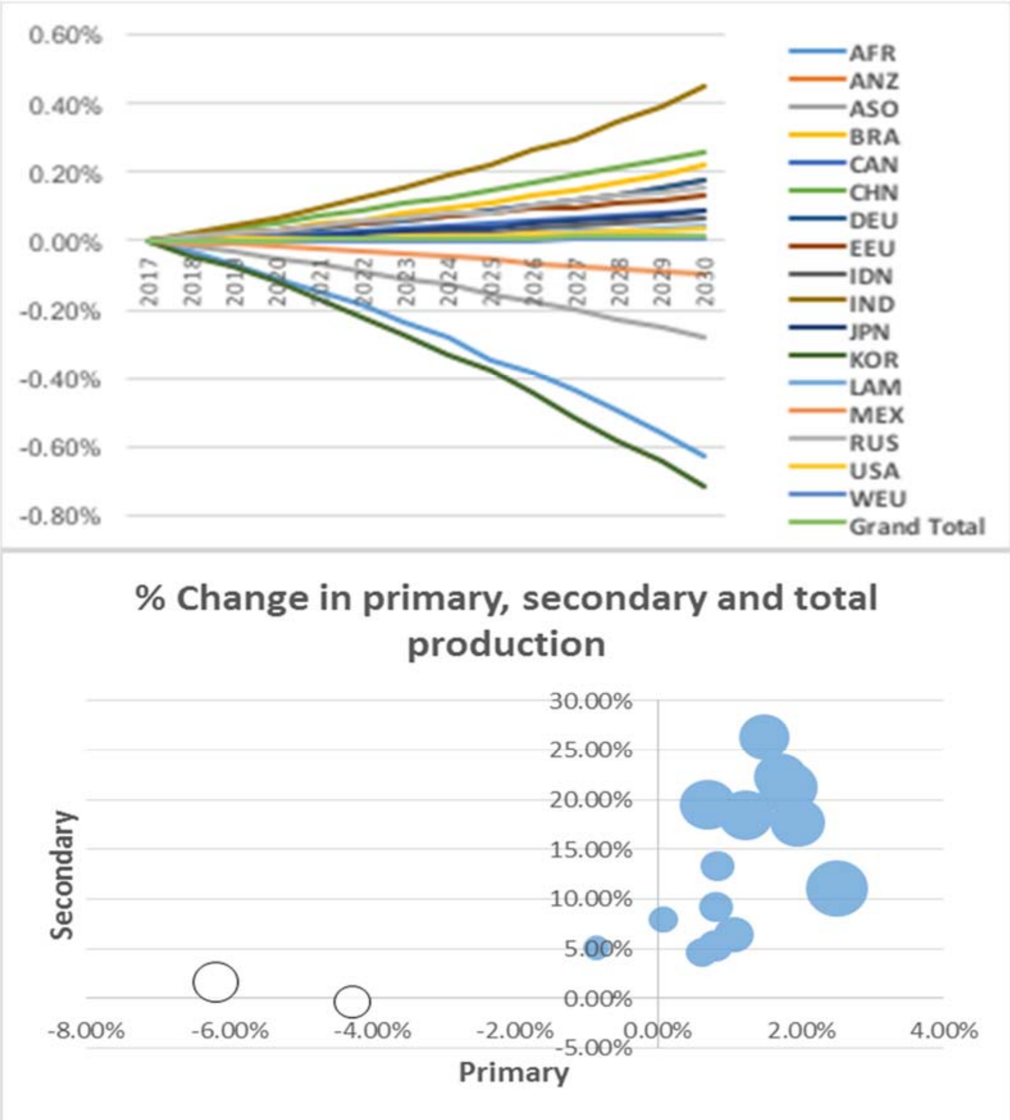


Figure 18 Regional GDP % change (a - upper) and primary, secondary and total production % (b – lower).

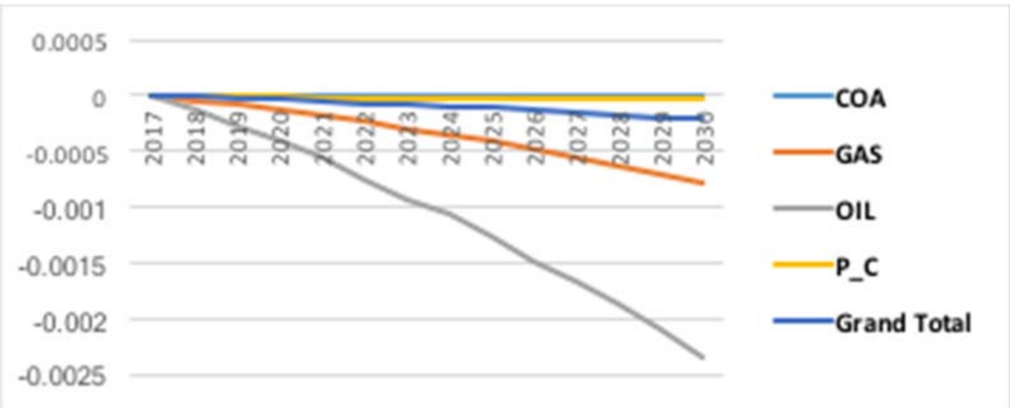


Figure 19 Emissions of fossil fuel sectors % change.

2.6.4. Discussion and Tentative conclusions

In this case study on CGE modelling of steel we conclude the following: The majority of global macro-economic models have focused on either standard economic variables, or energy and related GHG emissions; model development is still required for macroeconomic analysis of polices related to iron and steel. Many current models lack detail on specific resource extraction sectors and downstream resource-intensive sectors. In particular there is a lack of materials-specific sectors in macro-economic models. Using the EXIOBASE dataset is a good starting point but it is necessary to complement with national and steel-specific data where possible, as done in this chapter of D4.3 and in the new UCL ENGAGE model. There are, however, data issues as data availability on iron ore mining at national levels (e.g. Russia) is reasonable though not comprehensive, and data on secondary production are only sparsely available. Our early results, however, are in line with e.g. World Steel Association and could thus be the base for further analysis.

A key issue will be deciding upon assumptions in model baselines for future steel scenarios, in particular with regards to potential saturation levels in China. If China is assumed to saturate rather soon with regards to steel consumption, the implications for future production are significant. A macro-economic model such as UCL ENGAGE should be able to cope with such scope.

Initial results to explore potential policy implementations show that there will be positive economic and environmental effects of policies which increase the amount of scrap availability globally. Our test scenario on doubling of scrap availability seems to lead to modest increase in secondary steel production and an overall economic improvement although this varies by region. Regional differences are observed depending upon initial inputs and cost structure as well as the technological production structures. The overall GDP effects are relatively small and most are positive. We plan to analyse the wider sectoral impacts of such policies in more detail. Further work on sensitivity analysis is required to test model responsiveness as we have begun with a very ridged production structure for secondary steel production. There is a small overall reduction in fossil related emissions related to a shift in production from more emissions-intensive primary production towards secondary production that deserve attention. After all, supply of future scrap steel and pathways to market could be a fascinating area of collaboration between industrial ecology type of models (Pauliuk et al. 2017, or others here in D4.3) and macro-economic CGE type ones.

2.6.5 Next steps

We intend to undertake the following steps throughout the remainder of MICA:

- Finalise data work and calibrate the model
- Develop a baseline scenario, taking into account e.g. SSP II (shared socio-economic pathways project) and a saturation effect
- Start developing a new scenario with a saturation effect and some ambitions as regards to GHG reduction, resource efficiency and a circular economy
- Discuss findings, compare tentative results with e.g. World Steel Association and other studies (Pauliuk et al. 2017; Hatfield-Dodds et al. 2017) and arrive at conclusions for this project and beyond.

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2.7. Criticality Case Study

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References to other case studies/other areas of the MICA platform are colored blue

2.7.1. Introduction/motivation

The concept of “critical raw materials” (→ Method: Criticality) is both easy to use and to confuse. The ease of use comes from our intuitive understanding of “critical” as being something highly important or essential. A key difficulty is that no universal definition of “critical raw materials” exists and, in fact, cannot exist because raw materials are not critical in themselves but to somebody, for some set of reasons at some point in time (Tercero Espinoza 2013). The terms criticality and critical raw materials concern the possible scarcity of natural resources and the potential impacts of supply disruption to the economy and society (Graedel et al. 2014). The terms are not new but have a recurring presence in history. Assessments undertaken in the past followed similar approaches, but the lists of critical raw materials derived from those assessments were different.

Nevertheless, some form of ranking of raw materials is useful for guiding decision making both in governments and companies. Several studies have been undertaken proposing various methodologies for assessing the criticality of raw materials at different levels, including corporate, national, regional (e.g. for a group of countries; see review by Erdmann & Graedel 2011; and updates in Glöser et al. 2015; and Helbig et al. 2016), as well as for different groups of raw materials (e.g. metals, energy minerals; Graedel et al. 2015; JRC 2011, 2013; US DoE 2011).

In this case study, we explore some key features of criticality assessments and discuss issues associated with undertaking such assessments. The list of critical raw materials for the EU from 2014 (European Commission 2014b, latest revision just published) is used as an illustrative example as at the time that this case study was produced, the 2017 EU list of critical raw materials was not published. However, since September 2017, the third EU list of critical raw materials has been released (European Commission, 2017).

2.7.2. Methods and data

Criticality assessments can vary from 'broad brush' screening approaches intended as early warning systems (e.g. Risk List; BGS 2015) to detailed, quantitative multi-dimensional assessments (e.g. the EU study on critical raw materials; European Commission 2014a). There are numerous factors that may influence criticality, including but not restricted to: geological, economic, political, environmental, and technological factors (Graedel et al. 2014). Each factor can be assessed on the basis of a range of indicators that are measured by various metrics, which in turn can be weighted and combined in various ways. Therefore, the methodological choices behind any criticality study reflect the different perspectives and priorities relevant to the assessment undertaken, e.g. different purposes, aimed at different stakeholders or industry sectors, or within specific geographical boundaries. The results of each assessment are unique, fulfill a specific purpose and are not readily comparable (see examples in Table 12). Several authors have reviewed the methods used in the most high profile criticality studies and supply security strategies (e.g. Glöser et al. 2015; Helbig et al. 2016; Leal-Ayala et al. 2015; Mayer & Gleich 2015).

Criticality is a relative term: A material is classified as critical if the values of the assessment dimensions are greater than those for other materials and exceed certain threshold values. It is important to highlight that threshold values are – much like the choice of methodology – a decision, most commonly based on expert opinion. A two-dimensional view of criticality introduced by the National Research Council (NRC 2008) has become popular and a variant of this is used by the European Commission (European Commission 2010; 2014a, with modifications in the upcoming revision) in its periodic assessment, as illustrated in Figure 20.

Table 12 Selected methods for criticality assessment.

Methodology	Purpose	Assessment dimensions
EU Study on critical raw materials (European Commission 2014a)	EU wide perspective for the identification of critical raw materials	Two-dimensional (supply risk & economic importance). (Note: a revised methodology is currently underway).
Assessment of critical minerals: screening methodology and initial application (NSTC 2016)	Identification of critical raw materials with potential supply vulnerability issues to the U.S. economy and National security.	Two stage process: early warning step, followed by a detailed analysis of potentially critical materials. Three-dimensional (supply risk, production growth, market dynamics)
Methodology of metal criticality determination (Graedel et al. 2012)	Methodology for the assessment of the criticality of metals; may be used by different stakeholders and applied for different geographical boundaries.	Three-dimensional (supply risk, vulnerability to supply restriction, environmental implications)

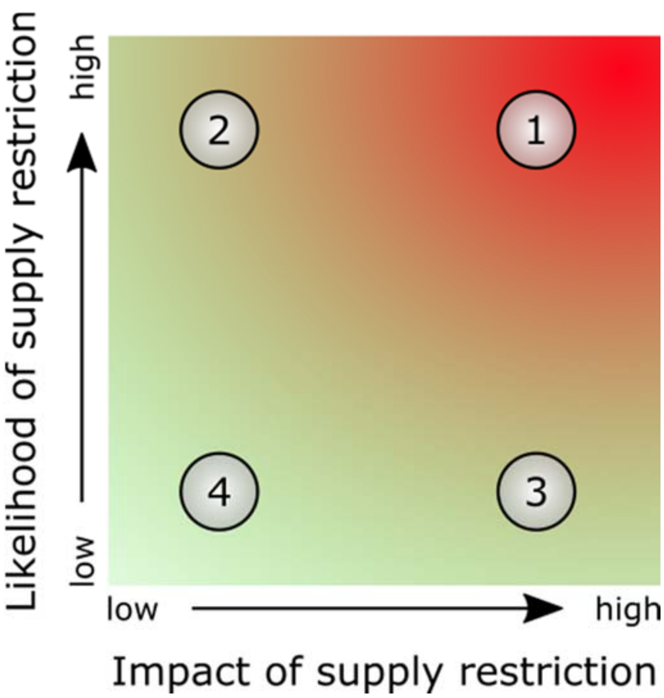

Figure 20 Two-dimensional criticality matrix as introduced by NRC (2008) and used in European Commission (2010, 2014a). Raw materials in the top right part of the figure (1) are more critical than materials located in the top left (2) or bottom right (3), and much more critical than raw materials in the bottom left (4). Figure modified after Graedel et al. (2014).

Good quality data for all metrics and for all the candidate materials being assessed are of fundamental importance to any criticality assessment. All methodologies require the combination of scarce or unreliable data, for example on market trends, substitution, and recycling, and more complete and reliable data such as on mine production, trade of raw materials and producer concentration. Even though data availability has generally improved in recent years, there are still many gaps that require the assessors to make assumptions or to elicit information from grey literature and expert opinion. When addressing commodities such as the so-called technology metals, data scarcity, even in well-established datasets, is significant and undermines the reliability of any assessment. For example, production data on indium and other by-product metals are not always readily available and often estimated. Datasets on mineral resources and reserves, recycling rates and substitution are poorly documented. It is also very important that data are interpreted correctly in any assessment and that data sources, assumptions and calculations are presented in a transparent way.

2.7.3. Results

The criticality exercise periodically conducted by an Ad-hoc Working Group on defining critical raw materials under the auspices of the European Commission (European Commission 2010; European Commission 2014a; 2017) defines two dimensions, "supply risk" and "economic importance", which are equivalent to the two dimensions shown in Figure 20. "Economic importance" and "supply risk" are estimated using the indicators shown in Table 13. Note that the indicators use several different datasets (e.g. production statistics (→ link to production data), gross value added of sectors) and assessments.

Table 13 Indicators used in the criticality exercise for the EU (European Commission 2014a). Key: (d) - data, (e) - expert assessment, (s) - survey.

Supply risk (~ likelihood of supply restriction)	Economic importance (~ Impact of supply restriction)
Concentration of production at country level (d)	Share of use of raw material in different sectors (d)
Governance in producing countries (s, e)	Gross value added of those sectors in the EU (d)
Substitutability (e)	
Proportion of supply coming from material recycled from end-of-life scrap (d, e)	

Figure 21 shows the results of the criticality exercise conducted in 2013-2014, leading to the 2014 list of critical raw materials for the EU (European Commission 2014b). The materials in the red box are considered critical, whilst commodities outside this area are not. The thresholds for "supply risk" and "economic importance" were set by the Ad-hoc Working Group on critical raw materials, following the compilation of individual assessment results and examination of their relative values.

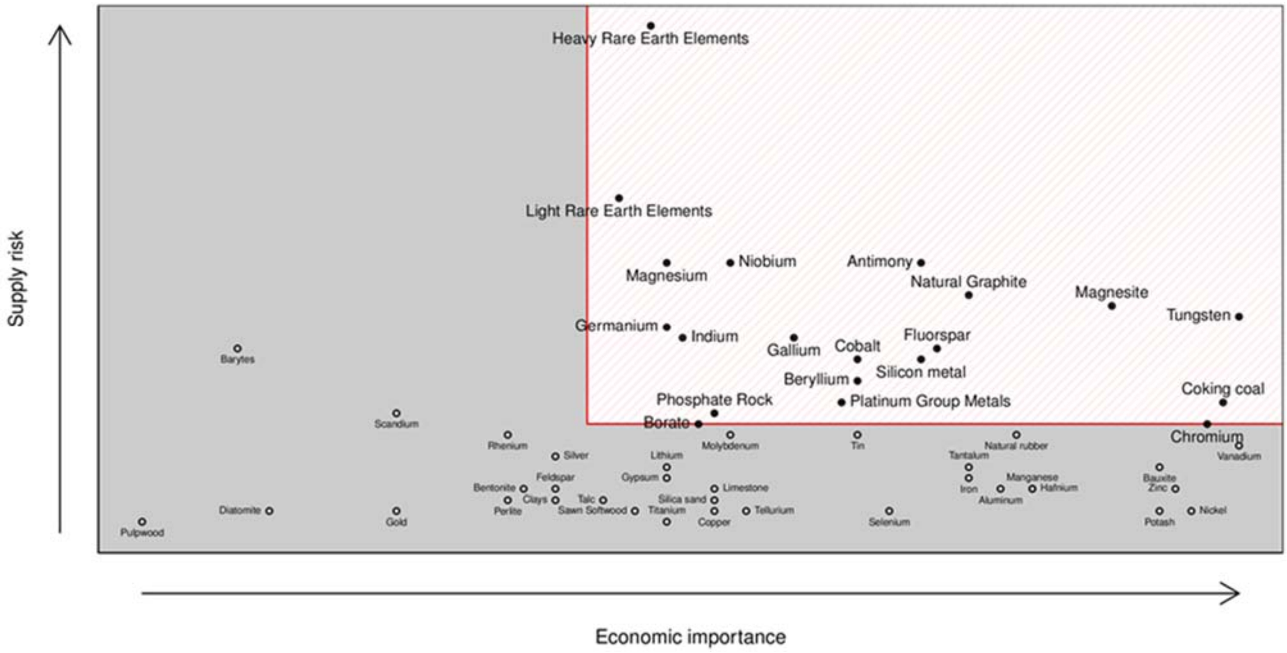

Figure 21 Criticality matrix for the EU, in which raw materials contained in the red box are deemed to be critical (European Commission 2014a). The latest list (2017) has assessed a much larger group of materials and identified 27 as critical. Materials are assessed based on their supply risk and economic importance scores, but the thresholds used in the 2017 study have changed (European Commission, 2017).

2.7.4. Interpretation/discussion

The EU study provides a broad overview of the materials that may be critical to the EU across many different industry sectors and countries. As an exercise, it is useful for decision makers in policy and industry to warn about issues of concern with supply and demand and potential impacts to security of supply. It is important to note, however, that only a subset of the materials identified as critical will be relevant to specific sectors because individual industry sectors tend to have specific requirements for raw materials. Furthermore, within a sector, different companies differ in the location of their operations, their market penetration and supply chains, all of which may influence the criticality of a raw material to their business. Therefore, no single criticality assessment is applicable to all situations or scenarios. Criticality assessments are unique and specific to the objectives of a study. In order to use the results properly, it is very important to understand what they say and what they don't.

Examination of Table 13 reveals that four different indicators are used to determine the supply risk score but only two to determine economic importance. Furthermore, the location of the thresholds more strongly discriminates by supply risk (most raw materials are below the threshold for supply risk [SR] while most raw materials are above the threshold for economic importance [EI]; Oakdene Hollins & Fraunhofer ISI 2013).

The scores for economic importance emphasize the added value of the sectors using the raw materials in the EU: materials used in "bigger" sectors (cf. Figure 22) are assigned a higher score than materials used in "smaller" sectors. Notice that sectors (termed "megasectors" in the EU criticality exercises from 2009-2010 and 2013-2014) are composed of different NACE codes. More importantly, the entire value of the megasector was assigned to the raw material and weighted by the share of the sector in demand for that raw material instead of the weight share of the raw material in the end products produced by the megasector.

This is a significant point which may become more clear with an example: the most important use of beryllium is in copper-beryllium alloys (>> 90% copper) for connectors, switches and other parts that need improved mechanical properties; these in turn are used in aircraft, mechanical equipment, road vehicles and electronics. The latter three megasectors have very high value added and have similar shares in demand for copper and beryllium such that beryllium (several hundred tonnes per year) is scored as high as copper (over 20 million tonnes per year) in these sectors although considerably more copper tonnage is involved. This bias towards "smaller" metals was a methodological choice and must be taken into account when reading the horizontal axis of Figure 21.

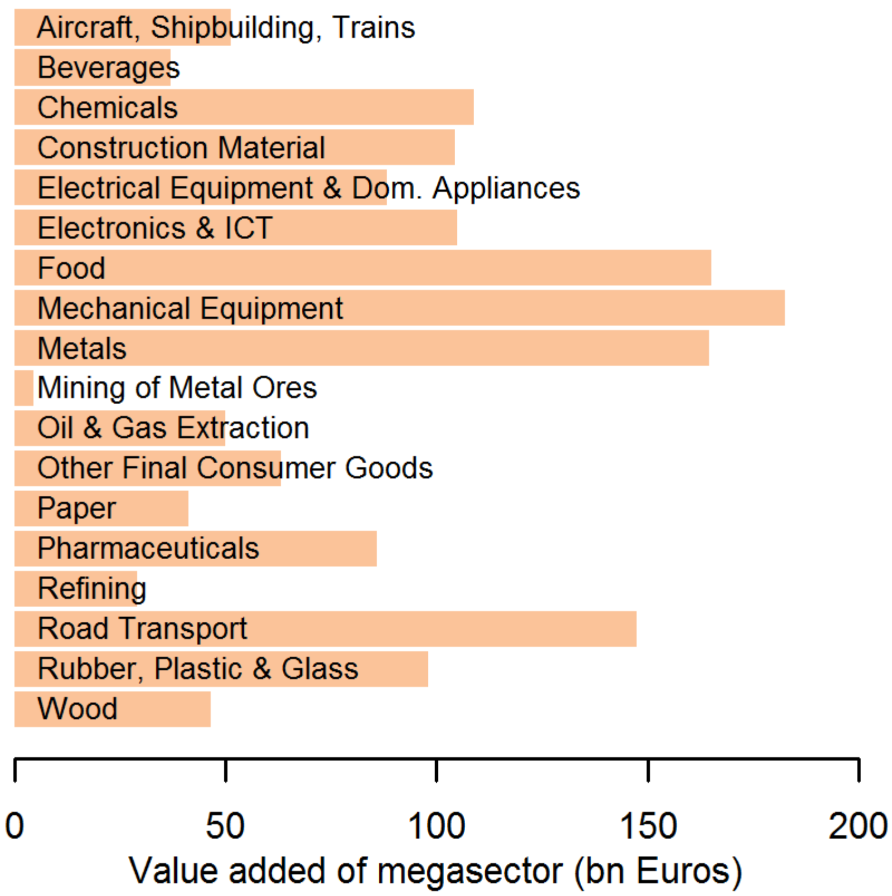

Figure 22 Value added data used to calculate the score for economic importance (data from European Commission 2014a, figure by Fraunhofer ISI).

The scoring for supply risk (vertical axis) contains four elements:

1. The concentration of production (key reason: monopolies are detrimental to a secure and stable supply),
2. A governance indicator for the producing countries (key reason: instability in the producing countries could lead to bottlenecks),
3. Share of recycling of post-consumer scrap in supply (key reasons: recycled material is not subject to the risks of primary production and recycling can and does take place in the EU), and
4. A compound substitution score showing how the function provided by the material in its different applications may be attained by other means (reasoning: it is primarily the function not the material per se that are needed by industry).

These four elements are combined by multiplication, such that the concentration of production may be seen as the "source" of possible severe bottlenecks in the supply of a raw material/function, the likelihood of this happening being changed by the other three factors considered. Examination of Figure 23 reveals that only raw materials with a high concentration of primary production (both prior and after considering governance) are considered critical. While some raw materials have comparatively high recycling input rates from post-consumer scrap, this in itself is not enough to be considered non-critical (e.g. tungsten) and vice-versa (cf. industrial minerals that are generally not recycled but only few are considered critical). The same applies to substitutability.

Criticality assessments are developed with the aim of highlighting current issues related to security of supply. Being based mostly on historical (snapshot, not dynamic) data and expert assessment, the criticality assessment of the EU (and others) cannot adequately provide a long-term perspective nor detect rapidly evolving short-term issues as the data that would enable such an approach are not available. Furthermore, criticality assessments tend to address a single stage within the value chain, rather than following a whole value chain approach. Hence, it is important to be cognizant of which stage is being evaluated in order to properly interpret the results (cf. discussion in Oakdene Hollins & Fraunhofer ISI 2013, Chapter 5.4). In order to improve their reliability and value to all stakeholders there is a particular need for better datasets, for all commodities of interest and across the entire value chain.

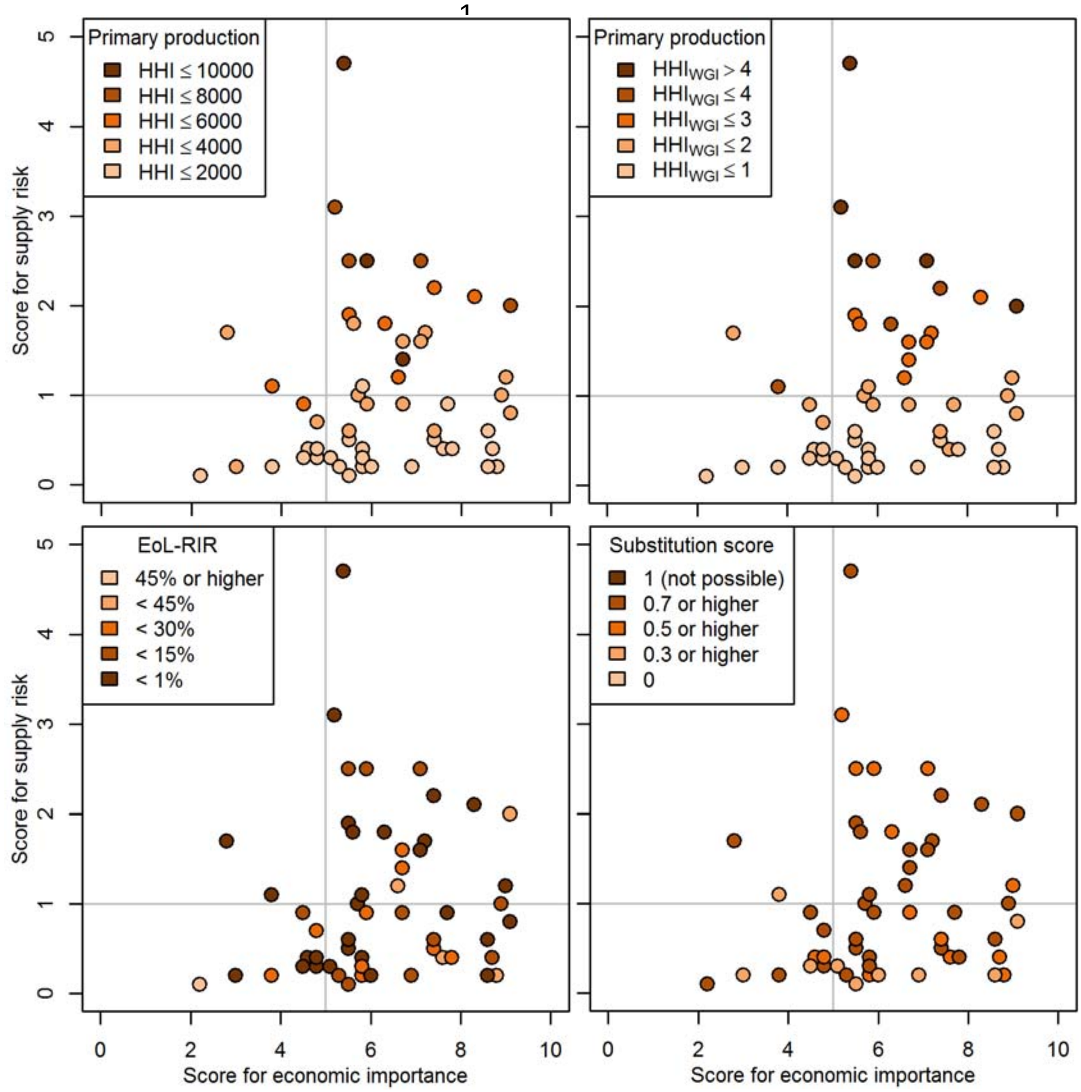

Figure 23 Indicator ranges behind the individual supply risk scores (vertical axis). The position of the dots represents the criticality status of the assessed raw materials as shown in Figure 21. Top left: country concentration of primary production; top right: country concentration of primary production after weighting by the World Governance Indicators (World Bank 2012); bottom left: share of recycling of post-consumer scrap in total supply; bottom right: substitutability of the raw material in its applications. The thresholds used by the Ad-hoc Working Group on Defining Critical Raw Materials are shown in gray. Figure source: Fraunhofer ISI.

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3. Discussion and Conclusions

The case studies presented in this report showcase the benefits of the MICA methods and how they can be used to answer stakeholder questions. It has been shown that stakeholder questions vary widely, and as a result of wide variety of methods is needed. Mineral intelligence covers many different aspects, from raw materials supply via choices in industrial processes and design all the way through to consumer choices and options for waste management and secondary production. Many stakeholder questions refer to more than one part of the supply chain. This means that to be able to answer these questions, just one method is usually insufficient. As concluded in D4.1 and D4.2, interdisciplinary knowledge is very important and is reflected in the application of so many different methodologies in addition to one another.

From the described case studies, we can also conclude that there are common challenges shared by all methodologies. They are highlighted below.

Data availability and data quality

The case studies demonstrated that robust quantitative data about material stocks and flows are both essential and often lacking. Data availability and quality tend to be better at the beginning of the material cycles (mining and production phases) and tend to become less available and of poorer quality further downstream. There are large differences in data availability and quality between materials: While bulk materials and expensive materials tend to be documented better, data quality for many critical raw materials, which are often used in small quantities, are generally poor. This data limitation has significant implications for criticality assessments (case study 7), which need to be conducted without being able to rely on quantitative information about the respective cycles.

The estimation of material stocks and flows further downstream can be estimated using mass balance and assumptions. Estimates of material stocks in use using this top-down approach (e.g. case studies 1 on aluminium and 6 on steel) tend to be limited by a poor understanding of the share in which a given material is used in different product categories and the lifetime of these product categories. It is therefore highly relevant to complement these top-down studies with bottom-up approaches illustrated in case study 5 on urban mining. Due to these limitations in data availability and quality, it is highly relevant to make these uncertainties explicit and to develop tools for dealing with these uncertainties (case study 4).

System definition

All of the case studies presented here aim to improve the system understanding by illustrating how different parts of the material cycles and their environmental impacts are linked with each other, and why these linkages matter for policy making.

The system of material cycles are generally relatively simple at the beginning of the supply chain and tend to become more complex downstream, particularly if materials have highly diverse applications. While a limited system understanding is unavoidable, it is of very high importance for the modeler to be explicit about the system definition chosen. This transparency greatly facilitates reproducibility and reduces overall uncertainties.

The case studies document well that the system definition is not only a question of *correctness*, but also the *usefulness* related to the model purpose and the stakeholder questions to be addressed. While a top-down approach (case study 1) may be useful for addressing questions related to the total stock of a material, a bottom-up approach (case study 5) may be needed to obtain a higher resolution of the material stocks in use, e.g. the amount of aluminium in vehicles. If the question is related to the qualities of a material and its down-cycling, the different material stocks may need to be grouped again in a different way in order to reflect the individual alloys used within a product.

Uncertainty

Scenario development (case study 2) and modeling (case studies 1, 3, 5, and 6) comes with large amounts of uncertainty. This is often associated with the aforementioned data gaps and, thus, the need to estimate data. Therefore, the results of the studies have to be understood within the context of the method (i.e. their strengths and weaknesses) and the underlying raw data quality. In addition, as case study 4 pointed to, there are several ways to estimate uncertainty with each method yielding different results. This can lead to challenges with communicating with stakeholders, as complex information needs to be communicated in a way that is both understandable but also illustrates the robustness of the results.

Despite the aforementioned challenges, substantial opportunities lie in combining methods for answering several stakeholder questions simultaneously. The methods and topics presented in these case studies highlight the complementarity of methods and point to the need for better data and increased data access.