A systems approach for the monitoring of the physical economy

MinFuture Framework

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Authors

Evi Petavratzi, BGS

Astrid Allesch, TU Wien

Daniel Beat Muller, NTNU

Gang Liu, SDU

Helmut Rechberger, TU Wien

Jonathan Cullen, UCAM

Maren Lundhaug, NTNU

Mark Simoni, NGU

Tom Heldal, NGU

Zhi Cao, SDU

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Glossary

Data Data represent observations of either stocks (at a given point in time) or flows (over a given time period).

Dimensions (MFA) Dimensions represent components of the physical economy framework.

Future scenarios Possible future and hypothetical occurrences.

Indicators Indicators are quantitative measures that are supposed to reflect how close we are to achieving set goals.

Layers (MFA) The layers dimension explores the interactions and changing characteristics of materials across their life cycle.

Material flow analysis Material flow analysis (MFA) is the method used to track the physical economy, namely the stocks and flows of material and energy in a system defined in space and time.

Mineral Resource Resources are a concentration of a mineral commodity that may become of potential economic interest.

Mineral Reserve Reserves are part of the resource, which has been fully geologically evaluated and is commercially and legally mineable with current technology.

Model Models are mathematical representations of material cycles and their drivers which are used to simulate historical changes in material cycles or to make forecasts for future changes through the- use of scenarios.

Physical economy Physical economy is concerned with natural resources and materials produced and consumed within specified spatial boundaries (e.g. regions, countries, cities).

Stages (MFA) The stages dimension represents the various transformation and use stages of materials across their lifetime.

System Systems define where materials are located, either in the form of stocks or in processes, but also, where they are moving to (flows).

The Pyramid Framework The pyramid framework includes essential MFA components used in the monitoring of physical flows and stocks of materials.

Time (MFA) The time dimension provides the basis for model calibration and future scenario modelling.

Trade (MFA) The trade dimension allows us to understand raw material dependencies, and the interlinkages between countries around the world.

Uncertainty Uncertainty is inherent in all MFAs due to errors in system definitions and the data used.

Urban Stock Urban stock is equal to "anthropogenic material stock" that consists of materials and products staying in the techno-sphere over a certain period of time. The anthropogenic material stocks could be categorised into mobile stock (e.g. consumer durables, machinery, and electronic equipment) and built environment stock (buildings and infrastructure).

Visualisations in MFA Visualisations in material flow analysis are used to represent data, information and systems that are inherently complex with the aim to simplify their meaning, to create context and convey important information and knowledge.

1 Executive Summary

The size and the complexity of the global material flows have increased drastically over the past decades as a consequence of population growth, urbanization, globalization, technological development (e.g., employment of more complex material combinations in manufacturing), and sophistication in supply chain management. The increased use of materials has been accompanied by and an increased energy use and a growing waste and emission generation along the supply chain. This transformation of the physical economy has resulted in growing concerns for the security of supply with critical raw materials and the sustainability of the economic system more generally.

Various strategies have been developed in order to address the consequences of this transformation, with an aim to control the physical flows of matter and energy (e.g., the Raw Materials Initiative or Climate Change and Circular Economy actions) (European Commission, 2008, 2011, 2015). However, the effectiveness of these strategies is severely hampered by a lack of a robust understanding of the physical economy.

The MinFuture project is based on the hypothesis that a robust map of the global physical economy is needed in order to address these challenges. Current monitoring programmes often have a monetary focus, which is insufficient due to the lack of addressing flows from and to the environment and the lack of mass-balance consistency. Many efforts have been taken over the last years to improve our understanding of the physical economy. Different government agencies, non-governmental organizations, research institutions, and industry associations have started to map individual aspects of the global physical economy, addressing individual countries or regions, and individual materials. While these efforts have increased our understanding, we are still far away from a sufficiently consistent and robust understanding of the global physical economy needed to inform effective policies and business strategies. These efforts are severely impeded among others by fragmented, inconsistent, non-transparent, and incomplete measurement programmes.

The report aims to address this challenge by developing a methodological framework for the monitoring of the physical economy that facilitates the users in reflecting more systematically about the problems mentioned above and to develop more effective strategies for addressing them. The framework proposed is based on Material Flow Analysis (MFA), a tool widely used for tracking materials and energy in the economy.

Four dimensions

The framework distinguishes four dimensions that need to be addressed for a consistent physical accounting of the economy:

- *Stages* represent the various transformation steps that materials go through during their lifetime, including mining, material production, manufacturing of products, their use, and end-of-life management. These principle stages can be analyzed either at an aggregate level or the stages can be refined using a variety of sub-processes. A material cycle is constructed by combining the different stages together and illustrating the flows and stocks of material.
- *Trade* represents the exchange of all goods along the supply chain (between all stages) among countries or regions. Material cycles can be constructed by either showing the trade between a country and the rest of the world, or with individual other countries.

- *Layers* (or linkages) explore the interactions and changing characteristics of materials across their lifecycle. Material flow layers may explore for instance interlinkages between goods, components, materials, chemical elements, as well as energy or value.
- *Time* refers to the possibility to track material flows over time, for example the measurement of historical stocks and flows or the exploration of future stocks and flows of materials by use of scenarios.

Depending on the purpose of an MFA, different dimensions need to be analyzed in more detail.

Seven components organized in a hierarchical structure (pyramid)

The framework further distinguishes seven components of MFA studies:

- *Systems* describe where the materials are located and where they are going within a given boundary. They form the foundation of any MFA as they define the "coordinates" of the measured and unmeasured stocks and flows.
- *Data* represent observations of either stocks (at a given point in time) or flows (over a given time period).
- *Uncertainty* occurs in all practical systems and can result from errors in the system definition or uncertainty in data.
- *Models* are mathematical representations of material cycles and their assumed drivers. Models are used to simulate historical changes in material cycles or to develop *scenarios* for future changes.
- *Indicators* are statistical values derived from the quantified system that provide an indication of the performance of the system. They represent complex systems with individual numbers. They are often used to describe targets and to measure the progress towards reaching the targets.
- *Visualizations* represent the essence of complex systems using graphical displays. They are used to support the interpretation of the analysis.
- *Strategy and decision support* represent the last step of an MFA, where the essence of the findings (interpretation) is expressed in terms of words. The findings can be interpreted from a methodological perspective (e.g., where should monitoring efforts be placed to make the results more robust) as well as from a business and government perspective (e.g., where do we expect challenges or where are opportunities arising).

The pyramid components form a hierarchical structure (pyramid), because the robustness of all components depends on the robustness of the components below.

Key principles for developing robust MFA components

The report describes key principles for each component. These allow practitioners to design each of the seven components in a more robust and transparent way, and to communicate the essence of the findings in a more powerful way.

2 Motivation

2.1 Increasing complexity of problems

Raw materials are the backbone of the value chain of industrial production, playing a prominent role as a source of prosperity, growth and competitiveness in Europe. By contributing to employment[1] and value generation, the secure supply of mineral resources is crucial for the European Union's growth and stability. The global use of mineral raw materials has increased exponentially over the past decades, both in overall quantity, and in number and combination of minerals and elements used for different applications. Population growth, rapid economic development, and urbanisation are now taking place mainly in non-EU countries, and are key drivers of increasing global demand for minerals and metals. The increased global competition for resources threatens the security of Europe's resource supply. The expansion of globalisation has led to a sequential widening of supply chains and their transformation into complex systems that form also the backbone of many sustainability challenges, such as resource depletion, climate change (energy use and greenhouse gas emissions are strongly interlinked with material supply chains), or the impacts of waste flows and emissions to the environment.

The European Commission (EC) has taken a variety of actions to address these challenges, including climate and circular economy action plans. To ensure a sustainable supply of raw materials, the EC has launched two interlinked actions: the Raw Materials Initiative (RMI) and the European Innovation Partnership on Raw Materials[2] (EIP-RM) which has developed a Strategic Implementation Plan (SIP) with 95 actions to foster innovative solutions (European Commission, 2008, 2013). The RMI has three pillars which aim to ensure (i) fair and sustainable supply of raw materials from global markets, (ii) sustainable supply of raw materials within the EU, and (iii) resource efficiency and supply of secondary raw materials through recycling. All of these policies aim at controlling or influencing the complex system of material and energy flows of the economy, which we call socioeconomic metabolism (SEM) or simply the physical economy.

A prerequisite for transforming the physical economy in desired directions is to understand the system to be changed. An understanding of the physical economy is highly relevant for the facilitation of decision makers ability to focus on the relevant parts and develop effective strategies to address the challenges outlined above.

2.2 Existing monitoring frameworks are insufficient

Currently, there are no monitoring programmes for the physical economy. Traditionally, several government agencies are monitoring different aspects of the physical economy, such as geological surveys measuring mineral reserves and mine production flows (in some cases also additional flows downstream, such as metal production or scrap flows), environmental protection agencies measuring specific waste and emission flows, or tax and statistical offices measuring trade flows.

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[1] It is estimated that at least 30 million jobs in the EU depend on the availability of raw materials.
[2] The Partnership aims to raise the industry's contribution to the EU's GDP to 20% by 2020 by securing its access to raw materials.

Current measurements of material (and energy) stocks and flows are insufficient to address the challenges outlined above due to several reasons:

- **Lack of a system perspective**: The current monitoring programs measure isolated stocks and flows, but neglect to show their connections. The lack of a system perspective makes it difficult for government agencies and industry to make use of the data for addressing more complex problems related to the entire supply chains.
- **Incomplete measurements**: Current monitoring programs include large gaps of stocks and flows that are not measured. Due to the lack of a systems perspective, these gaps may not be recognized by policy makers or industry. Of particular relevance are data on critical raw materials, which often are used in comparably small amounts.
- **Fragmentation of data and harmonization needs**: Government agencies in different countries and regions often use different reference points for their measurements. This results in difficulties for comparing data of different countries or for developing aggregate level information, for example on European or global scales. Fragmentation of measurements is a problem within specific sectors such as geological surveys, where a lot of effort is made to subsequently harmonize the inconsistent data. However, it is also a problem between sectors, such as the harmonization of production and trade data.

Several attempts have been undertaken to integrate data from various sources for providing a more systematic overview of the physical economy. Here are three examples:

- EUROSTAT has established a monitoring programme on economy-wide material flow accounts (EW-MFA) (EUROSTAT, 2013). These EW-MFAs track material flows into and out of the economy of interest, but they neglect to observe the processes within the economy in sufficient detail.
- DG-GROW commissioned a study on Raw Material System Analysis (RMSA), which forms one of the pillars of the Raw Materials Information System (RMIS). The RMSA tracks the flows of (mainly critical) raw materials in the European Economy (BIO by Deloitte, 2015). The RMSA provides more detailed information than the EW-MFA, however, the system approach used is crude and not transparent, and therefore of limited use for informing strategies and decisions.
- Several industry associations have started, often in collaboration with universities, to develop MFAs of their materials of interest. Examples include the International Aluminium Insitute (IAI), Worldsteel, or the Nickel Institute. The resolution and the transparency of these studies vary significantly. While these MFAs track individual metals, they tend to neglect the linkages between the different materials (e.g., metals produced as by-products from refining of other metals).

Thus, despite the European initiatives and on-going EU-funded international co-operations, current methods and models for global cycles of materials are based on data that are: (i) highly fragmented, (ii) inconsistent, (iii) measured but not available due to confidentiality reasons, or (iv) not measured at all and need to be estimated, often on weak grounds resulting in large uncertainties. Existing models are thus heterogeneous, incompatible, unreliable, and difficult to understand for scientists and policy-makers alike. In response to these challenges, the MinFuture project is designed to take the lead in coordinating international R&D actions in the field of raw material flow analysis and forecasting.

Efforts to monitor the physical economy are not systematic. The focus is on the monetary economy and the existing system is developed to record monetary rather than physical transactions. Disconnected, non-harmonised data, often describing single flows of materials exist from a variety of sources, but they are not used in a system context and it is therefore impossible at present to monitor material cycles from cradle to cradle. Monitoring of the physical economy is vital, but there are several challenges to overcome to enable moving towards this goal, with the principal one being the development of a framework that can facilitate its systematic development.

2.3 Need for a system-based monitoring

A system-based monitoring of the physical economy is needed in order to effectively address the challenges outlined above. A system based approach would have several benefits:

- Compared to the monetary monitoring, a physical monitoring would provide relevant information about the **economy-environment interaction**.
- It would help the user to better **interpret** the existing physical data.
- It would provide information about the **linkages** between the different data points and thereby add information to the existing data.
- It would allow for a **mass balance consistent accounting**, which is more robust than monetary accounting or an observation of isolated flows.
- It would greatly facilitate the **data harmonization**, which would in term save time and money in the longer time.
- It would make the existing data more **robust** due to the possibility of conducting uncertainty analysis for the entire system.
- It would allow for **model and scenario** development in order to forecast material flows to anticipate challenges and opportunities, or to test alternative strategies.

In short, a system-based monitoring of the physical economy is essential to effectively inform government policies, industry strategies, as well as future measurements programmes.

The following sections of this report describe such a framework. It includes an analysis of its components and provides guidelines to assist its implementation. Moving forward, efforts from governments and industry will be required, including global adoption to ensure its success. This document therefore represents only the start of a 'journey' to monitor the physical economy.

3 Framework for monitoring the physical economy

Material flow analysis (MFA) is the method used to track the physical economy, namely the stocks and flows of material and energy in a system defined in space and time (Baccini and Brunner, 2012). The outcomes of MFA can be used to inform strategies for resource management and emissions control.

The purpose of the framework is not to provide a step-by-step guide to developing MFA. Several other documents can satisfy such needs. Instead, it aims to deliver clarity on the different components of MFA needed for monitoring the physical economy. Benefits and challenges associated with individual components of the framework are described and illustrated with examples, where possible. More detailed examples and analyses on specific challenges can be found in additional deliverable reports developed by the MinFuture project.

3.1 The four dimensions of MinFuture

MinFuture aims to integrate four core dimensions, (1) Stages (2) Trade (3) Layers and (4) Time.

3.1.1 Dimension 1: Stages

The dimension 'stages' represents the various transformation and use stages of materials across their lifetime. The stages can be specific to a material under investigation (e.g. beneficiation stages of crushed rock), but commonly materials are tracked across the whole life cycle, from extraction, through to refining and manufacturing, to use and eventually disposal and recycling. In MFA, materials are tracked using the principle of mass balance within a system that is defined in both space and time (Baccini and Brunner, 2012). The dimension 'stages' is applicable to all non-energy raw materials and a material cycle is constructed by integrating all lifecycle stages.

Material cycles can be developed with different levels of aggregation representing the supply chain. The level of aggregation is governed by the scope of the study. For example, if the aim is to provide a crude overview of the flows of materials in the economy the level of detail in the stages dimension might not need to be on a highly disaggregated level, Figure 1.

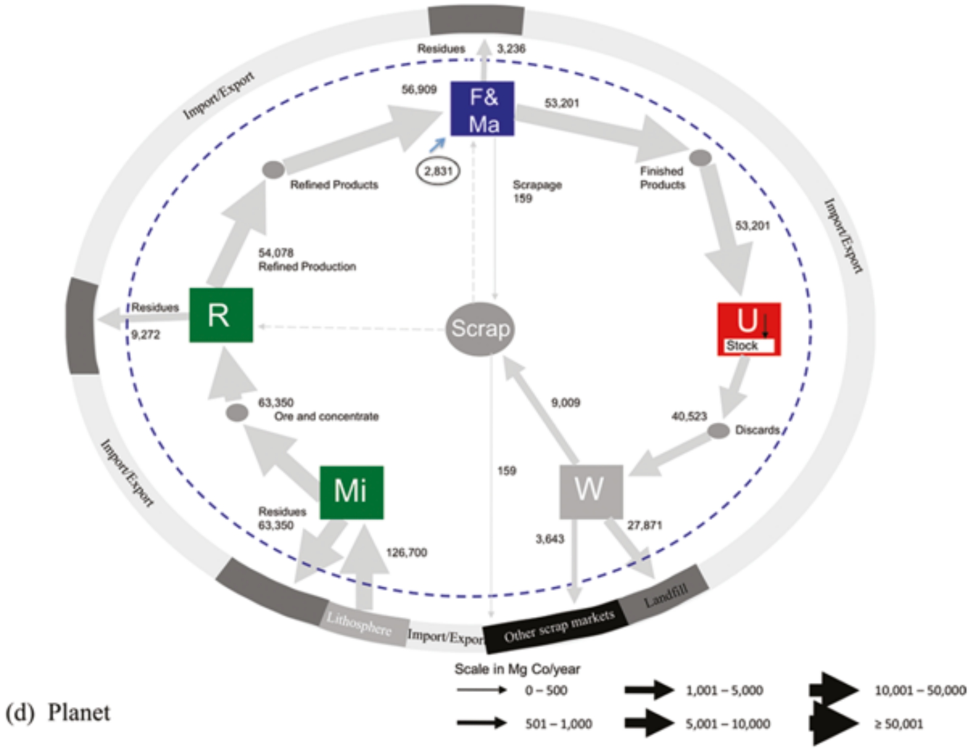


Figure 1: The global cycle of cobalt (Harper, Kavlak and Graedel, 2012)

However, if the aim is to create a detailed understanding and to identify issues and potential solutions, then a higher resolution is needed. For instance, Figure 2 below provides a detailed representation of the global cycle of aluminium in which additional stages and disaggregation has taken place (Liu and Müller, 2013a). This enables to further understand how aluminium flows through our economy and to look for pathway to more efficiently use these resources.

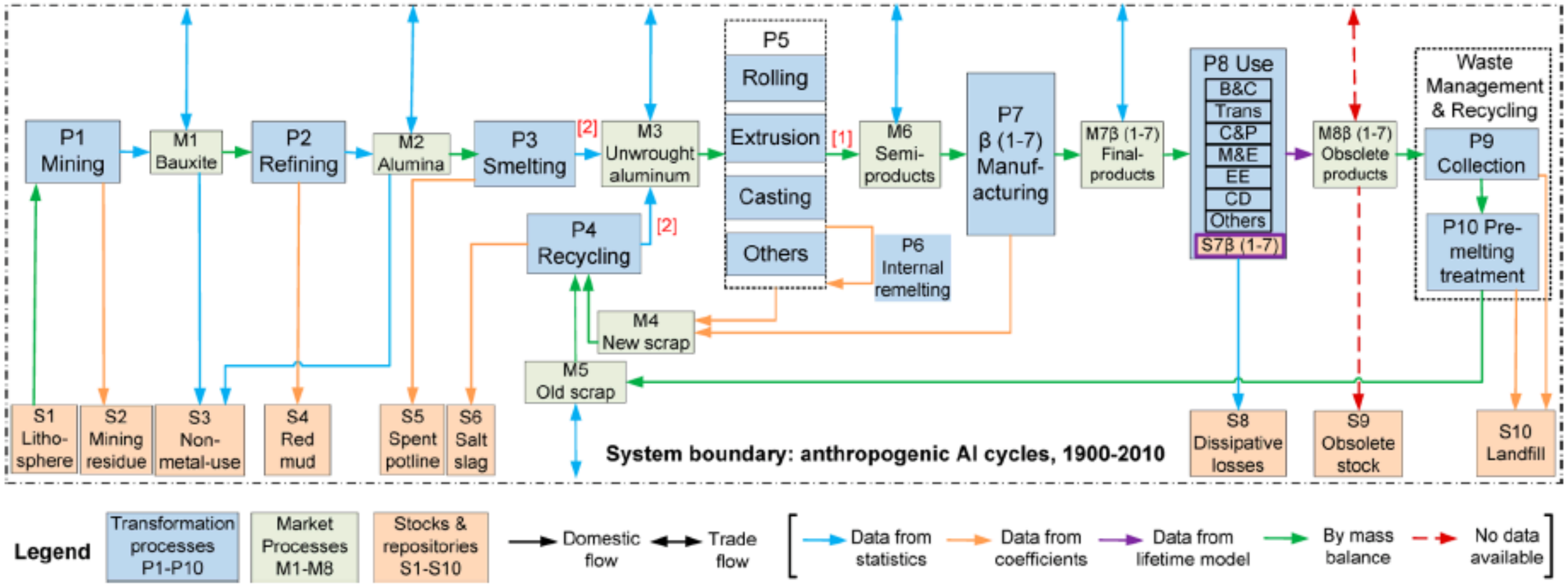


Figure 2: The global cycle of Aluminium (Liu and Müller, 2013a)

3.1.2 Dimension 2: Trade

The EU, along with other developed countries, depends on the supply of raw materials from international markets. Understanding and visualising the global nature of raw materials value chains to ensure a sustainable supply of primary and secondary raw materials for the EU, requires a good understanding of how the EU material cycles are linked to other regions/countries by international trade. The international trade market provides the boundary conditions for global resource flows, and includes country-to-country trade relationships of minerals and goods.

The trade dimension allows us to understand raw material dependencies, and the interlinkages between countries around the world. In our globalized society, most commodities today are traded, either due to the geographical position of resources, or production sites. The trade dimension is linked to the stages dimension in which the stages of a material cycle can occur in different countries; this is exemplified in Figure 3.

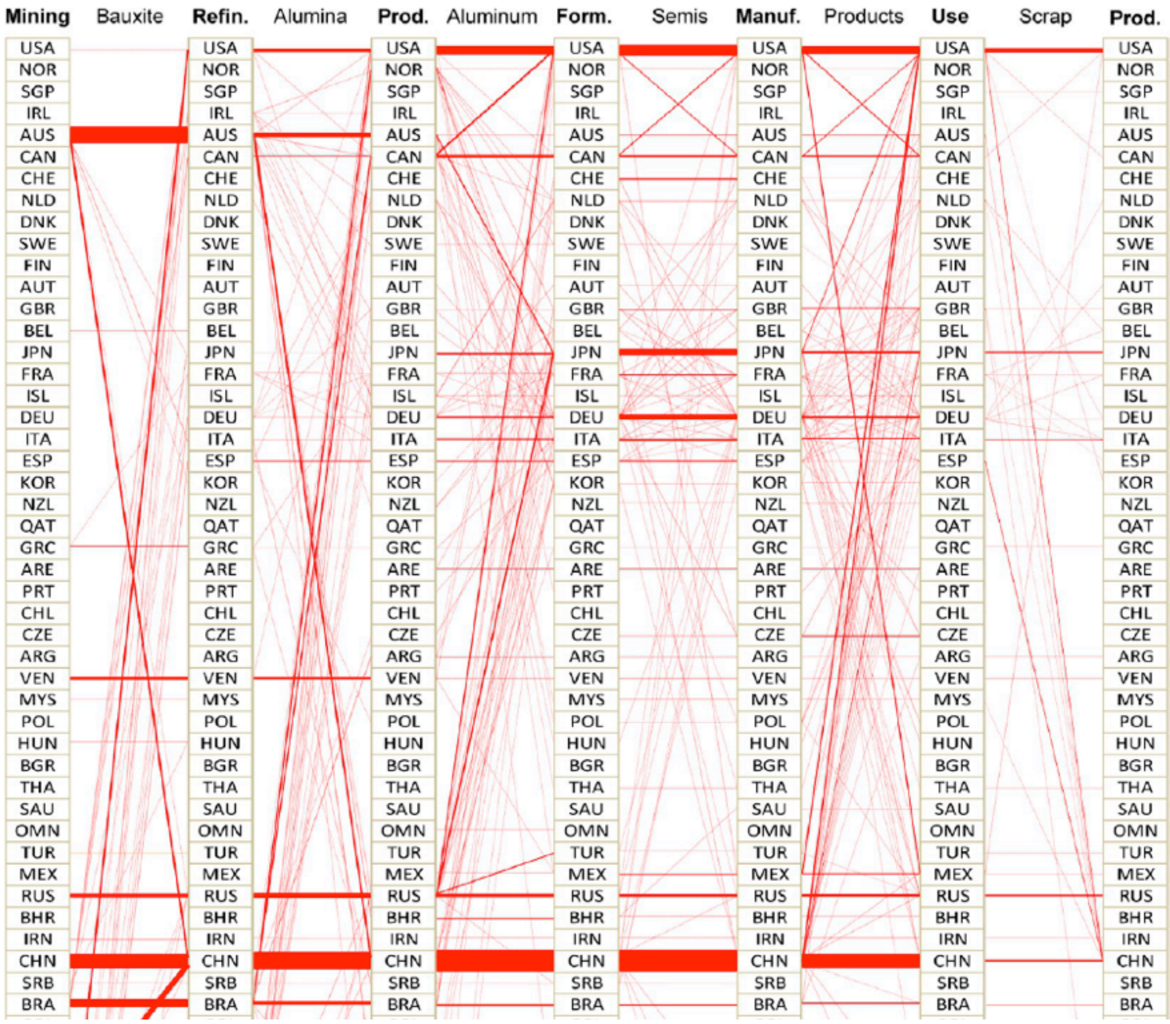


Figure 3: Trade of aluminium across the stages of the material cycle (Liu and Müller, 2013b)

3.1.3 Dimension 3: Layers

The layers dimension explores the interactions and changing characteristics of materials across their life cycle. For example, the layer dimension could explore the transformation of a raw material into different forms of refined materials, semi manufactured products and finished products. Also, materials do not exist in isolation in products, so developing maps where the interlinkages between materials and products are identified can form an additional layer to the mass balance model. Integrating layers into MFA can also be for the purposes of tracking alloying elements, energy, greenhouse gas emissions, monetary values and so on. An example of phosphorus, in which the layer of biomass is the base layer and additional layers are developed to track the dry matter, phosphorus, energy and water within the same model is shown in Figure 4.

Tracking these characteristics is particularly important for critical raw materials (CRMs). They are often found in small quantities and produced as co-products or by-products of other minerals. Technological development however relies on critical raw materials and the transition to clean energy means that more of them in terms of both numbers and quantities will be needed to produce new innovative products. Everyday technology, such as our mobile phones include numerous critical metals and without them, it would not be possible to develop them to the level they are now. However, CRMs are characterised by opaque supply chains and issues around their production (for example, artisanal mining, resource nationalism), market monopolies and low supply from secondary resources, which means that there is a growing need to understand their material cycles in detail. This would enable the development of strategies on security of supply and sustainability to ensure better resource management from both primary extraction and secondary raw material recovery.

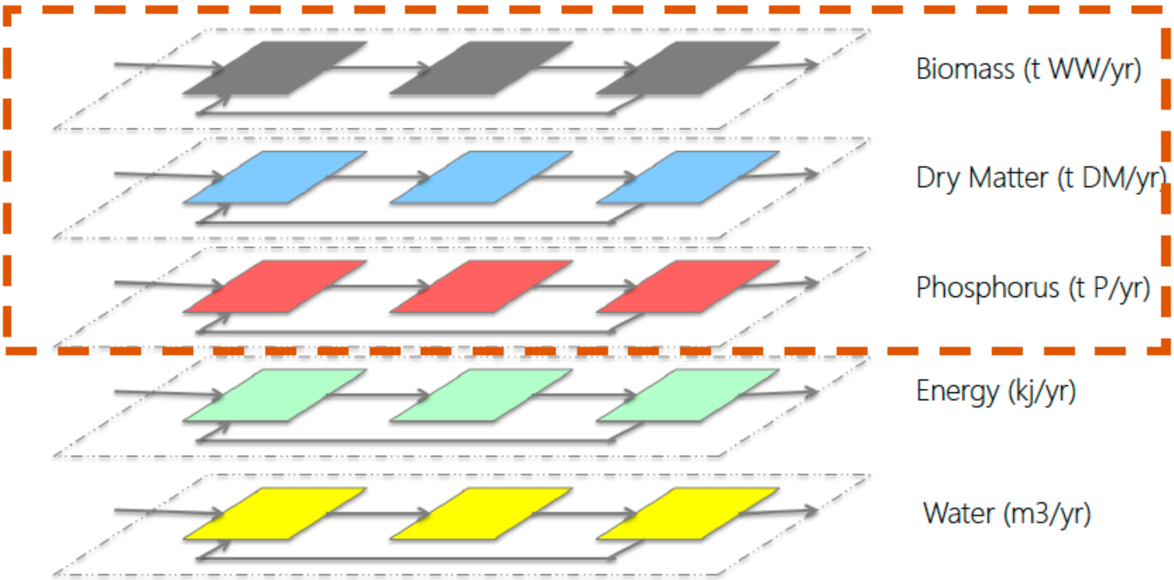


Figure 4: Layers of a phosphorus model (Hamilton, 2017)

3.1.4 Dimension 4: Time

The time dimension provides the basis for model calibration and future scenario modelling (see example in Figure 5). The analysis of historical material flows and their relationship to population dynamics is a key factor for determining system responses and parameter responsiveness for future scenarios. Understanding the dynamics of demand-supply interdependencies, and relating these to, for instance, the planning process for new mining activities (time from exploration to mining often exceeds 10 years) is a key decision making element for supply chain planning. Strategies to secure a sustainable supply of resources for future urban development include balancing future primary and secondary resource potential, as well as accounting for domestic and trade flows. Several other conclusions can be made from models that embed time in their analysis, such as for instance on decoupling, consumption and production, concentration of production over time and changes in patterns of import reliance.

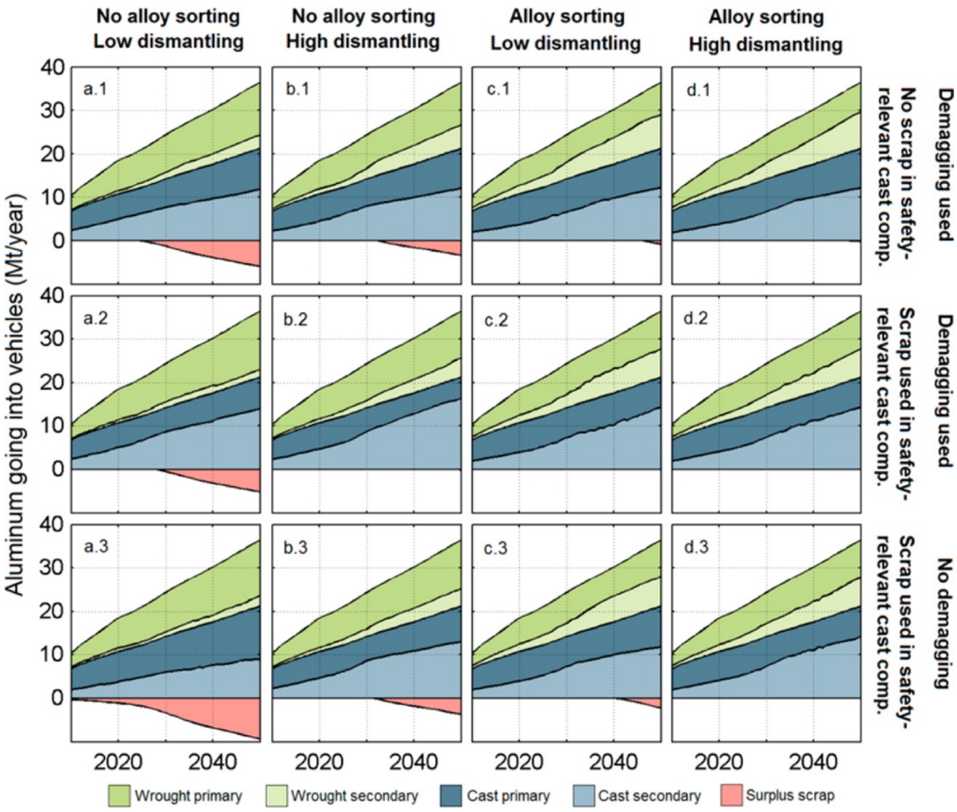


Figure 5: Potential future production of aluminium (Løvik et al. 2014)

In Figure 6 an example of how time can be integrated in MFA is shown. This is based on a dynamic model of the global trade linked model of aluminium in which the flow of aluminium is tracked from 1962 until 2017 with scenarios for the future.

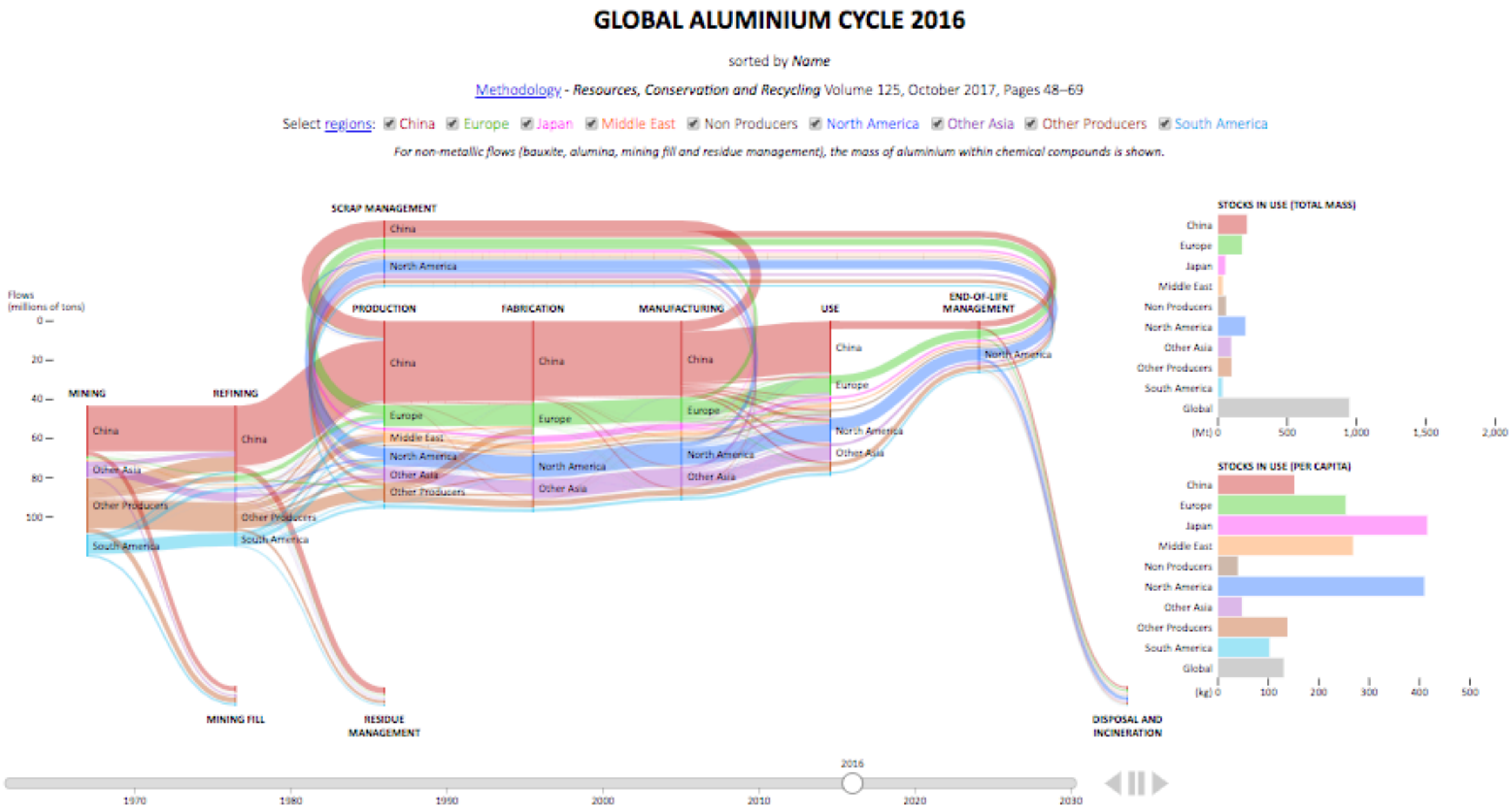


Figure 6: The global aluminium cycle 2016. The model allows investigating the evolution of the aluminium cycle since 1962 (World aluminium, 2018)

3.2 Seven components of MFA

The MinFuture pyramid includes essential MFA components used in the monitoring of physical flows and stocks of materials. These include: systems, data, uncertainty, models and scenarios, visualisation, indicators, and strategy support. The pyramid components are organised using a hierarchical order, because the robustness of components found in the upper level is impacted by the robustness of components found in the lower level. The MinFuture framework provides an assessment of these seven components to support MFA practitioners in their work.

Figure 7: The MinFuture Pyramid comprises the physical economy monitoring framework

Systems define where materials are located, either in the form of stocks or in processes, but also, where they are moving to (flows). Mathematically, systems are defined through (mass or energy) balance equations, which include observed and unobserved flows (e.g. material dissipation). Systems can be defined using different levels of aggregation. This is determined by the objectives of an investigation. Strong system definitions reflect the real system adequately at an aggregation level that serves the purpose of their models. Without good system understanding, the MFA will be of poor quality and may even lead to wrong conclusions. Spending therefore adequate time to understand the real system and how best to reflect it in MFA, is very important. The development of systems requires substantial background research, as well as engagement with multiple stakeholders and industry to ensure that it aligns well with the real one. Ultimately, the system represents a map of the processes, material stocks and flows in a supply chain.

Data represent observations of either stocks (at a given point in time) or flows (over a given time period). A system should be able to reflect reference points of measurement where data are collected. However, often enough, data collection on the physical dimensions of materials is not taking place having the system context in mind. The implication of this is ambiguous datasets that cannot represent the real system well and cannot be used to their full potential in MFA without introducing assumptions on their definition. This often has as a result the wrong interpretation of data. Ideally, data collection should be based on system understanding to reflect the real situation. This in turn will lead to high quality and robust data that can be used to monitor material systems. Data used in MFA are collected from a variety of sources, including national statistical offices, international trade statistics databases, data from geological surveys, trade associations and industry. Assumptions are often needed to fill in gaps in data. In addition, data from different sources are not usually harmonised, for example production and trade nomenclatures may use different definitions, which is also problematic during the MFA compilation process.

Models are mathematical representations of material cycles and their drivers which are used to simulate historical changes in material cycles or to make forecasts for future changes through the- use of scenarios. **Scenarios** are plausible developments for the material cycles that are consistent with the mass balance principle and the assumed drivers. Strong models and scenarios depend on robust system definition and data. There are different approaches to model development, which are explored in more detail in section 4.

Uncertainty is inherent in all MFAs due to errors in system definitions and the data used. Approaches to uncertainty analysis aim at making uncertainties transparent and reducing them. They enable the users to make more robust assumptions and to become aware of the model's strengths and limitations. A good uncertainty analysis addresses both systematic errors (e.g., system definition) as well as random errors (e.g. data). There are different ways to deal with uncertainty, which are presented in more detail in section 4.

Indicators are quantitative measures that are supposed to reflect how close we are to achieving set goals. They are used to analyse and compare performance of businesses, sectors or economies across countries and to determine policy priorities. Strong indicators or indicator sets adequately reflect the system to be controlled in order to effectively reach the goals and avoid problem shifts. There are further information on indicators in section 4.

Visualisations are different maps of complex systems. They can inform decision making in industry and government, by visualizing current status, historical trends, and potential future developments under different conditions. Visualization tools are developed to support the recording (monitoring), exploration (analysis), and explanation (interpretation) of information. The usefulness and quality of visualizations therefore strongly depends on the quality of the underlying system definition, data, and models.

MFA outcomes can support **decision-making** and assist **strategy development**. The following areas may be considered:

(i) Supporting industry and governments to make informed decisions and develop strategies and policy for raw materials. MFA results may find application in a variety of fields that aim at reaching different goals, such as those of the Strategic Implementation Plan (SIP) of the European Innovation Partnership on Raw Materials, the Circular Economy Action Plan, or the Sustainable Development Goals;

(ii) Supporting strategies for more effectively monitoring and forecasting of material cycles, such as the Raw Material Information System (RMIS), through improved measurement strategies, data harmonization, and data integration.

More information about the applicability of MFA to strategy and decision support is provided in section 4.

3.3 The hierarchical structure of the components

The MFA components are organised and linked in a hierarchical order. The robustness of components at the upper level depends on the robustness of the component(s) found in the lower levels. The hierarchical structure of the pyramid is of fundamental importance. Material flow analysis cannot be developed without a system in place and without data that can map to that system.

Forecast models and scenarios are developed upon the availability of systems and data. MFA uncertainty analysis normally takes place during the stage of model development and once a mass balance model is constructed. However, uncertainty is also found in each individual component in the pyramid and may be analysed separately and not part of the MFA during data collection, indicator development and so on.

Visualisations are produced to communicate the outcomes of models and their uncertainty and are therefore located in the pyramid in the level above. Indicators should be developed once an MFA is produced, namely once the complex system of a material cycle is understood and intervention areas have been identified to enable quantitative measures to be produced.

At the top of the pyramid stands the strategy and decision support component. This represents the ultimate goal of MFA, namely to support the decision making process and to facilitate the development of strategies from governments, authorities and industries. Strategies can have diverse purposes, but often around the subjects of resource management and security of supply.

4 Key monitoring principles for the pyramid components

The key monitoring principles presented in section 5, aim to assist practitioners to make informed decisions when conducting MFAs of any given material. They represent guidelines rather than determining what is right or wrong in an MFA. They aim to provide recommendations on how to conduct MFAs or issues that MFA practitioners should pay extra attention to.

4.1 Systems

Systems form the foundation of any given MFA, they represent the coordinate system of the physical economy being examined. Without a coordinate system, the measurements provided by data cannot accurately be placed to flows or stocks. The key principles below aim to illustrate how systems can be developed in order to provide better coordinate systems for some known challenges. Systems are very much linked to data and without proper systems in which the data can be placed within robust interpretation can become a challenge.

4.1.1 Crude ore versus beneficiated ore

Some geological surveys report the crude ore in their statistics, whilst the majority report the beneficiated ore, namely the valuable part of the ore. The difference between the two represents the waste rock, Figure 8. Let us assume now that the aim of a study is to understand global production of a mineral commodity. When compiling data from different sources that report at different points in the system and do not provide sufficient metadata information, for example, the metal content of the crude ore, then it is highly likely that errors are introduced during the calculation process.

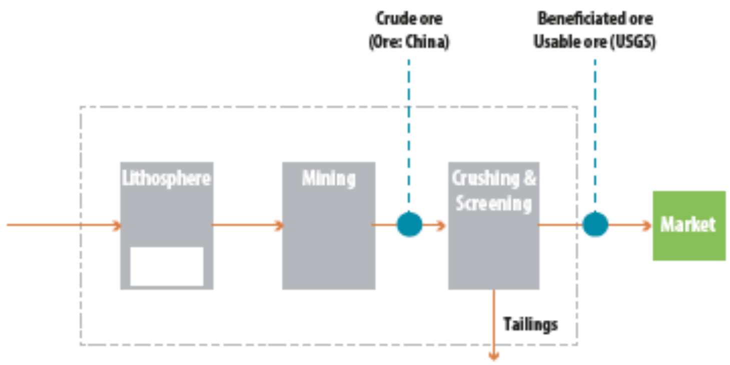


Figure 8: An illustration of the measurement points for crude and beneficiated ore

4.1.2 Production versus sold production

Most statistical agencies and geological surveys report data on production, sold production, or shipment, Figure 9. However, these terms represent different parts of the value chain. Production is the quantity of a material produced directly from a mine in a given year. Shipment and sold production represent the quantity of a material that has been sold in a given year. Often companies have inventories where material is stored after production. Sold production or shipmen may represent a quantity of a material that originates from an inventory. Therefore, the terms production and sold production or shipment do not mean the same thing and should not be used interchangeably as they may introduce errors to MFA. Equally, data providers should try to remove any inconsistencies associated with these terms by providing additional information on the measurement point they represent

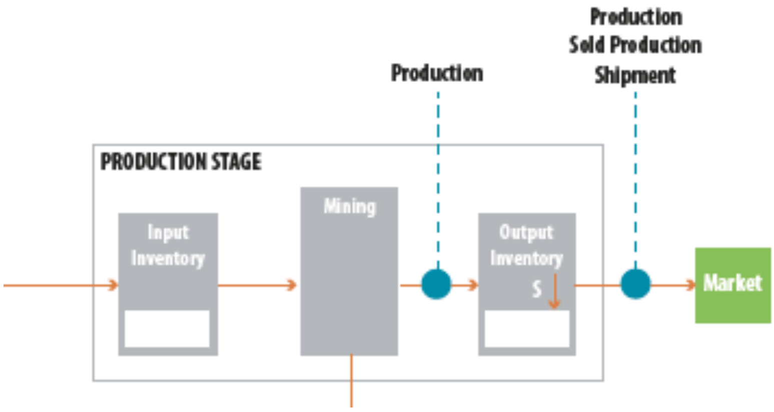


Figure 9: An illustration of the measurement points for production and production sold / shipment

4.1.3 Finished products (steel)

The term finished steel or finished products may correspond to various different production stages, Figure 10. It can be interpreted as the sum of the production of all steel companies, or as the sum of finished steel production by a country. Interpreting the numbers wrongly, for example due to product from company A feeding into company B, may results in double counting especially when attempting to calculation production at country level.

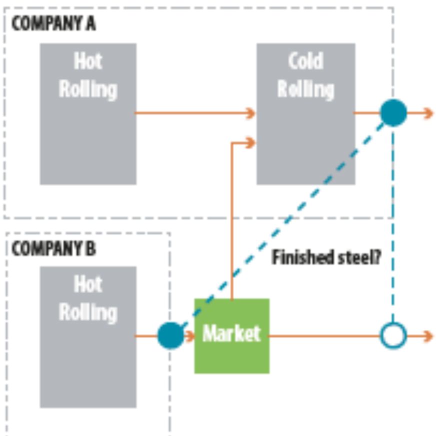


Figure 10: An illustration of the different measurement points that may be accounted for when quantifying 'finished steel' products from different companies

4.1.4 End Use

The term end use is relative and has different meanings for different sectors, Figure 11. Wrongly interpreting the end use statistics can result in inconsistencies throughout the material cycles.

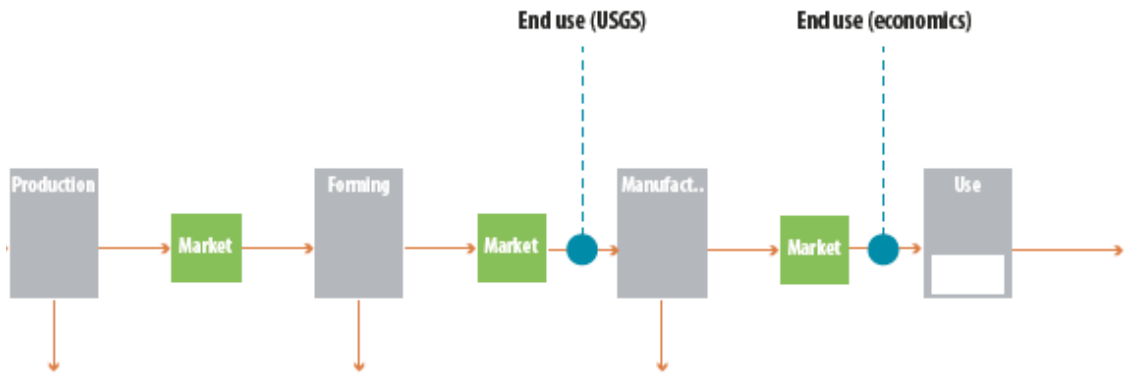


Figure 11: An illustration of different measurement points for end use products

4.1.5 Domestic shipment

Domestic shipment (DS) the "trade" within a single country, cannot be visualized directly when using markets. However, it can be visualized if trade is visualized without markets (Figure 12). To be able to understand the relationship between what a single country produces for own use and their import reliance, it is important that these concepts are properly understood. Production and apparent consumption (AC) can be calculated if DS, import (I) and export (E) are known (see formula), provided that there are no significant stock delays in the market.

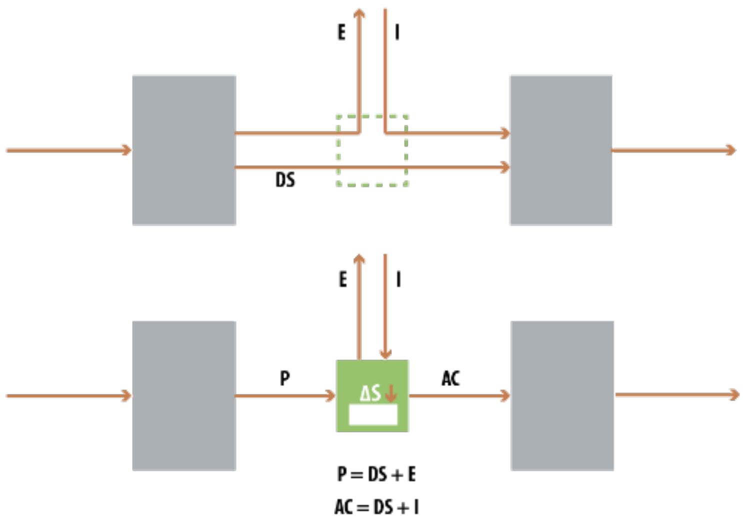
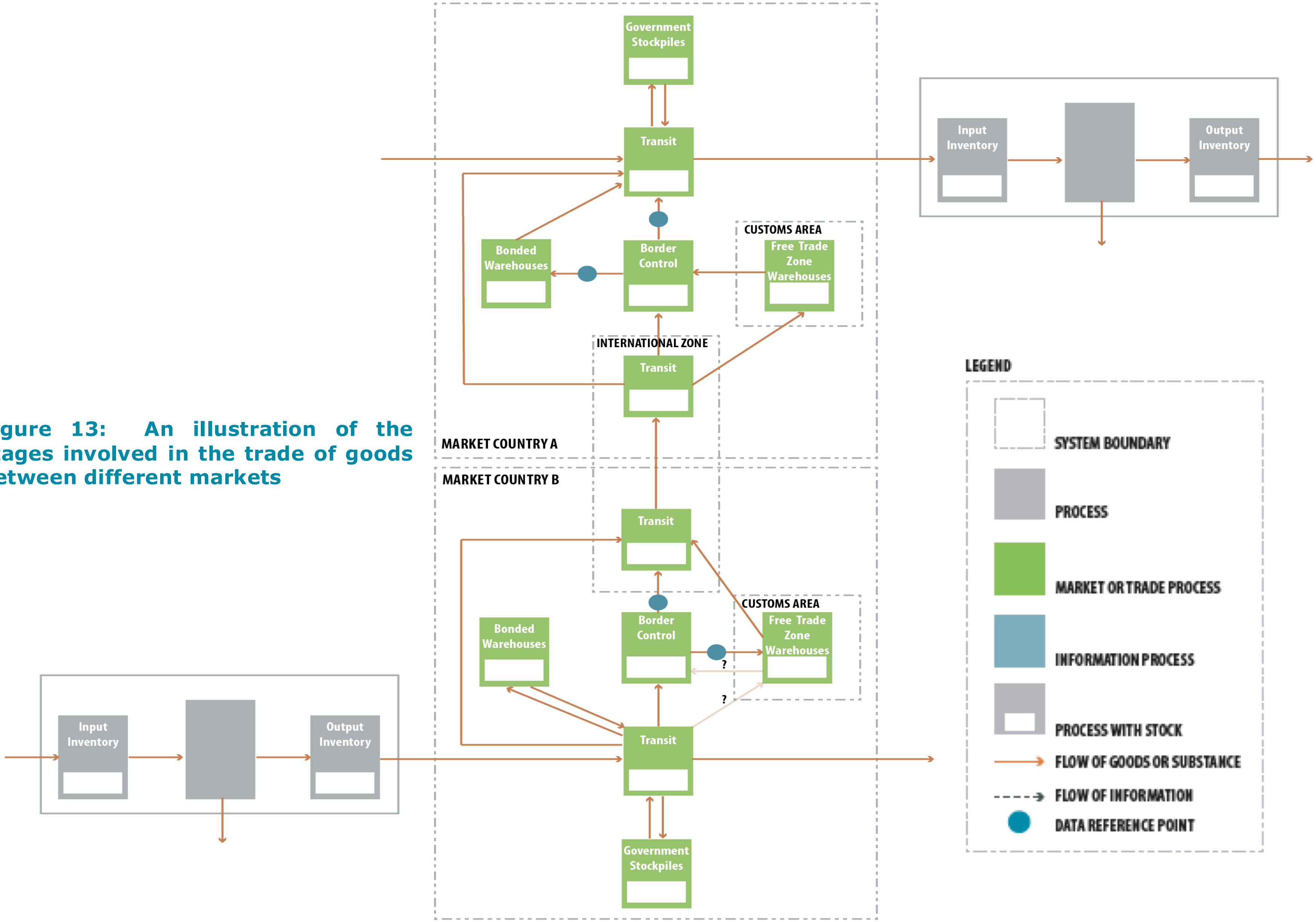


Figure 12: An illustration of how domestic shipment may be accounted for in MFA

4.1.6 International trade

Trade is visualised using markets, however, trade between countries does not happen instantly and can occur in a variety of forms. Markets consists of several sub-processes such as transit, boarder control, customs and warehouses that all can contain stocks which can further lead to delays in the system and to inconsistencies between the measurement (statistics) of import and export. In addition, trade can happen illegally (smuggling), in which the materials are not tracked at all. As an example of possible delays in the system, it is possible to export materials for storage in a bonded warehouse where the material can be stored for some time (possibility to speculate in material prices) before being imported to another country (Figure 13).

Figure 13: An illustration of the stages involved in the trade of goods between different markets



4.2 Data

Data represent observations of either stocks (at a given point in time) or flows (over a given time period). Enabling an efficient monitoring of the physical economy is a data intensive task and requires data along the entire supply chain and across regions and nations. However, currently the data needed for compiling material cycles are often fragmented, inconsistent and not harmonized.

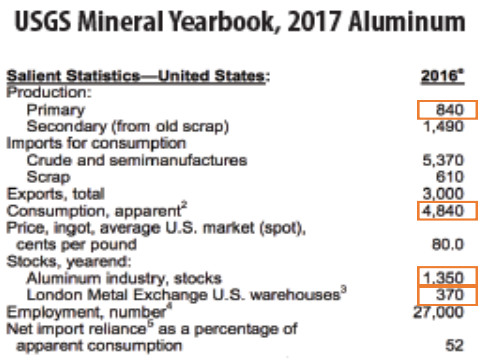
The current data collection is done by several governmental agencies for a variety of purposes. This often leads to different reference points for the measurement and further leads to difficulties in compiling data from several nations and institutions. Data used in MFA are collected from a variety of sources, including national statistical offices, international trade statistics databases, data from geological surveys, trade associations and industry. The data is also not reported within a system context and for this reason individual MFA practitioners needs to gather data from a variety of sources, interpret the data and place them to the best of their abilities within a system. The implication of this is ambiguous datasets that cannot represent the real system well and cannot be used to their full potential in MFA without introducing assumptions on their definition. This often has as a result the wrong interpretation of data. An example of challenge is illustrated in Box 1, in which two systems are shown one aggregated and one refined. Due to the first system being on such an aggregated level it is not clear which measurement done by the USGS that should be placed on the flow between production and manufacturing, production or apparent consumption. However, in the refined system, serval of the reported measurements can be placed at the same time highlighting the gaps.

To be able to monitor the physical economy in a consistent matter data needs to be collected and provided with a system context in mind. Reporting data within a systems context adds information and increases the robustness as it provides coordinates to the measurement. In the figures shown in the section on systems above, the reference points are mapped within a system which reduces the potential for miscommunication. It further allows for an increased level of transparency, by mapping reference points within a system, what we know and our knowledge gaps are made explicit.

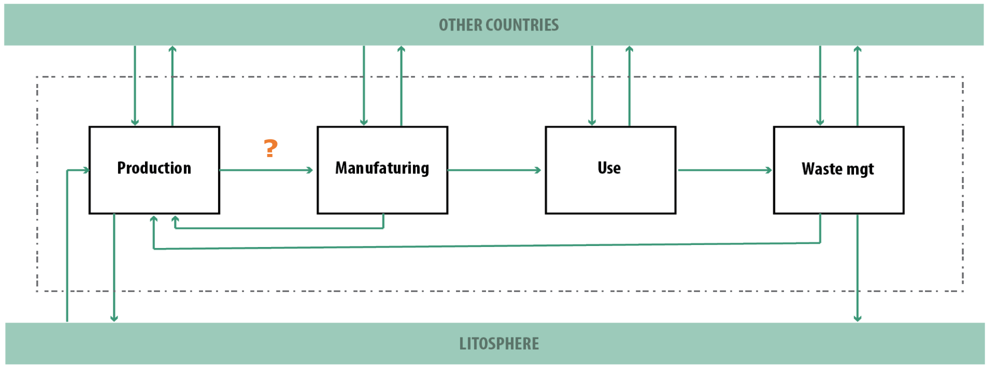
Box 1: Issues with data use in crude systems vs the benefits of a refined system.

From "crude maps with hidden gaps" to "refined maps with explicit gaps"

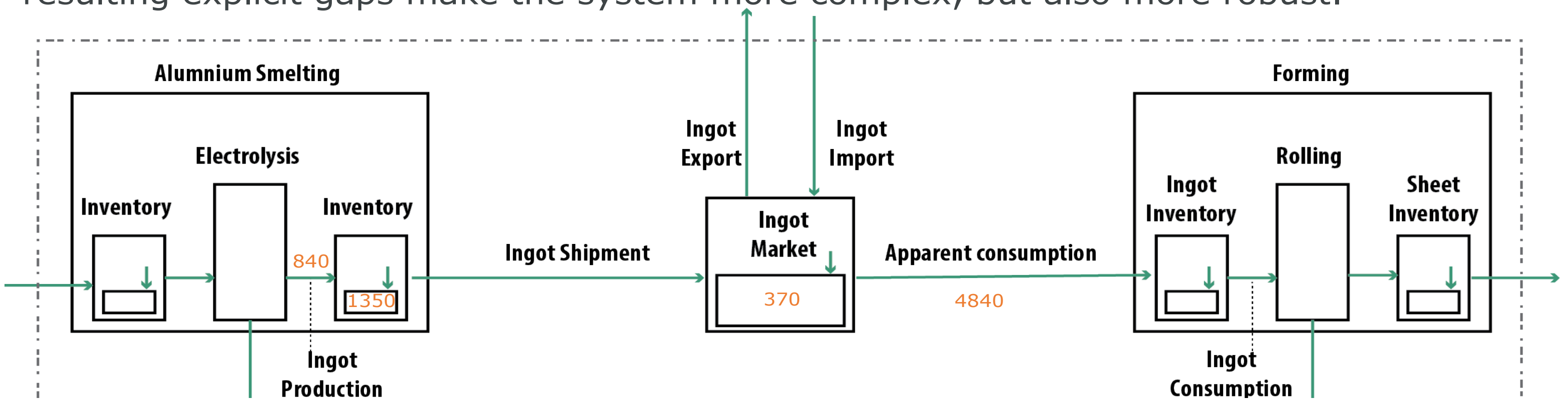
Systems often don't reflect reality of data collection. Aggregated systems can nevertheless be useful for providing a crude overview, but relevant information is lost.


USGS Mineral Yearbook, 2017 Aluminum

Salient Statistics—United States:	2016[e]
Production:	
Primary	840
Secondary (from old scrap)	1,490
Imports for consumption	
Crude and semimanufactures	5,370
Scrap	610
Exports, total	3,000
Consumption, apparent[2]	4,840
Price, ingot, average U.S. market (spot), cents per pound	80.0
Stocks, yearend:	
Aluminum industry, stocks	1,350
London Metal Exchange U.S. warehouses[3]	370
Employment, number[4]	27,000
Net import reliance[5] as a percentage of apparent consumption	52



Refined system definitions can be made to reflect the exact location of the measurements. The resulting explicit gaps make the system more complex, but also more robust.



4.3 Uncertainty

(A more complete description of uncertainty is included in the report of deliverable D3.3, uncertainty influenced by other sectors affecting the physical economy is not discussed here.)

Material flow analysis (MFA), is a term used by a wide range of approaches to describe material and energy stocks and flows in systems defined in space and time. A model can never perfectly represent a real system. Because of that, model predictions are always uncertain. Besides MFA concerns gathering, harmonizing, and analysing data about physical flows and stocks from different sources with varying qualities, therefore data limitations are unavoidable (Chen and Graedel 2012; Džubur and Laner 2017). Although studies of material flow systems can provide useful information, they also depend on data and information and their absence can be a limiting factor. In addition, results of limited or unknown accuracy may have negative impacts on subsequent decision-making processes. Clearly, if MFA is seen as a way of compiling data to create information about material stocks and flows and to aggregate this information to create knowledge about material flow systems, the quality of its fundamental components, data, is crucial (Schwab 2016).

4.3.1 The nature of uncertainty in MFA

In MFA, uncertainty analysis should consider all available information about the system and data and reflect its purpose and data quality. The uncertainty of the data and the accuracy of the results are fundamental derivatives of the evaluation process. As MFA concerns gathering, harmonizing and analysing data about physical stocks and flows from various different sources with varying quality, limitations of data are unavoidable. The majority of data used in MFA are empirical quantities with uncertainty arising from different sources (Laner et al. 2014). The causes, sources and types of uncertainty are summarised in Table 1, Table 2 and Table 3.

Table 1: Causes of Uncertainty

Causes of Uncertainty	Explanation
Non-deterministic behaviour of a system	Chaotic behaviour of a system; As the initial state of a system cannot be reproduced, any imprecisions in the initial state may influence the future of a system in a much greater degree.
Uncertainty of model parameter values	This is due to unknown model variables that have to be adapted empirically.
Uncertainty of model structure	This refers to structural model errors, For example, inadequate selection of model variables, processes, process formulation or spatial and temporal resolution.
Uncertainty due to external influence factors	For example, the influence of environmental, political, governance and other factors that cannot be taken into consideration during the model development.
Uncertainty due to numerical solutions of model equations	This is associated with the misuse of numerical techniques in model equations. In many cases, such uncertainty can be neglected, as it is small.

Table 2: Sources of uncertainty

Sources of uncertainty	Explanation
Statistical variation	This arises from random errors during direct measurements. For example, the copper content in the same type of mobile phones.
Variability	Variability in values due to temporal and spatial changes. For example, the copper content in mobile phones in the period 2000 – 2010.
Inherent randomness and unpredictability	Uncertainty is irreducible in principle because of indeterminacy (i.e practical unpredictability). For example, forecasting copper recovery efficiency in future mobile phone treatment processes.
Subjective judgment	Estimating values of interest using as proxy values measured under different conditions. This often results in systematic error. For example using the copper content of one type of mobile phone to estimate the content of another.
Disagreement	No consensus is reached between scientists, often due to lack of data. For example, long-term mobilisation of copper in landfills.
Linguistic imprecision	The use of imprecise language may lead to misunderstanding and misinterpretation of values. For example, the 'non-ferrous metal content (mainly Cu) in mobile phones is…'. The meaning of the term 'non-ferrous metal' in this sentence is ambiguous.
Approximation	Models are simplifications of real systems and their parameters are approximations of the real properties of the system. For example, assuming that a linear relationship between the copper content of a mobile phone and the content recovered from end-of-life phones is an over simplification.

Table 3: Types of uncertainty

Types of	Explanation
Parameter Uncertainty	This arises from incomplete knowledge about the true value of a parameter, e.g., due to imprecise measurements, (expert) estimations and assumptions
Scenario Uncertainty	Normative choices made during scenario analysis lead to uncertainty, as different choices may generate different outcomes. Normative choices may include the allocation of environmental impacts to different processes, the setting up of thresholds, the time horizon of the analysis, the spatial boundaries and others.
Model Uncertainty	Assumptions and simplifications are made during the development of the model in an attempt to describe real world systems, which leads to uncertainty regarding the validity of the model prediction and its outputs.

4.3.2 Ways to deal with uncertainty

Statistical analysis uses inaccurate data samples to get as decent as possible knowledge of one entity. If there is enough data available, it is possible to use statistics (median, standard deviation). In some situations, however, problems may occur with statistical methods (Hedbrant and Sörme 2001), therefore, different approaches to treat uncertain data have been developed. Methods to deal with uncertainty in MFA range from qualitative discussions to sophisticated statistical approaches, Table 4.

Uncertainty is often characterized without the use of formal procedures, which impairs statements about the reliability of the MFA results based on uncertainty analysis. Therefore, consistent and transparent procedures are imperative for uncertainty analysis in MFA. In addition, different uncertainty types need to be addressed by different concepts used to express and propagate uncertainty.

Based on Laner et al. (2014) a systematic iterative procedure for handling uncertainty in MFA is presented in Figure 14. Depending on the specific application, only parts of the scheme may be completed. Some studies may not warrant full uncertainty analysis because of different emphases of the MFAs. If the MFA is mainly used to quantify material balances to improve the database, steps 1 to 3 are of major importance and step 4 resembles the uncertainty result. If the goal of the MFA does not require describing the inherent uncertainty of model outputs resulting from the data used, then the characterization of data uncertainty (step 2) is less important, but sensitivity analysis and/or scenario modelling (step 5) are important elements to be taken into consideration.

Table 4: Approaches to deal with Uncertainty

Approaches		Explanation
Data classification uncertainty	Asymmetric uncertainty intervals	They are calculated by assigning uncertainty factors to each uncertainty level. Depending on the data source (e.g. recognized authorities vs. informal estimate) and the specificity (e.g. data related to the specific region vs data on a general level), MFA input data are categorized into groups with predefined uncertainty levels.
	Symmetric intervals	Symmetric intervals use probability distributions to represent uncertain values and indicate the uncertainty.
	PEDIGREE Matrix	This matrix consists of five independent data quality indicators, which are used to communicate data limitations, to assess data quality and associated uncertainty.
	Information defects	A quantitative method based on quality indicators and information theory.
Uncertainty analysis	Gauss's law of error propagation	The propagation of uncertainties can be evaluated by applying Gauss's law of error propagation to a function of interest.
	Data reconciliation	The idea of data reconciliation is to statistically adjust the measurements and estimates in order to resolve contradictions and find the values that fit the model the best.
	STAN Software	STAN is a ready-to-use tool for doing MFA while taking into account uncertainty.
	Mathematical material flow analysis	Uncertain model parameters are specified using different kinds of probability density functions.
	Probabilistic material flow analysis	This is a modelling approach for probabilistic MFA
	Monte Carlo simulation	Monte Carlo simulation was devised as an experimental probabilistic method to solve difficult deterministic problems since computers can easily simulate a large number of experimental trials that have random outcomes.
	Fuzzy set theory	Fuzzy mathematics provides a computationally efficient alternative to probabilistic methods for representing data uncertainty
Sensitivity analysis		Analyses the effects of parameter uncertainty or variations on the model results relatively, without trying to capture the true range of variation

Approaches	Explanation
Comparison of model structures	Comparisons of model structures are not common, but they are possible and some examples are available.

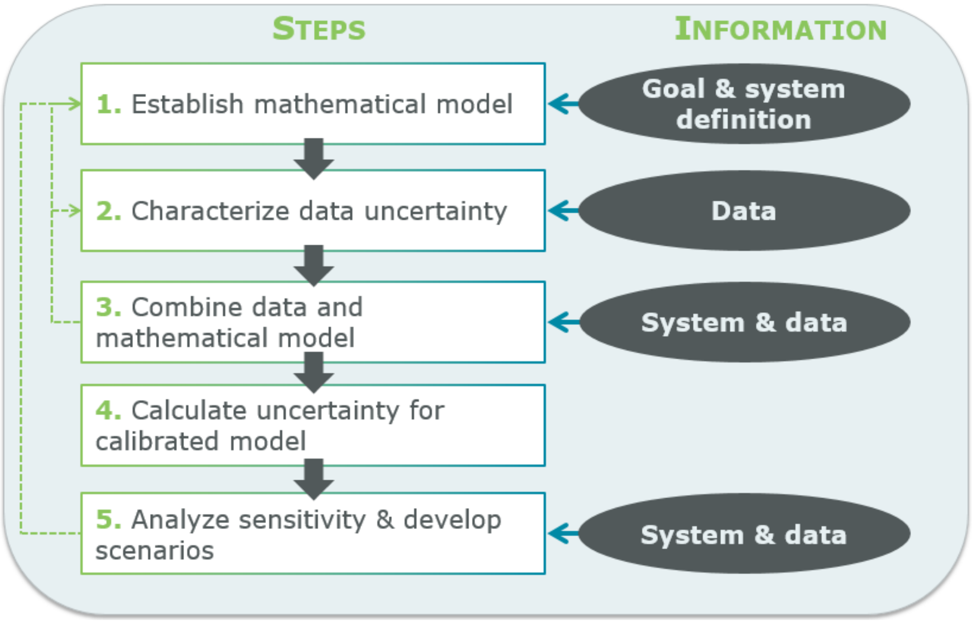


Figure 14: Schematic illustration of a systematic procedure for uncertainty analysis in MFA

4.3.3 Recommendations for considering uncertainty in MFA

The schematic framework in Figure 14, should be considered when incorporating uncertainty analysis in MFA, but could also be used to justify the approach followed for quantifying uncertainty in a study.

In the pyramid, uncertainty is associated with all of its components as illustrated below.

- System: A model is a simplified version of the real system, which is difficult to replicate perfectly and therefore uncertainty is inherently present. The first step for handling uncertainty in MFA is to define the elements of the system and the mathematical relationships between them in consideration of the mass balance principle.
- Data: Because data often originates from different sources, it is unavoidably of varying quality. To deal with uncertain data appropriately, functions need to be characterised. If sufficient empirical evidence is available, statistical parameter estimation techniques or goodness-of-fit tests can be applied.
- Model: Assumptions and simplifications are made that lead to uncertainty regarding the validity of the model predictions to reflect real world situations. Usually, model equations are solved numerically and therefore associated uncertainty is low. For exploratory MFA, sensitivity analysis is used to evaluate the effects of parameter variation on the model outputs. It forms the basis to identify critical model parameters, which can influence the material flows in the system and therefore the final outcomes.
- Indicators: The calibrated model, where satisfying agreement between data and model results has been achieved, is used to calculate the model outputs (material

flows and associated uncertainty). Indicators and their associated uncertainty can therefore be calculated. It is also possible to interpret uncertainty estimates for the resulting flows.

- Visualisation: It is possible to visualise uncertainty in many different ways, depending on the kind of visualisation of the MFA itself (e.g. resolution), the related results (e.g. Sankey, Pie, paired bar, maps, stacked column) and the available data.
- Decision-making: Although studies of material flow systems can provide information and convey knowledge, they also depend on information and knowledge in their production process. A lack of useful information can be a limiting factor about the level of detail provided in an analysis with subsequent influence on decisions to be taken when considering such result. New challenges emerge when the qualitative discussions of political science meet the quantitative approach of physical science. There seem today to be little support for how few, subjectively estimated data with large uncertainties should be taken into account. Still, there is a need to consider and calculate results from uncertain data (Hedbrant and Sörme 2001). It is important therefore to convince data providers to include data uncertainty in their publications. In addition, often decision-making, whether this is policy or strategy development have a broader scope and focus and may account for multiple parameters that have not been taken into consideration in the model development (e.g. social impacts, job opportunities etc). In an ideal scenario, the scope of a study should be informed about parameters of influence that are beyond the scope of MFA to account for uncertainty accordingly.

In conclusion, there are a handful of applicable approaches to consider data uncertainty in MFA. The employment of MFA software would facilitate the implementation of these approaches and reduce the additional workload. However, such software support is not yet on the market (with the exemption of STAN3, which is limited to normally distributed values) and there is a strong necessity to fund such development. Only then, MFA could enter into an era where reporting uncertainty ranges of stocks and flows is integrated during the study development stage. This would help to judge or gauge the reliability of MFA studies and allow comparative studies to take place.

4.4 Models and Scenarios

MFA is a quantitative assessment of material flows and stocks in a system and thereby provides a basis for system optimisation. Models are mathematical representations of material cycles. MFA models are developed to address issues around resource management, for example, monitoring material cycles, development of strategies to address resource utilisation concerns, waste minimisation, identification of supply bottlenecks, investigation of environmental implications associated with material use and others.

Forecasting future material flows and stocks is another significant use of MFA models. Estimation of future material flows is important and finds use in several policies, for example environmental (Van der Voet et al. 2002), raw material safeguarding, land use planning, but also in market analysis and economic studies.

The optimisation of material flow systems is typically done by comparing alternative management scenarios. Scenarios represent plausible futures. Demand and/or supply of raw materials can be predicted by scenario analysis, which uses predefined assumptions in mathematical functions to provide prediction results. Various different scenario drivers are perceived in investigations of material systems. A driver is any natural or human-induced factor that directly or indirectly causes a change in a system. A direct driver unequivocally influences ecosystem processes. An indirect driver operates more diffusely by altering one or more direct drivers. Global driving forces include demographic, economic, socio-political, cultural and religious, scientific and technological, and physical and biological parameters. Drivers in categories other than physical and biological are considered indirect. Important direct, namely physical and biological drivers include changes in climate, plant nutrient use, land conversion, and diseases and invasive species (Nelson et al. 2006).

4.4.1 Key principles of MFA models

A range of criteria is used to define MFA models. These are grouped in the four dimensions (i) stages, (ii) trade, (iii) layers, and (iv) time, as presented in Table 5. Additional criteria relevant to data and the overarching scope of the MFA model (general issues) are grouped together under the "transversal" attributes (Table 5).

Table 5: Criteria to characterize MFA models

	Attributes	Criteria
Four dimension	Stages	processes within the system boundaries, losses,
	Trade	spatial Level
	Layers	material, substances, end-use sector categories, products, environmental aspects
	Time	time interval, modelling approach, Lifetime modelled as
Transversal	Data	database, data requirements, type of analysis, visualisation, data uncertainty
	General	purpose, contribution to decision making, shortcomings

MFA models can have different spatial boundaries (stages and the trade flows). A fix or standardized system definition has the advantage of making different systems (or economies) comparable. A flexible system definition allows for a detailed analysis of critical parts of the system. The system definition is therefore problem- or case-oriented, but less suitable for making comparisons. A key challenge when developing refined system definitions is data availability and the compatibility between different datasets, for example production and trade data.

MFA models can address one or several properties of the stocks and flows of goods in a system. The selection of the layer dimension properties (e.g. total mass, substances, energy, monetary value, multi-layer approach) is a consequence of the problem description.

MFA models can integrate the time dimension in different ways.

- Static models are available on global and national scale. A static MFA is concerned with generating a better understanding of a material system based on simple accounting principles (i.e., mass-balance equations).
- Dynamic models are primarily used to investigate the stock build-up of materials in society (i.e., secondary resources) and in the environment (i.e., dissipative losses) based on the investigation of material flows over time.
- Stationary models also consider time, however in stationary models, things do not change over time – all system variables are invariant under time shift. Stationary

models usually consist only of flows, while stocks are omitted or assumed not to be changing. Traditional input-output models are typical examples of stationary models.

- Quasi-stationary models are similar to stationary models; however, the stocks may change linearly over time, while flows are assumed constant.

Stocks of materials can be measured by two different methods (Box 2).

- The top-down approach usually derives the material stock from the net flow; the difference between inflows (consumption) and outflows (discard). The methods used in top-down studies are further differentiated in input-driven (driven by the input in the stock) and stock-driven (driven by service units provided by the in-use stock) approaches. Furthermore, the modelling approach can be either a delay approach (based on lifetime functions) or a leaching approach (based on fractions of the presented stock.
- The bottom−up approach directly estimates the stock by summing up the material in question present within the system boundary at a certain time.

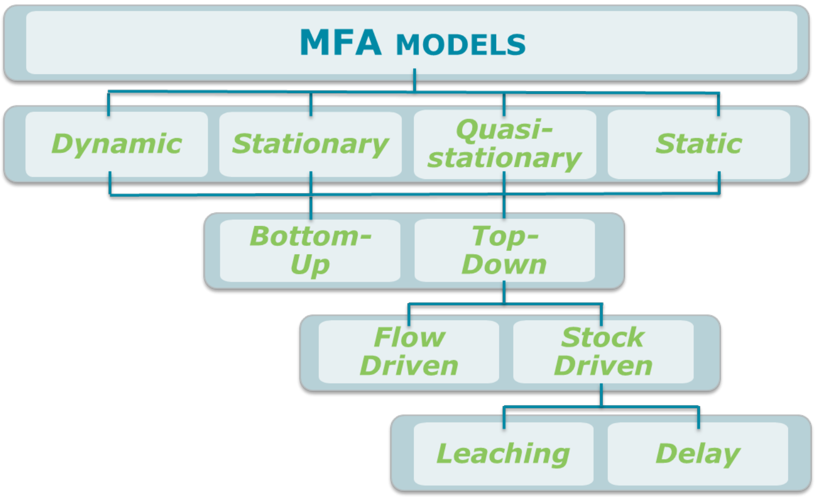


Figure 15: MFA Models and approaches used for estimating material stock

MFA and other related methods integrate the attributes of time (vertical axis) and space (horizontal axis) as shown in Figure 16. MFA and SFA models present substantial advantages when compared to other common methods, such as EW-MFA (Economy wide material flow analysis). Overall, they provide more detail, are more flexible as spatial and temporal boundaries can be varied and they can take into account both material flows and stocks.

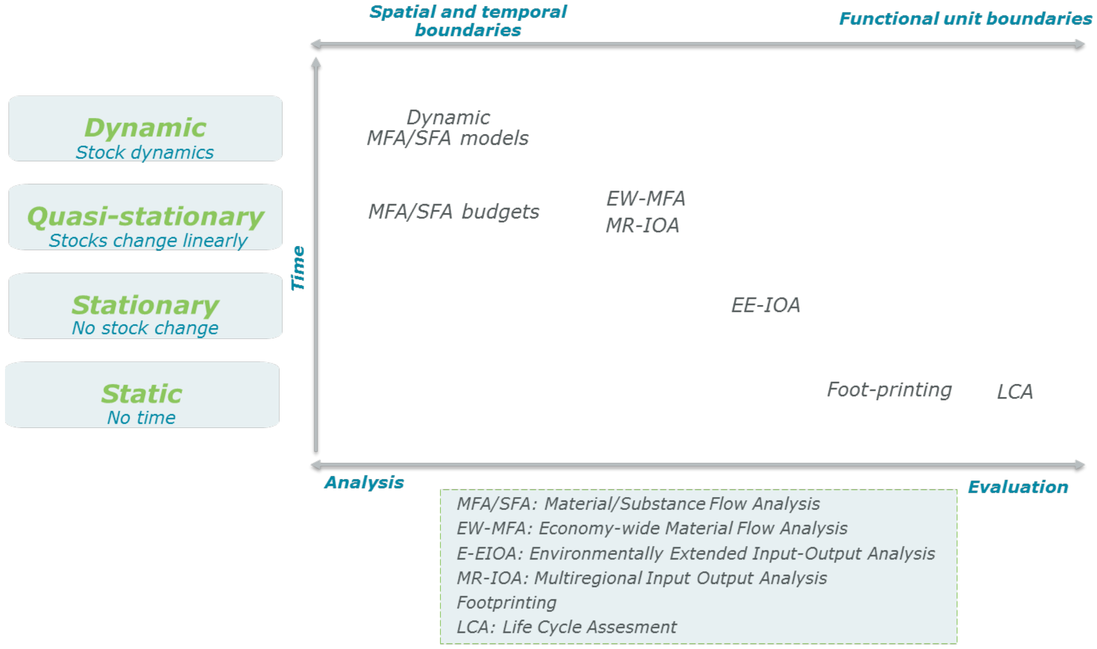
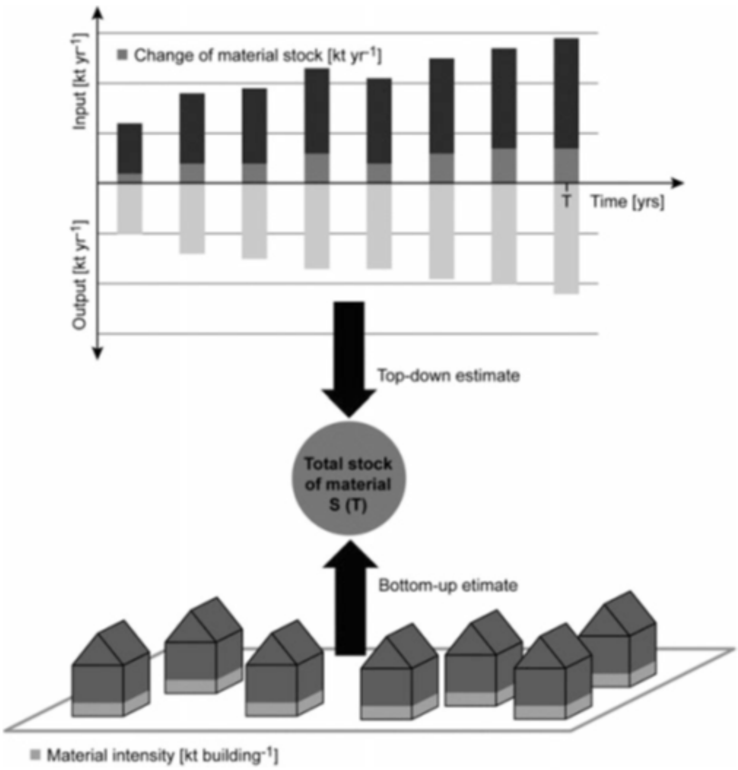


Figure 16: Assessment of different MFA approaches and related tools, and the way they integrate time (vertical axis) and space (horizontal axis) in their analysis.

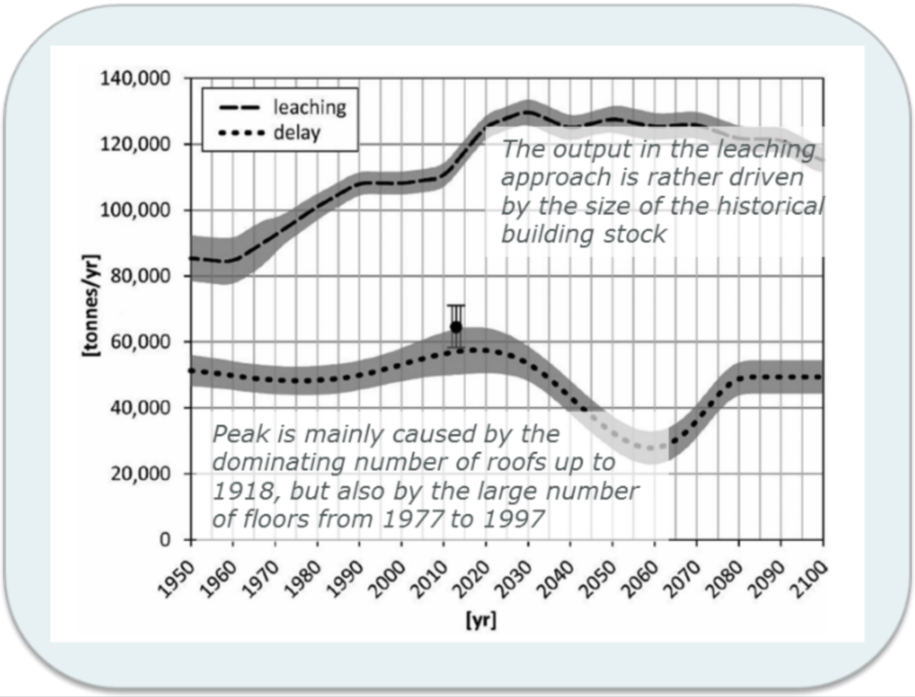
Box 2: Top-down and bottom-up approach use in estimating material stocks (Laner and Rechberger 2016)

The two different approaches (top-down and bottom up) are used to determine stock in buildings of a specific material at time T. For the top-down estimate, a time series of input-output balances is used to calculate the total stock. The bottom-up approach derives the total stock by estimating the material intensity in all relevant products.



Box 3: Estimating material stocks. The delay versus the leaching approach.

A comparison of end of life (EOL) wood between the leaching and delay approach in presented in the figure below (Džubur and Laner 2017). In the leaching approach, wood stock in buildings is calculated by accounting the building stock at specific time intervals combined with estimates of demolition and renovation rates and wood content in buildings at the same time intervals. In the delay approach, End of Life (EoL) wood flows and contaminants contained therein (e.g. lead) are determined based on past wood inputs and product lifetimes. The two approaches reach substantially divergent results due to differences in the employed methodologies and data deficiencies. The decision to use one approach over another should be based on the scope of the study, the availability of data and their associated uncertainty.



In order for MFA models to be widely applicable, it would be appropriate to establish standardised system definitions in all four dimensions of the physical monitoring framework proposed here. This implies, for instance, precise definitions of the life cycle stages, the required layers, as well as the methodology for estimating outflows in a prospective modelling approach. For the layer dimension in particular, a multi-level approach would be desirable, where environmental and economic aspects are included alongside the mass balance layer to provide different viewpoints and a holistic approach. At the "substance" layer it would be valuable to account the quality of the substance in addition to the quantity. This is especially relevant for critical raw materials, which otherwise would be negligible, and therefore dismissed, in a mass flow context.

A more complete description of the diverse MFA approaches, models and related tools is included in the MinFuture deliverable report D3.2 (Villalba et.al, 2018).

4.5 Indicators

Indicators stand for quantitative measures that aim to reflect the status of complex systems. They are used to analyse and compare performance of businesses, sectors or economies across countries and to determine policy priorities. The use of indicators in policymaking is very tricky. On the one hand, the indicator should provide a basis to control a complex system, but on the other hand, few well-intended but poorly selected indicators may not be able to capture the relevant parts of the system.

A careful selection of indicators or indicator sets is therefore of uttermost importance for transforming the socio-economic metabolism in a desired direction. If the system of the socio-economic metabolism is not reflected well in the indicator set, there is a risk that policies based on indicators have unintended side effects that impede rather than facilitate the overall goals. A substantial amount of indicators is available.

4.5.1 Key principles of indicators

Existing indicators relevant to raw material can be characterised by various criteria. The first box in Figure 17 includes a list of diverse criteria that may find use during characterisation (e.g. Units, Life Cycle stage). Based on these criteria, indicators can be grouped in different evaluation groups, which reflect their objective, like "material flow and stocks indicators among other groups as illustrated in the second box of Figure 17. Each of the evaluation group includes a list of indicators. The third box of Figure 17 shows some of the indicators included in 'Material flow and stock indicators', such as 'EU share of global production', 'Export restriction', 'spatial distribution of material flows', etc.

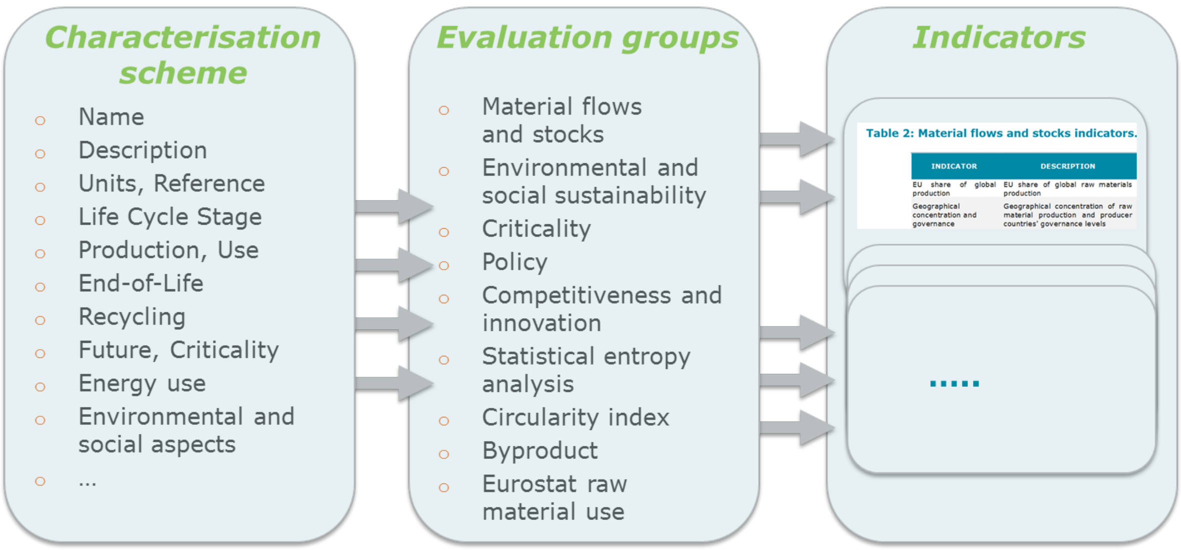


Figure 17: Characterisation and evaluation of indicators

Indicators should be used to complement consistent monitoring of the socio-economic metabolism. Therefore, the following conditions should be respected.

- Indicators are needed to represent both the goal and the means to achieve goals. In general, there is a trend for a service-oriented economy and indicators should reflect this shift from owning to using. For example, people are not interested in having natural gas to heat their house, but they are interested in having a warm house. Consequently, materials are not in focus but the service these materials provide.

- There is a need to differentiate between goals (e.g. increase resource efficiency, reduce environmental impact) and the means to reach that goal (i.e. increase recycling, use renewable energy).
- Indicators should primarily provide information if goals are achieved and secondarily, how they will be achieved.

Different stakeholders should be able to understand the definition of the indicators and loopholes must be closed, so that indicators should not me be misused.

- Individual indicators can be defined using MFA.
- Data availability is important.

Quantitative physical indicators need to be complemented by a set of different indicators, used for different purposes to provide a holistic approach, for example environmental, financial, social indicators.

- A set of indicators is needed. Reliance on a single indicator should be avoided.
- The selection of the indicators can be adjusted to the properties of the system.

4.5.2 Recommendations for the use of indicators

A poorly chosen set of indicators may lead to a situation where industry makes large efforts to reach the targets, but this has detrimental side effects on other parts of the system. It is important to complement indicators with consistent monitoring of the socio-economic metabolism. The following recommendations are made regarding the use of indicators.

- MFA can be used to understand the reasons behind certain regions being able to reach their targets/objectives easily, while others face difficulties.
- MFA scenarios can be used to test the usefulness and the effectiveness of different indicators / indicator sets. These scenarios help to identify potential synergies and goal conflicts between individual indicators.
- Indicators need to be based on a system. To create an indicator you need to have a good system understanding.
- Capturing systemic change with indicators solely is challenging.

Indicators are extremely important, but their scope can be limited. Indicators on raw materials are used to define problems, to formulate policies, and to implement policies. The aim of the policies informed by raw materials indicators is always to change certain aspects of the socio-economic metabolism. Since the different parts of the socio-economic metabolism are all linked with each other, we can also say that the aim is to transform the socio-economic metabolism in a desired direction. This is a not a trivial task, because (i) the socio-economic metabolism is highly complex (dynamic, multi-layer, international supply chains); (ii) the socio-economic metabolism is still poorly understood; (iii) indicators provide a simplified picture of the socio-economic metabolism; (iv) the desired direction is often not clearly defined; and (v) there are many, often diverging, interests of different stakeholders.

In conclusion, it is important not to rely entirely on indicators. It is not possible to represent the systemic nature of material cycles with indicators only. Policy and decision makers need to have an understanding of the system in focus prior to proposing targets and setting measures. A more complete description of indicators is included in the MinFuture deliverable report (D3.2) (Villalba et.al, 2018).

4.6 Visualisations

Visualisation in the modern world is essential and foundational for communication. It is easy to overload the readers' senses with too much information, yet with some time and effort, we can convey and impart complex ideas and structures using visual aids that otherwise may be difficult to explain through the written word alone. Good visualisation is the art of simplifying, creating context, and imparting meaning to data, to tell a coherent story.

The physical economy monitoring framework seeks to provide methods and guidelines for structuring MFA data, enabling a more comprehensive understanding of mineral and material systems. Visualisation is one of the key components described in the Pyramid (see section 3), while the MinFuture Core Dimensions (see section 3) describe four dimensions which are key to MFA studies: stages, trade, linkages, time. Uncertainty and stocks are added to this list to create six core dimensions for which visualisation might be required.

4.6.1 Review of visualisation theory and principles

There is a long history of visual theorists and designers defining principles of analytical design' with key contributors including Edward Tufte, Jacque Bertin, Stephen Few, and Jock Mackinlay. Effective visualisation is found in simplicity, data visualised in its most naked or pure form, void of frivolous additions. Tufte (2006) presents six foundational principles of analytical design for communicating the essential information in visualisations:

Principle 1: Show comparisons, contrasts, differences.

Principle 2: Show causality, mechanism, explanation, systematic structure.

Principle 3: Show multivariate data.

Principle 4: Integrate words, numbers, images, diagrams.

Principle 5: Describe the evidence.

Principle 6: Content must be relevant, have integrity and be of significant quality.

Bertin in his book 'Semiology of Graphics' (1983) describes seven foundational variables of graphical perception, which relate to the way we perceive information through sight. Figure 18 below shows these position and retinal variables against their strengths and weakness for displaying information as a point, area and line.

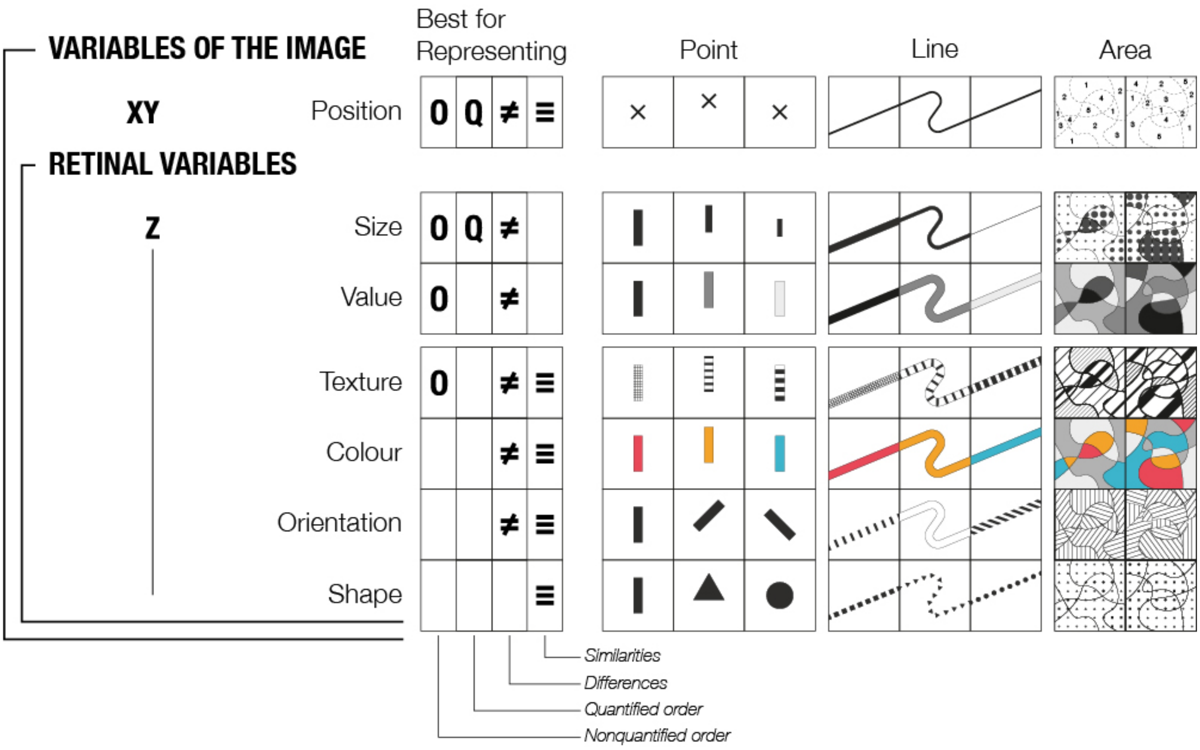


Figure 18: Foundational variables of graphical perception and their strengths and weaknesses (Bertin, 1983).

4.6.2 Good visualisation

Visualisation matters because it is an essential part of the way we communicate information to others. Tufte (2006) comments that 'the world we seek to understand is profoundly multivariate' and therefore visualisations by association must also be multivariate. The aim of the visual designer is to draw out clarity from this complexity.

Two types of visualisation tools are required for telling data driven stories.

- Elicitation tools are used for extraction and interrogation of the MFA data, to ensure credibility and extract clear narratives.
- Communication tools are used to convey the data structure and narrative to the reader.

The process of telling a visual story is analogous to the Google Mapping approach which takes traditional maps, creates journey options and keeps standout routes, Figure 19.

Similarly, for visual story-telling, an interactive data environment can be developed, where tables of MFA data (maps) are structured, allowing the creation of data stories (journeys) and communication of these stories to decision makers (standout routes), Figure 20.

Figure 19: Visual storytelling processes analogy to Google mapping

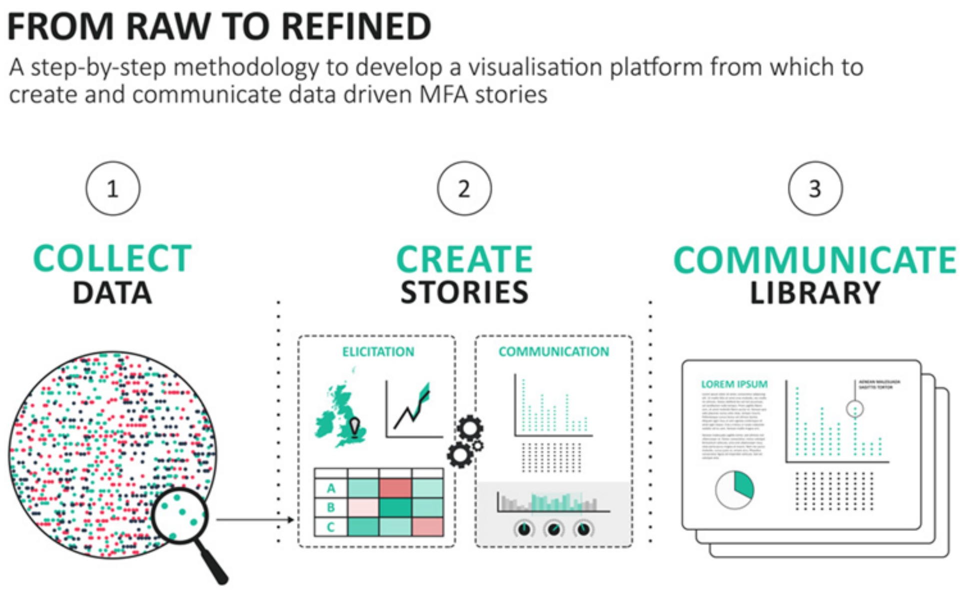


Figure 20: A systematic approach to developing data driven MFA visual stories

4.6.3 Use of visualisation in MFA

An analysis of the types and forms of visualisation used across 48 MFA studies, sourced from research publications and online interactive models was undertaken. The charts below show the frequency with which the Core Dimensions (plus Uncertainty and Stocks) and Bertin's retinal variables, were included in these studies. Clearly stages, time and stocks are important dimensions in MFA studies, while size is used almost exclusively for displaying quantitative data. Yet, apart from size, there was little consistency across the MFA studies in the use of retinal variables to display information. Many of the visuals reviewed were judged overly complicated and difficult to interpret.

This finding suggests that designers of visualisations in the MFA community are mostly ignorant of the long history of visualisation theory and design principles. MinFuture seeks to redress this problem by providing a Best Practice Guide for Visualising MFA data.

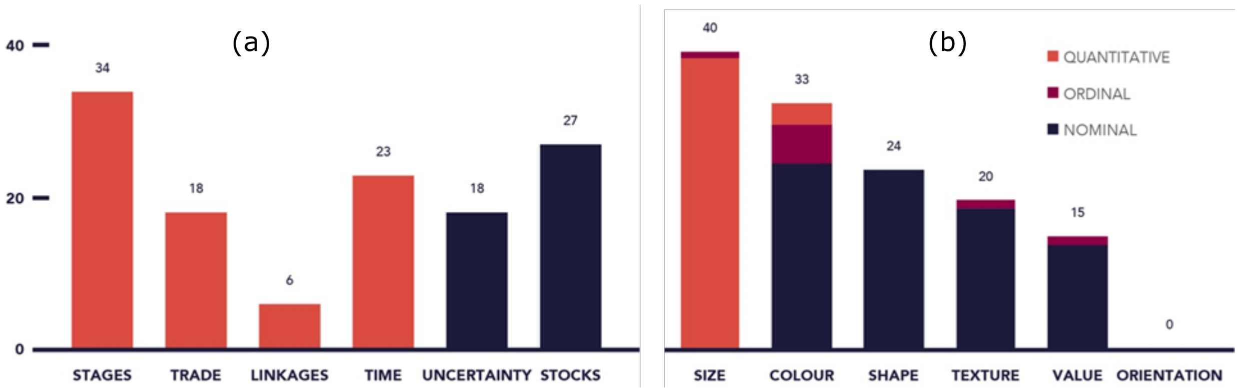


Figure 21: An analysis of the frequency of use of (a) the core framework dimensions (see section 3, plus uncertainty and stocks) and (b) Bertin's retinal variables included in examined MFA studies

4.6.4 Best Practice Guide for Visualising MFA

Sankey Diagrams are judged as the preferred primary diagram for visualising MFA data, as they convey both the material system structure and the quantitative values of material flows in a clear manner. However, to communicate all of the Core Dimensions, plus uncertainty and stocks, requires the use of secondary visuals (the most important are shown in Figure 22. These diagrams support the data and invite the viewer to see deeper insights. The use of interactive visual platforms, allows 'pop-up' windows to be simply accessed with a 'click'. A full catalogue of best visual options approaches for communicating the core dimensions is provided in the Appendix.

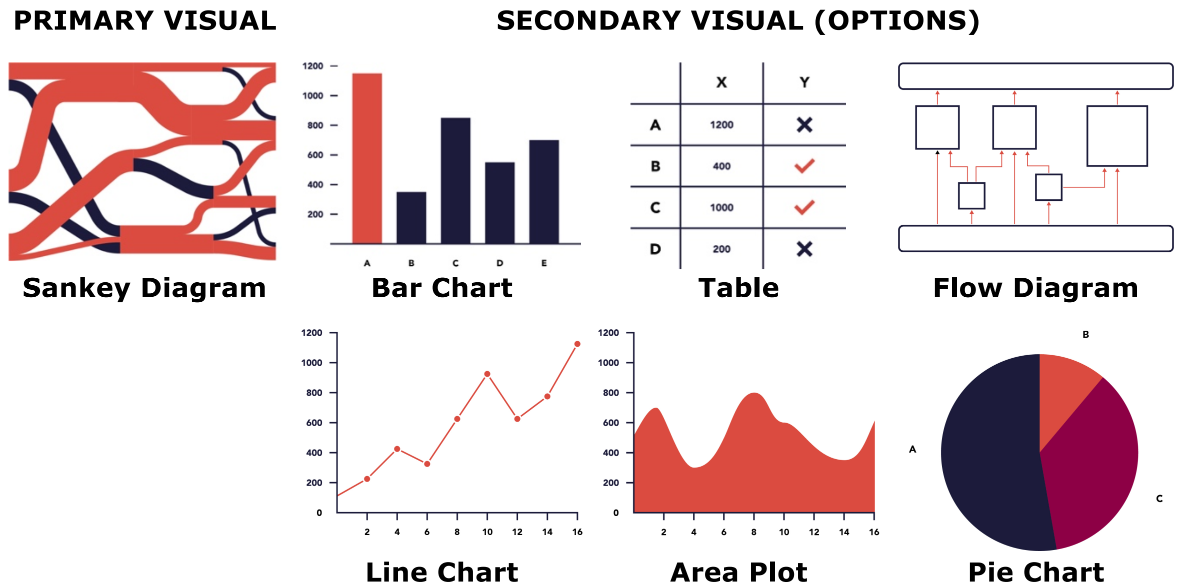


Figure 22: Primary and secondary visualisation options for MFA

4.6.5 Creating good visualisation

The following list of questions is useful creating good visuals from complex MFA data:

- What is it for?
- What are my audience needs?
- What is the best way to represent the information?
- How should I display multivariate information?
- What does the data look like? Sketch a wire frame
- Have I included titles and captions?
- Does it support the literature, is it consistent with other visualisations?
- Does the visualisation tell a narrative?
- Can the visualisation be made interactive?

Our final word is a plea that more time be given to creating visuals in MFA research. When a researcher undertakes a typical MFA study, the data collection takes many months, the writing up takes several, yet we are lucky to spend more than a few days on the visuals. However, the reader under time pressure looks first at the title, followed by the abstract, and then dwells on the figures. A wealth of information on visualising material systems is provided by the MinFuture Deliverable report D3.4.

Good visualisation takes time and requires multiple iterations to perfect. Allocating more time to visualisation, not only helps us communicate our message well, but it also gives us the skills to create better visuals in the future. Practice makes perfect!

4.7 Strategy and decision support

MFAs are developed to facilitate the reflection about material (and energy) systems. They are typically developed to address two fundamental questions: (i) How well do we understand the physical system, and how can we improve our understanding of the system most effectively? (ii) What are challenges related to the real world system analysed, and how can we control the system most effectively to reach certain goals? While the first question addresses the understanding of the system (methodology), the second question aims at changing the system (interventions).

a) Strategies for enhancing system understanding

Following the logic of the framework presented here, the interpretation of an MFA should include interpretations of the results that answer the following methodological questions:

- How robust is our understanding of the system? Do we consider all of the relevant stocks and flows at an adequate granularity?
- How well is our quantitative understanding of the system? Do we have relevant data gaps?
- Where do we have major uncertainties that need to be considered when drawing policy-relevant conclusions?
- How good and useful are the models and scenarios for addressing the specific questions at hand?
- Are the indicators developed sufficient to adequately reflect the performance of the system?
- Are the visualisations suitable to communicate the main findings?
- How well is our overall understanding in order to support policy-relevant conclusions? Where can we be confident, and where do we need to be cautious?

Carefully answering these methodological questions is considered best practice in MFA. Ensuring transparency and reproducibility in the MFA research community involves pointing out the strengths and limitations of the approach and data used. It is a prerequisite for developing **research strategies** of individual research groups, research institutions, as well as research foundations.

However, the relevance of these methodological findings is not restricted to the research community. Also governments, NGOs, and industry associations have started to monitor various aspects of the physical economy. Answers to the questions laid out above are therefore highly relevant for informing the development of **monitoring strategies**. For example, the findings of MFAs can be used to identify relevant *data gaps* and effective ways to address them, either by using the mass balance principle, by making informed estimates, or by proposing new measurements or proposing amendments to existing measurement programmes. Another important aspect of monitoring strategies is *data harmonisation*. Section 4.1 & 4.2 pointed out how a reporting of the system context in addition to the measured values (adding specific metadata) can facilitate harmonisation efforts. But most importantly, MFAs can facilitate the reflection about the *scope of monitoring programmes*, including the identification of relevant aspects that should be monitored at different levels of granularity.

b) **Strategies for system interventions (governance and business models)**

MFAs are designed with many different purposes in mind, but most commonly to identify or describe problems related to the physical economy, to test alternative strategies for mitigating these problems, or to identify potential business opportunities. The relevance of MFA results is always limited by the system definition chosen. It is therefore critical that the purpose of the model is stated explicitly and upfront, and that it is aligned with the system definition. The MFA component at the top of the pyramid ("strategy and decision support") should therefore not be considered the last one, but rather the first and the last, with the first one (purpose, scope) informing the base of the pyramid (system definition).

MFA results cannot provide policy makers and industry representatives with meaningful strategies. The problems typically analysed in MFAs are too complex, and cannot be solved by one scientific discipline alone. Policy-prescriptive interpretations of the results are therefore not consistent with the scientific principles. Nevertheless, MFAs can inform decisions and strategies with relevant findings. The art of interpreting MFA findings is therefore to be policy- (and business-) relevant while avoiding to be policy-prescriptive.

MFAs are also poorly suited to distinguish between "good" and "bad" solutions or outcomes or to blame specific actors for certain phenomena. Changes in the physical economy may involve aspects that are desired by some actors and undesired by others. What we perceive as problems is usually generated by the entire system involving many stakeholders that are all linked with each other through the physical economy. On the other side, MFAs are well suited to facilitate the reflection about complex multi-stakeholder problems (how different processes and stakeholders are linked with each other through the physical economy) and how they can be addressed most effectively through multi-stakeholder interventions.

MFAs can inform government and industry strategies in many ways:

- MFAs can demonstrate where materials are "lost" or ineffectively used along the supply chain, and thereby point out the largest potentials for resource recovery and recycling. This information is highly relevant for informing strategies related to resource management, circular economy, or (critical) raw materials supply. Whether or not governments or businesses should focus on the recovery of these resources, however, may be determined by many other factors that are out of scope.
- MFAs have been developed to forecast future scrap availability. This information can be relevant for informing investments in new recycling facilities or the development of new sorting technologies needed to separate different fractions of the scrap.
- Other MFAs have been developed to forecast demand for certain materials. This information is relevant for investments into mining and production of these materials.
- Some MFAs for individual materials have been linked to models of energy use and greenhouse gas emissions, which allowed the model developers to develop scenarios for greenhouse gas emission in these sectors, and to test the effectiveness of alternative intervention options for overall reduction of greenhouse gas emissions.

These examples illustrate that MFAs have a potential for informing strategies, among others for resource management and circular economy, critical raw material supply, climate change, and investments. Since many of the great problems of humanity today are linked with each other through the physical economy, MFA has also a great potential to inform strategies that aim at simultaneously addressing several sustainable development goals.

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6 Annex

Creating good visualisation

Trade

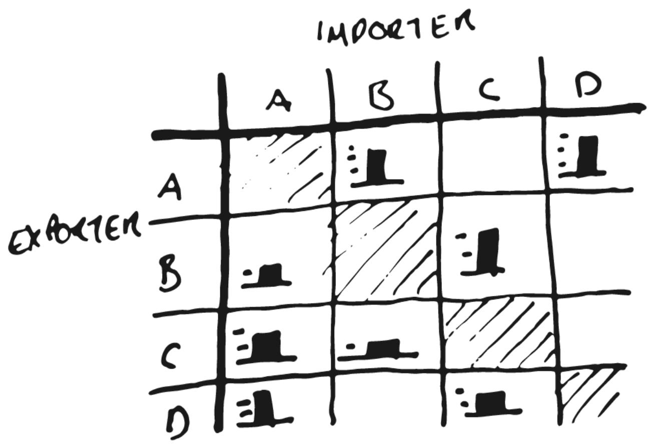

Figure A1: A trade matrix of countries, used primarily for elicitation purposes.

Figure A1 shows how a simple Multiples Matrix can be used for elicitation and communication of trade data. Exporter countries are listed in rows and importer countries in columns, and the trade amounts can be read from the table.

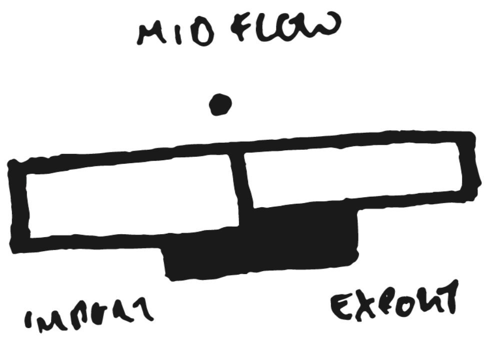

Figure A2: Imports and exports for an individual flow on a Sankey diagram.

Figure A2 shows the import and export flows as 'stubs' for an individual material flow in a Sankey., and how they balance supply and demand flows. The approach shows the trade flows for the country involve, but not the source of target countries for trade flows.

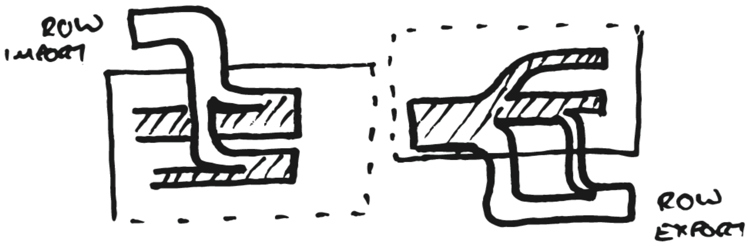

Figure A3: Trade shown on a Sankey diagram, with imports coming from the top and exports leaving at the bottom.

The import and exports flow ‘stubs’ can be extended and grouped to show the total import and export flows for a stage in the Sankey Diagram, as shown in Figure A3. Summing up the imports and exports in this way draws attention to the interactions of the country or region with external entities not in the MFA. This method could be adapted to show just the imports and exports from a specific country.

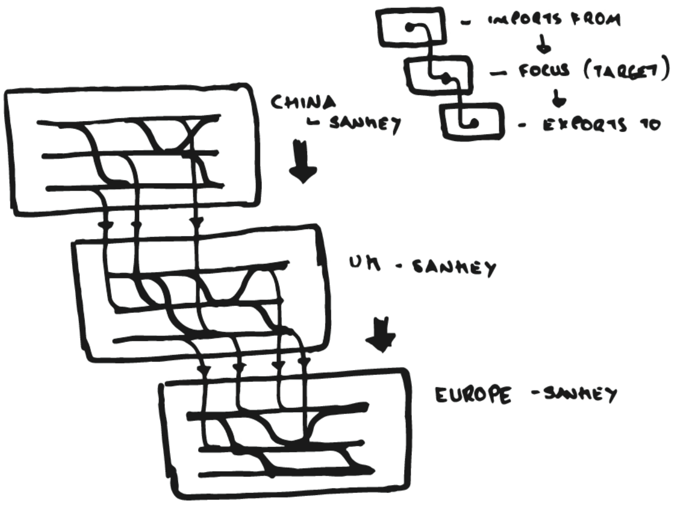

Figure A4: ***Multiple Sankey Diagrams with trade flows shown between each.***

Feil! Fant ikke referansekilden. Figure A4 shows this visualisation method expanded one step further, using a ‘trade layer’. A Sankey Diagram is created for each country in the study, with trade flows visualised between the countries. Or a single country could be shown with aggregated trade flows to the rest of the world. This method retains the primary variable of size to denote mass flow and gives insight into the specific areas of trade along the stages in the material system. This approach would work best in an interactive online platform.

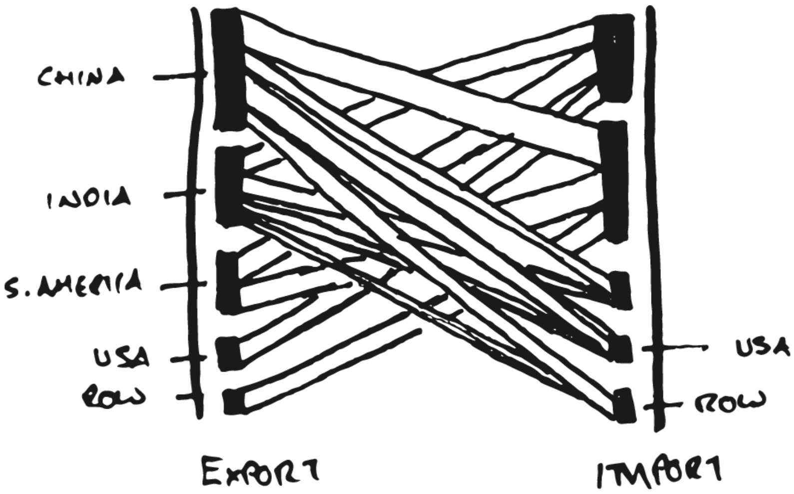

Figure A5: Trade shown as a parallel coordinate plot for a group of countries, with exporters on left importers on the right.

Figure A5 describes an alternative non-Sankey approach, which allows the trade between multiple countries to be shown more clearly by omitting the Stages in the material system.

Linkages

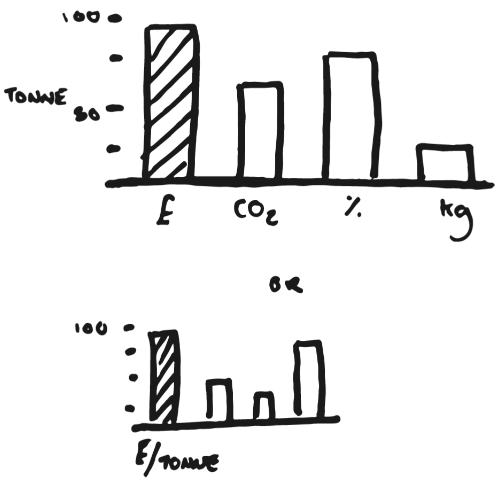

Figure A6: Linkages presented in Bar Chart form with different scales.

The simplest method is to present the linkages for each stage as a bar chart, as shown in Figure A6. Linkages such as cost, carbon emissions or percentage composition can be reported on the basis of per tonne of material or as mass percentages.

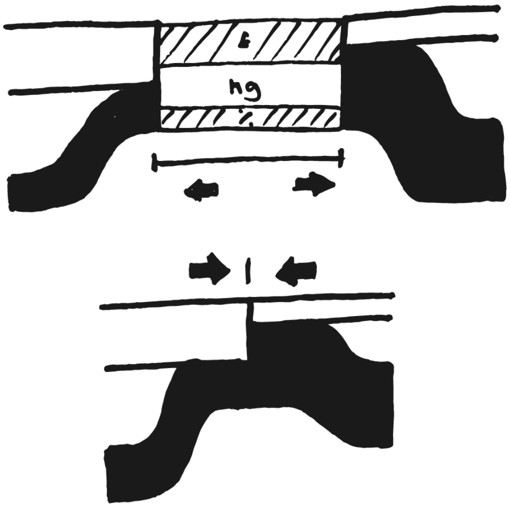

Figure A7: Linkages presented in Sankey Diagram format, expanded (top) and collapsed (bottom)

The second more complicated visualisation option displays the Linkages within the material flow in the Sankey diagram, as demonstrated in Figure A7. If an interactive online model is used the linkages information could be shown/hidden or expanded/collapsed with a click. This approach allows the relative proportions of the Linkages to be compared within a single flow and to other adjacent flows in the diagram.

Time

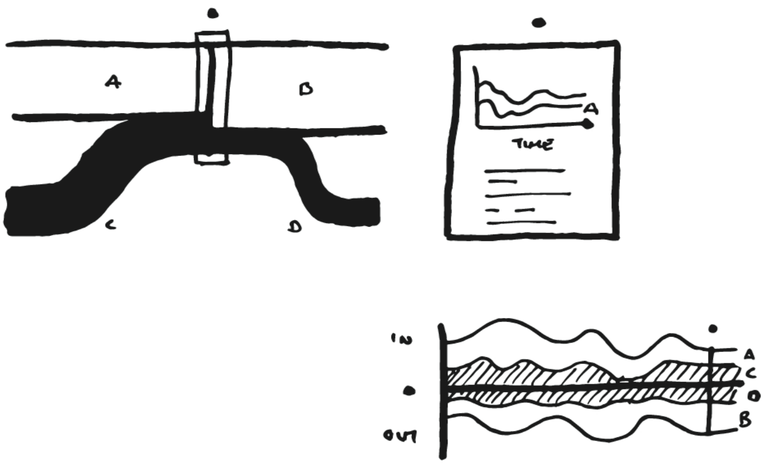

Figure A8: Stages changing over time, presented on line chart or as a stream graph in pop out tab or side menu.

Stream graphs can be employed for comparing changes in individual stages or material flows, over time. Information can be presented as a Line Graph, or as the changing breakdown of inputs and outputs for a specific stage. These options are shown in the Figure A8.

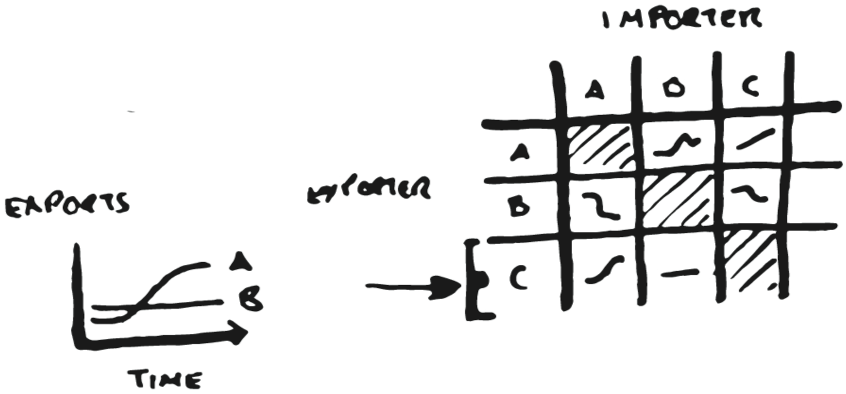

Figure A9: Trade changes over time, presented on line chart or as small multiples in matrix form for elicitation purposes.

Net Trade can be traced over time using a line chart and Small Multiples Matrices can be used for elicitation purposes. This can identify trends and patterns within the data, from which unique stories driven by the data can be formed. Diagrams are shown in Figure A9.

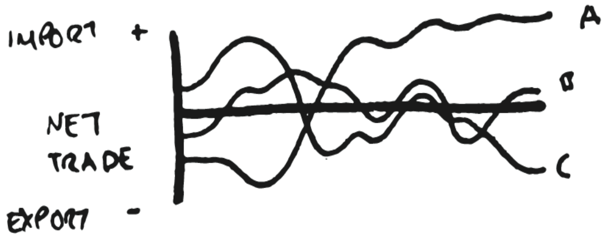

Figure A10: Trade over time as presented on line chart with net trade.

Individual exports or imports for a country or region can be plotted on a line graph, as shown in Figure A10. This method of visualisation displays the net trade with other countries. For change in import or export over time then a line chart plotting this would suffice.

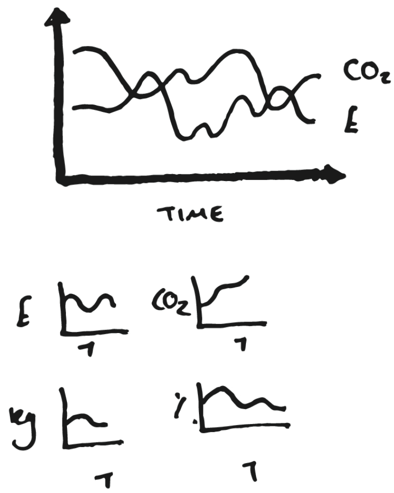

Figure A11: Linkages over time as presented on line chart or as small multiples.

Changes in Linkages can be visualised using Line Graphs over time, as shown in Figure A11.

Uncertainty

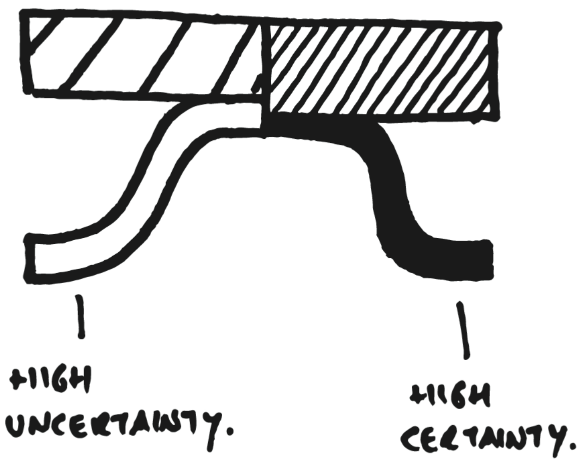

Figure A12: Uncertainty on Sankey diagram, with texture is used to symbolise colour hues.

For communication, Lupton and Allwood (2017) adopt a linear colour spectrum to show uncertainty on a Sankey Diagram. Using colour for quantitative differentiation is not highly recommended in the design principles, however colour works as a secondary layer of information overlaid on the original Sankey Diagram. This approach does not allow for accurate parsing but can highlight specific trends in the data. A simple example of this visualisation approach is shown in Figure A12.

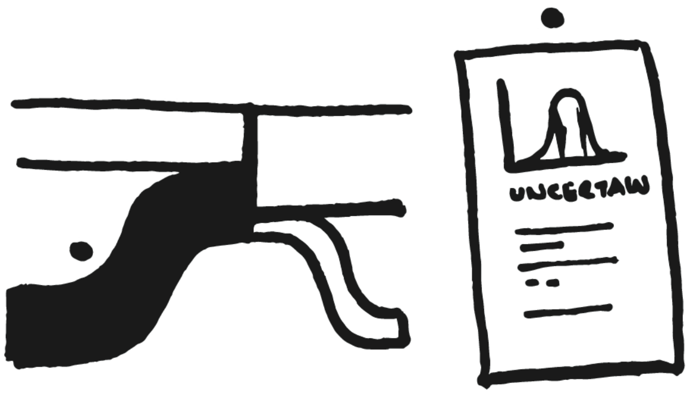

Figure A13: Uncertainty shown using a histogram for flow in a Sankey Diagram.

Detailed uncertainty data for a specific material flows (i.e. distribution curves) can be provided as a secondary visual accessed from the Sankey diagram, as an interactive 'pop-up' window, as shown Figure A13.

Stocks

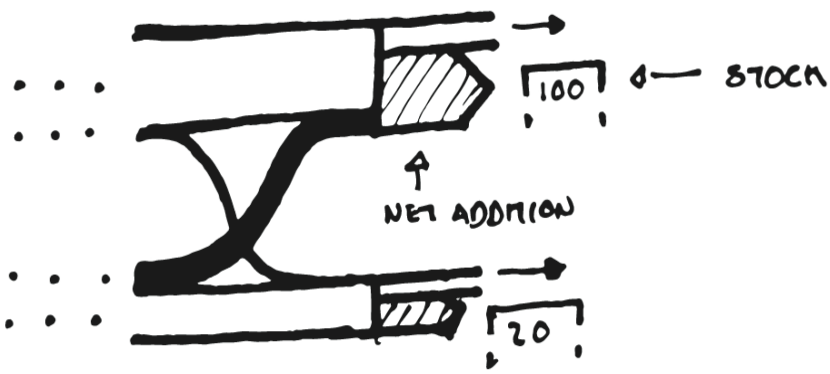

Figure A14: Stocks on Sankey diagram at stages as icon with net addition flow.

Figure A14 shows the net addition to stock as arrow 'stubs' which splits from the material flow and a total stock total. Using this approach requires much visual focus from the viewer and the stocks must be compared in serial rather than in parallel, however stocks at many stages in the material system can be shown.

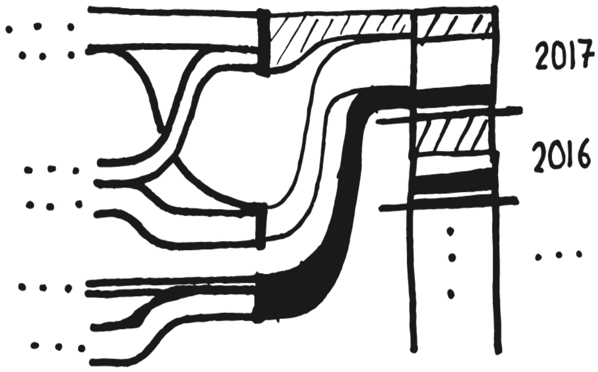

Figure A15: In-use stocks on Sankey diagram as a stacked bar chart with line widths proportional to the flow of each year/time period.

Figure A15 shows in-use stocks visualised as a stacked column at the right-hand edge of a Sankey diagram. Flows from each end-use sector add to the in-use stock stack in every year, while previous years stocks are shown in horizontal bars below. The overall height of the stack equates to the total stocks in use and can is directly comparable with the material flows (line widths) in the rest of the Sankey diagram. Outflows from in-use stock could be shown leaving the stack, in yearly cohorts, capturing the amount of material in products reaching end-of-life, and whether they are discarded or recycled.