Visualising Material Systems

List of features for which visualization is required and detailed requirement profile for optimal visualisation tool

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Executive Summary

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 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.

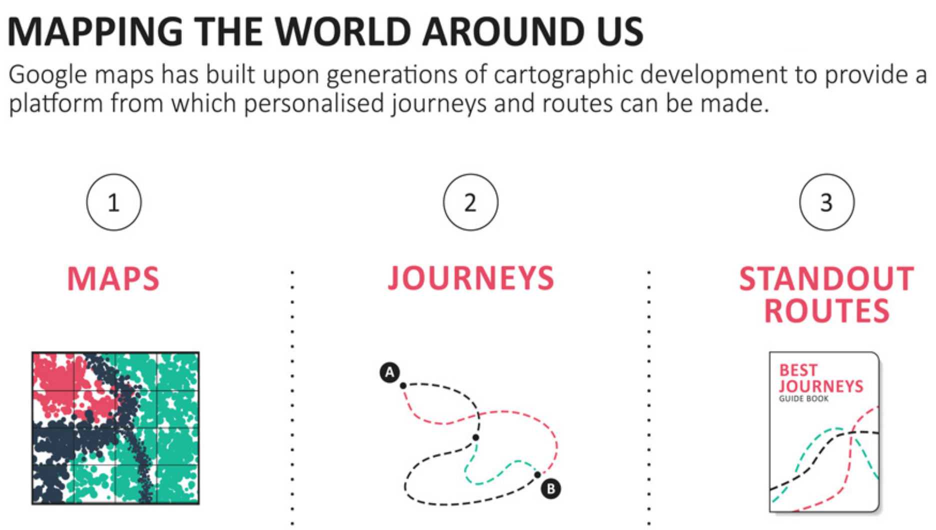
The MinFuture project seeks to provide methods and guidelines for structuring MFA data, enabling a more comprehensive understanding of mineral and material systems. Visualisation is one of the key components described in the MinFuture Pyramid, while the MinFuture Core Dimensions describe four dimensions which are key to MFA studies: stages, trade, linkages, time. We add uncertainty and stocks to this list to create six core dimensions for which visualisation might be required.

Good visualisation

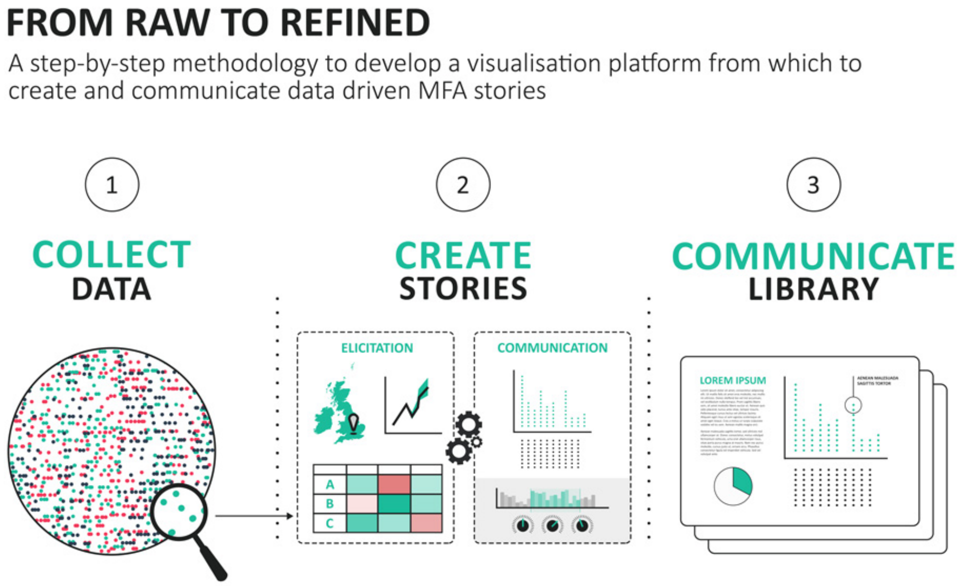
Visualisation matters because it is an essential part of the way we communicate information to others. Tufte (2006) comments that 'the world we seek to understand is profoundly multivariate' and therefore visualisations by association must also be multivariate. The aim of the visual designer is to draw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



Similarly, for visual story-telling, MinFuture sees an interactive data environment 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).



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.

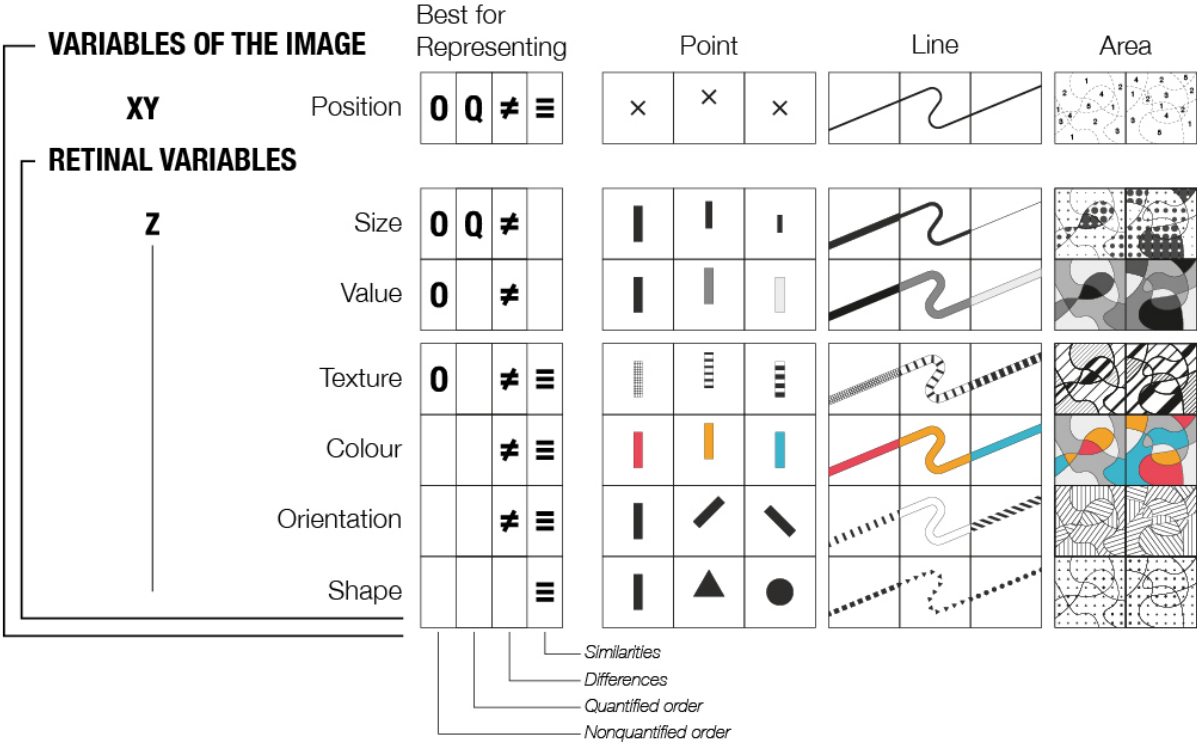
Principle 3: Show multivariate data.

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.

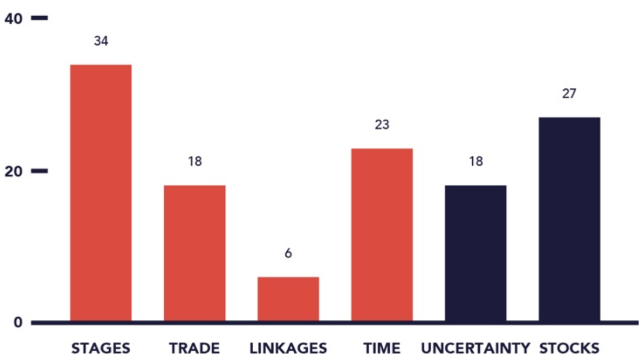
Bertin in his book 'Semiology of Graphics' (1983) describes seven foundational variables of graphical perception, which relate to the way we perceive information through sight. The illustration below shows these position and retinal variables against their strengths and weakness for displaying information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

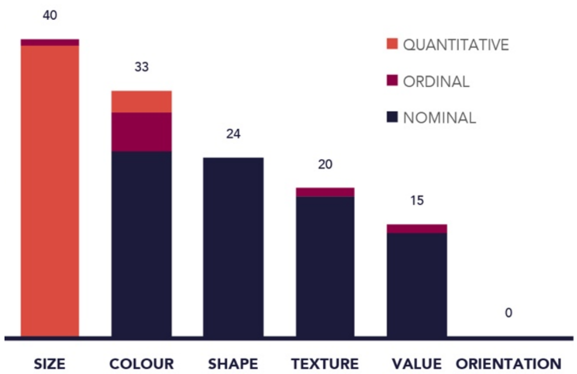


Use of Visualisation in MFA

As a part of the MinFuture project we undertook of the types and forms of visualisation used across 48 MFA studies, sourced from research publications and online interactive models. The charts below show the frequency with which the MinFuture 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 to be 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.





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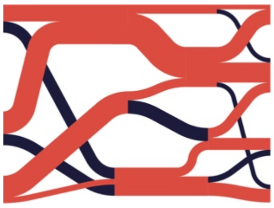
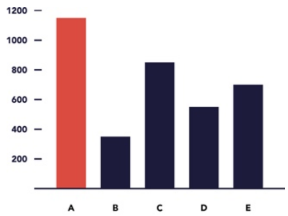
Best Practice Guide for Visualising MFA

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 ins a clear manner. However, to communicate all of the MinFuture Core Dimensions, plus uncertainty and stocks, requires the use of secondary visuals (the most important are shown below.) These diagrams support the data and invite the viewer to see deeper insights. The use interactive visual platforms, allows 'pop-up' windows to be simply accessed with a 'click'.

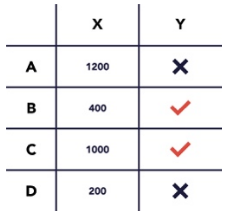
A full catalogue of best visual options approaches for communicating the core dimensions is provided at the end of this section.

PRIMARY VISUAL **SECONDARY VISUAL (OPTIONS)**

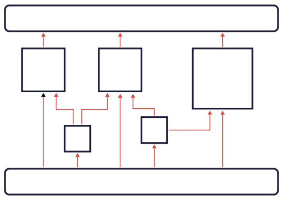

Sankey Diagram

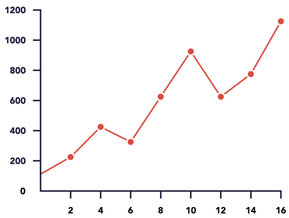


Bar Chart

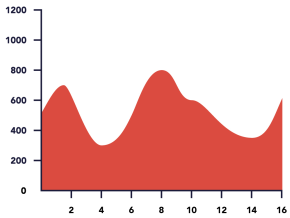


Table

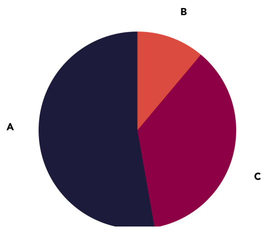

Flow Diagram



Line Chart



Area Plot



Bar Chart

Creating good visualisation

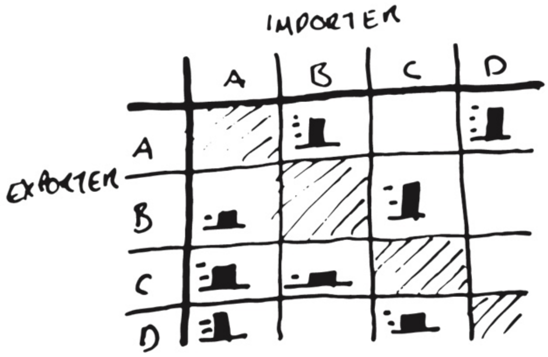
The following list of questions is useful creating good visuals from complex MFA data:

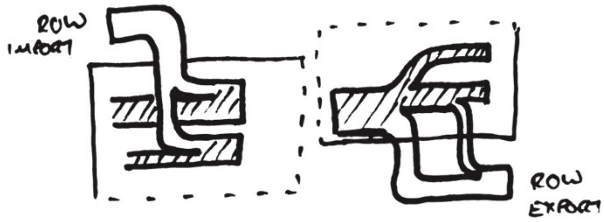
- What is it for?
- What is the best way to represent the information?
- How should I display multivariate information?
- What does the data look like? Sketch a wire frame
- Have I included titles and captions?
- Have I included titles and captions?
- Does it support the literature, is it consistent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

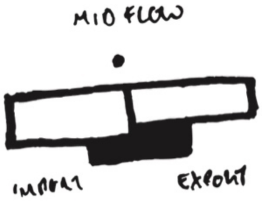
Our final word is a plea that more time be given to creating visuals in MFA research. When a researcher undertakes a typical MFA study, the data collection takes many months, the writing up takes several, yet we are lucky to spend more than a few days on the visuals. However, the reader under time pressure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

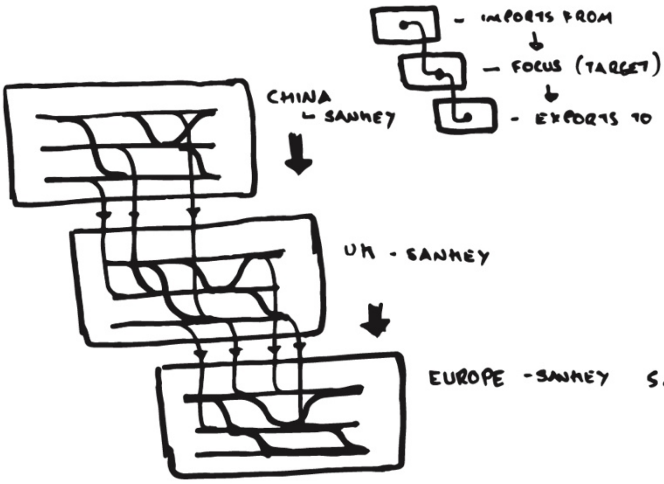
Good visualisation takes time and requires multiple iterations to perfect. Allocating more time to visualisation, not only helps us communicate our message well, but it also gives us the skills to create better visuals in the future. Practice makes perfect!

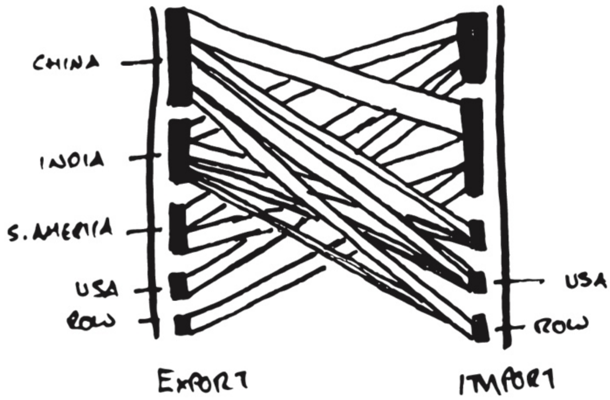
TRADE



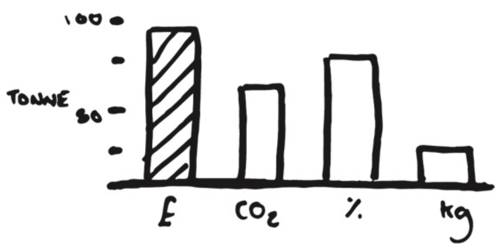


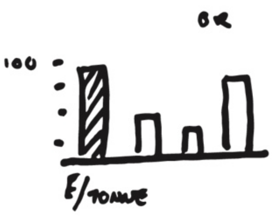


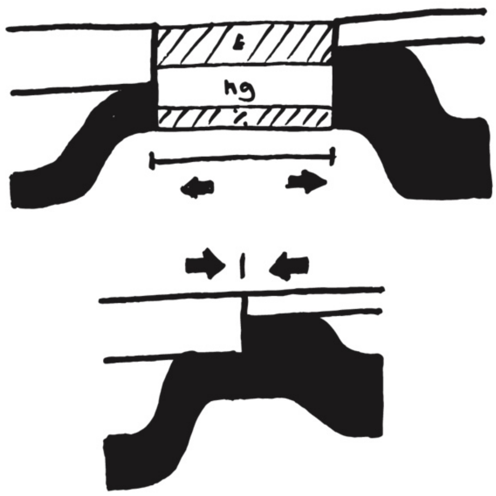




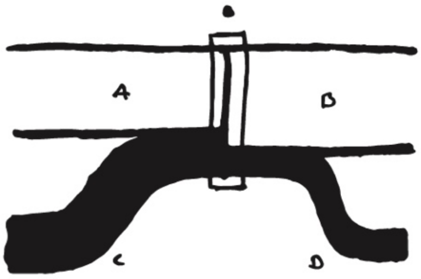
LINKAGES

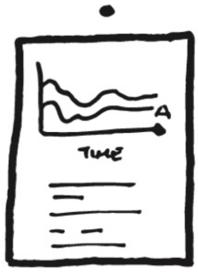


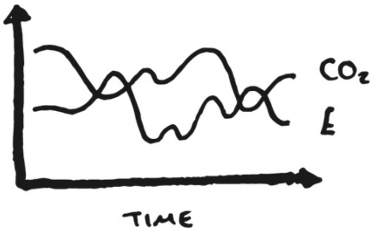


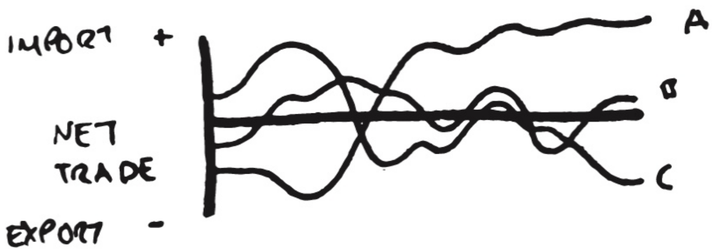


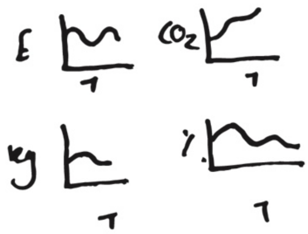
TIME



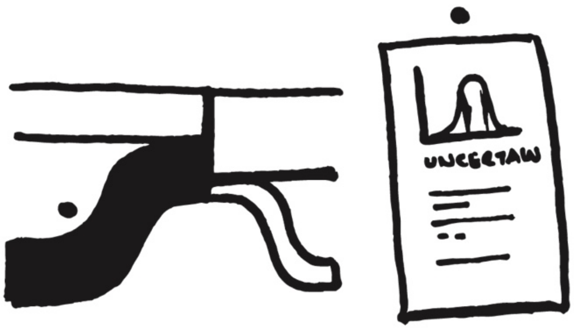


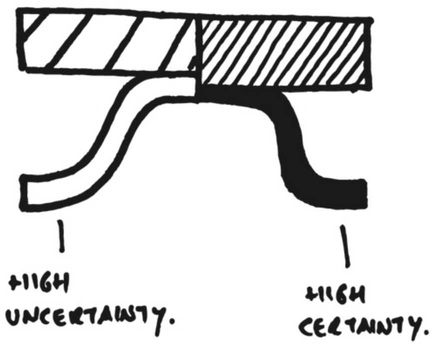




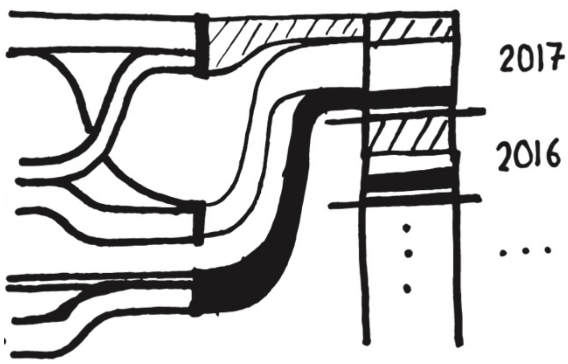


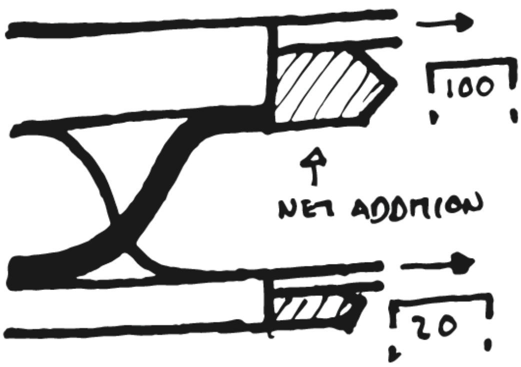
UNCERTAINTY





STOCKS





1 Visualising Material Systems

Our experience of the world is built upon our visual interaction with it. Every day we are bombarded by visual stimuli that, if humanly designed, are created to impart meaning, direction and information. Language and communication in its primary form is visual, with shapes forming letters, then words, that convey associative meaning. Through the use of design and visualisation we can convey and impart complex theories and structures that otherwise may be difficult to explain through the written word alone.

Visualisation in the modern world is essential and foundational for communication. As such we are constantly, either consciously or subconsciously, aware of this information that is streaming into our eyes. The eyes and minds are incredible in the way that they can associate and provide context to the assortment of shapes and colour. However, it can be easy to overload the senses and this makes it difficult to build order and convey meaning. This is specifically important when interacting with data visualisation, where inherently large amounts of data require visualisation to make sense of the system or structure from which the data are sourced. Being able to simplify, create context, impart meaning and tell a coherent story from the data leads to good design and a clear understanding of the data.

Within Material Flow Analysis (MFA) data visualisation plays a key role in facilitating understanding and presenting core aspects of analysis. Within this task of the MinFuture project we aim to develop a common language of data visualisation for the presentation of MFA and the core dimensions that have been defined for the project.

1.1 MinFuture Pyramid

MFA models can be used to serve different purposes in material management, such as monitoring systems, forecasting changes, or evaluating alternative strategies. For this reason, MFAs are comprised of different components, depending on the purpose of the analysis. Figure 1 presents these components in the form of a Pyramid which has been developed to guide the MinFuture project. The components are structured hierarchically, where the impact of the components at higher levels depends on the robustness of the lower level components. Integrating several of these components in a MFA study provides a more holistic view of the many factors influencing a material system and helps highlight strategies to improve the effectiveness of the material service provision. Each of the components of the MinFuture Pyramid in Figure 1 is now discussed.

Figure 1: MinFuture Pyramid, showing the hierarchy of the components for Material Flow Analysis (MFA).

1.1.1 Systems

Systems form the foundation of any MFA. System level analysis places each data point into a structured framework, which records the boundary of the analysis and the interactions between flows and stocks. The structure needs to be flexible to accommodate different levels of data aggregation or disaggregation. The system provides the context within which data can be analysed and is critical to avoid drawing the wrong conclusion from data. Statistical data is frequently reported without a clear definition of the material system, leading to misunderstanding and poor decision-making at the company and policy level.

1.1.2 Data

Data includes measurements or estimates of material flows (over a given time period) or material stocks (at a given point in time). It is important to record data points carefully, taking note of the metadata around each point, such as the units, source, location and uncertainty. Good quality traceable data provides a strong foundation for higher level analysis and decision making.

1.1.3 Models and Scenarios

Materials systems are often modelled mathematically (i.e. matrices) and enable material data to be mass balanced through transformation processes. Scenarios are assumptions of plausible future cycles that are consistent with the mass balance principles and assumed drivers. They are used to illustrate possible configurations of future material systems and to evaluate the effectiveness of possible interventions.

1.1.4 Uncertainty

Uncertainty is inherent in MFAs, including both historical, present and future studies, and results from measurement uncertainty or errors in the data, the system configuration, and the scenario assumptions. Dealing with uncertainty involves identifying and reducing errors, and making uncertainty more transparent. Good uncertainty analysis enables more robust assessments to be performed and aids better decision making.

1.1.5 Indicators

Indicators are the quantitative metrics used to measure the performance of certain aspects of a material system. They allow benchmarking between similar material systems, the monitoring of improvement potential overtime, and are using for setting policy targets. However, care must be taken to avoid unintended interactions between indicators, where efforts to improve of one indicator result in a deterioration of another; this issue can arise from setting indicators without a robust understanding of the underlying material system.

1.1.6 Visualisation

Visual techniques are useful for depicting material systems (i.e. Sankey diagrams) and reporting analysis results (i.e. graphs). They can inform decision making in industry and government, by showing current "snap-shots", historical trends, and potential future developments under different conditions. Visualisation tools have been developed to support the recording (monitoring), exploration (analysis), and explanation (interpretation) of information. For the purposes of this document, we focus on analysis and interpretation of material data, which we label as elicitation (analysis) and communication (interpretation).

1.1.7 Strategy and decision support

Strategy and decision support involves: (1) the support of strategies and policy for raw materials, such as the Strategic Implementation Plan (SIP) of the European Innovation Partnership on Raw Materials and the Circular Economy Action Plan or the SDG's; (2) the support of strategies for expanding the use of robust MFA and structured data collection in academia, governments and industry.

MinFuture is engaged in providing common guidance and direction for each of these components. Case studies are employed for specific material and product systems to demonstrate best practice in MFA. A glossary of terminology is defined to allow more effective communication between actors studying Raw Material strategies.

1.2 MinFuture Core Dimensions

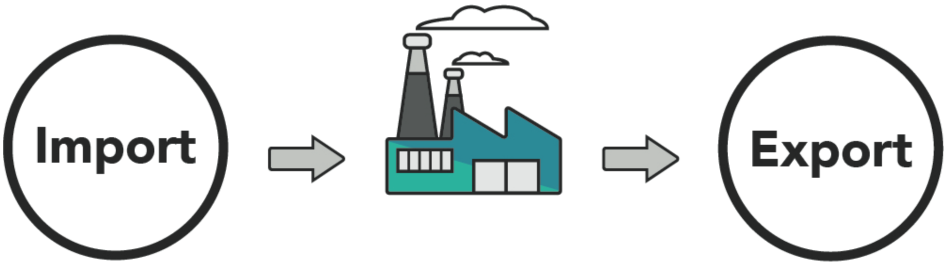
MinFuture has identified four core dimensions related to material systems. Effective visualisation incorporates these four dimensions into the diagrams and figures used. Visualising all four dimensions with a single static diagram is challenging, however dynamic diagrams (i.e. online, digital) offer the possibility of multiple visual layers and dynamic boundary changes (i.e. zooming), significantly expanding the amount of information that can be conveyed to the reader.

1.2.1 Stages

This dimension aims to delineate the system structure within an MFA, for example, the mining, smelting and manufacturing stages for a steel product. The core dimension applies to all non-energy materials and the combined stages together make up the material system. Visualising the flow of materials through these stages is important for understanding materials cycles and for prioritising which interventions aimed at improving the system will have the largest benefit.

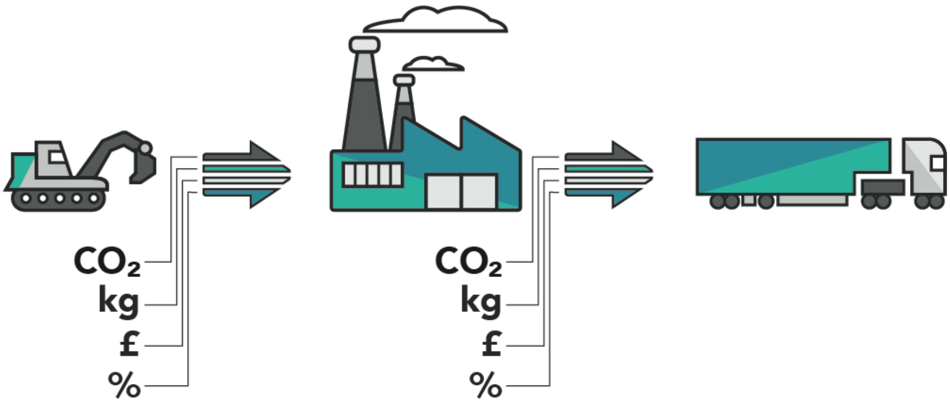
1.2.2 Trade

Countries depend on the trade of raw materials and products via international markets. MFA can capture the import and export of materials/products at each stage in the material system. Linking trade statistics with domestic production in a country, provides an improved picture of the drivers of resource consumption. Moving from production-based data to consumption-based data (production + imports – exports) allows countries to take responsibility for the global impacts of their material demand. The sum of exports and imports from all countries should balance to zero, for a given time period; studies of global material systems do not need to track trade explicitly. Tracing the imports and exports of materials/products across many countries is aided by visualisation.



1.2.3 Linkages

Material flows can be disaggregated by composition (i.e. alloy contents for metals or multi-material product flows) to highlight key elements like criticality. Material flows can be measured in alternative units to mass (i.e. atomic fraction, price) or display associated impacts (i.e. embodied carbon, toxicity). These linkages can be visualised in MFAs and allow topical features to be traced through the material system, aiding decision-making.



1.2.4 Time

Tracking the changes in material flows over time gives opportunity to understand how material systems respond to external dynamics (i.e. population, GDP, recessions, resource shortages) and to create scenarios about possible future material use. Tracing inputs and outputs of materials to a defined system allows for the assessment of the depletion of materials reserves, the build-up of material stocks in use, and the accumulation of discarded materials.

1.3 Good Visualisation

Material Flow Analyses (MFAs) are often detailed and complex. Effective visualisation of MFA is critical for communicating the system structure in which the MFA data sits and leads to improved understanding of the impacts of material systems. This can be achieved through the use of a simple line chart, or a complex Sankey diagram. Being able to 'see' the data, its context and relationships, significantly increases the insights gained and options for discussion. Data journalism, is one area which has seen significant development and interest, where visual stories are created to improve understanding. This is exemplified by the 'Information is Beautiful Awards' hosted by David McCandless, a leading data visualisation journalist. These awards celebrate the best infographics and visualisations from around the world, celebrating the beauty of data and the stories told by data, and how they have changed the visual communication landscape.

Edward Tufte, a pioneer in visualisation techniques states 'The purpose of analytical presentation is to assist thinking' (Tufte, 2006); an effective visualisation not only looks aesthetically pleasing, but must also assist the viewer to think and understand. However not all visualisations are effective. Examples of unstructured and poorly designed visualisations are common, and often inhibit thinking and understanding. This can result from, for example: the text being too small, the data scale being incorrect, insufficient explanation of the data, or poor use of colour. Poorly designed visuals can lead to the misinterpretation of data and misguided decision-making.

So why does 'good' visualisation matter? Visualisation matters because it is an essential part of the way we communicate information to others. Good visualisation enables understanding, provides insight and informs. Humans are a visual species and our communication tools are built around visualisation; advertising, written language, film, and photography, are addressed primarily through the sense of sight. We are bombarded daily with visual communication and the visual messages that we remember are the ones that connect with us and make us think. Large sets of data allow for the writing and sharing of many data stories. Hans Rosling, a founder of the Gapminder foundation, tells a story global health trends and economics, where he emphasises the importance of letting the data change the mindset of the audience (Rosling, 2006). Stories like this, if written well and inspired by the data, can lead to change and profound insight.

In analytical presentation, there should be a drive to draw out clarity from complexity. A good visualisation will illuminate patterns and trends from complex data. Tufte argues that 'the world we seek to understand is profoundly multivariate' (Tufte, 2006). Therefore, we should expect that data collected from the real world will also be multivariate and complex, with many causally related connections in the data.

MFA data are typically complex and multivariate, and it is important that data connections are presented with visual clarity if the data is to be understood. For example, Kerr and Phaal (2015) highlight the current issues with road-mapping visualisations and their lack of design principles, which devalues their ability to act effectively as communication tools. The authors outline a methodical structure for creating narrative in visualisations and focus on designing a structure in which to place the data. They identify the need for two type of visualisation tools. Firstly, elicitation tools which are required for data interrogation and the extraction of a clear narrative from the data. Secondly, tools to create communication visualisations which convey the data structure and narrative to the reader.

1.4 Data Driven Stories

Google maps has become a leading entity in the digital landscape of cartography. The richness and quantity of the data has provided a platform on which developers (internal to Google and external) have been able to create topological layers, complex and insightful interactions and personalised data stories.

Figure 2 shows the approach used by Google to transform traditional maps, into journeys and standout routes, allowing many layers of useful data to be visualised by the user. This approach is used as analogy to describe a possible vision for how material system data might be visualised in the future. Rather than just collating and reporting tables of data, MinFuture sees an interactive environment where these tables of data (maps) are located within the material system structure, allowing the creation of data stories by experts (journeys) and the communication of these stories to decision makers (standout routes). The three stages shown in Figure 2 are explained in more detail.

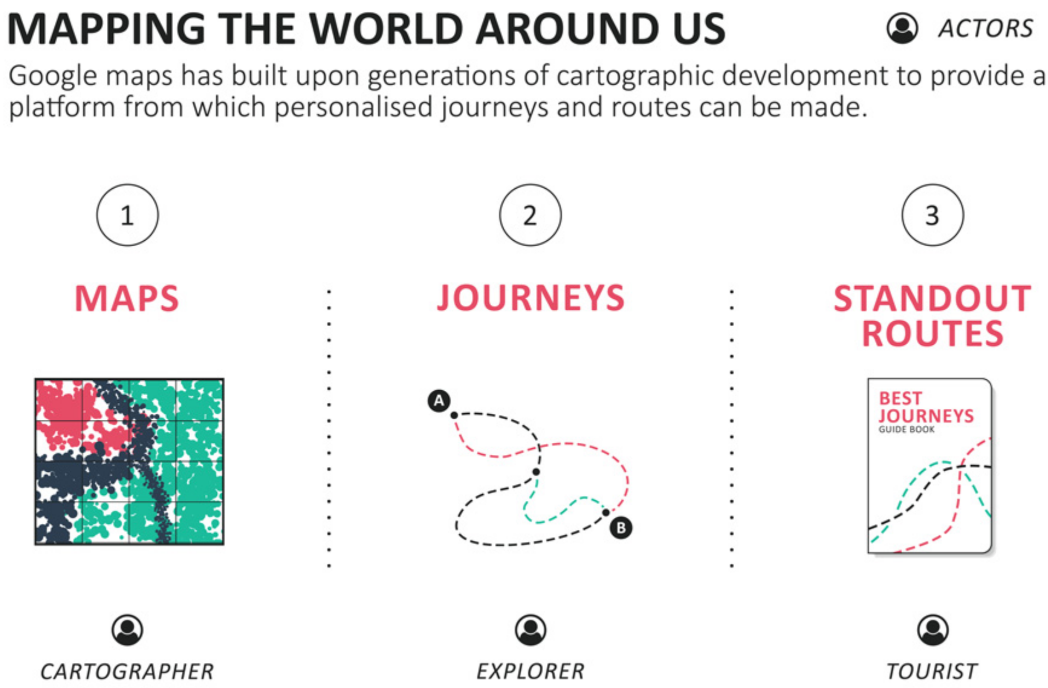


Figure 2: Graphical representation of a systematic approach to generating visualisations using the Google Maps analogy.

1.4.1 Maps – Cartographer

It takes a great deal of skill and care to accurately record and visually describe an environment. Each stroke on the map is recorded to a pre-set scale and positioned relative to the previous strokes on the page. The work of the cartographer is seldom fished; no sooner has a map been completed, that it is time to collect more measurements details.

The Cartographer explores the surrounding world, collates data, creates raw maps, and interprets the surrounding spatial landscape into a format that can be used as a reference for others. However, the maps produced provide only the underlying information; planning a journey requires this information to be interpreted into routes, stops, distances and travelling times.

1.4.2 Journeys – Explorer

The Google 'route planner' uses base maps created by cartographer to design journeys through the landscape, from a source to a destination, while providing a clear and concise narrative. This may include highlighting points of interest, circumventing potential hazards, and providing clear instructions and simple routes along well-trodden paths. Given a final destination, the route planner provides several possible journeys, with durations and other important travelling information, allowing the user to make an informed travel decision.

A route planner requires an up-to-date map, a true compass (GPS), and a means to communicate the possible journeys. Before Google Maps, the Automobile Association provided a service for members where you could send in your start and end points and receive, in return, a route map specifically for that journey. This included points of interest like petrol stations, landmarks, and rest areas along the journey. This service relied on travel experts to provide members with the best possible journey options. Satellite Navigation systems (i.e. TomTom) allowed the user to create their own journey and change the journey en-route. While online mapping tools (i.e. Google Maps) presented multiple journey options, updated traffic diversions, multiple transport modes, and the ability to search for interesting landmarks or services. This digitalisation of basic maps has transformed the travelling experience for the user and allowed more informed and responsive travel planning.

1.4.3 Standout Routes – Tourist

For as long as maps have existed, travel experiences and journeys have been recorded and plotted onto maps. Successful journeys are not just kept for memory's sake, but also shared, to guide the travelling experiences of others. These journeys were historical published in guide books and more recently have been shared online. Mapping software allows users to generate bespoke journeys that are specific to them and share these with likeminded travellers. Furthermore, these tools allow the overlaying of different data layers (i.e. satellite view) and provide unique insights into the data. These technology advances have allowed the modern tourist to access mapping data, popular journeys and notable travel stories, all from a simple phone.

The Google Map approach serves as a useful guide for how material data might be better utilised and communicated. The MinFuture vision is for MFA data to be: structured to reflect the material system (data integrity), able to be interrogated at multiple layers to create helpful stories, and available for dissemination to decision makers through targeted diagrams and reports. Visualisation plays a key role in each of these steps, from raw data (maps) to elicitation and communication (routes), through to stories (guide book/standout routes).

Figure 3 describes three stages of the vision, as a framework delivering data driven stories and effective visualisation of MFA data.

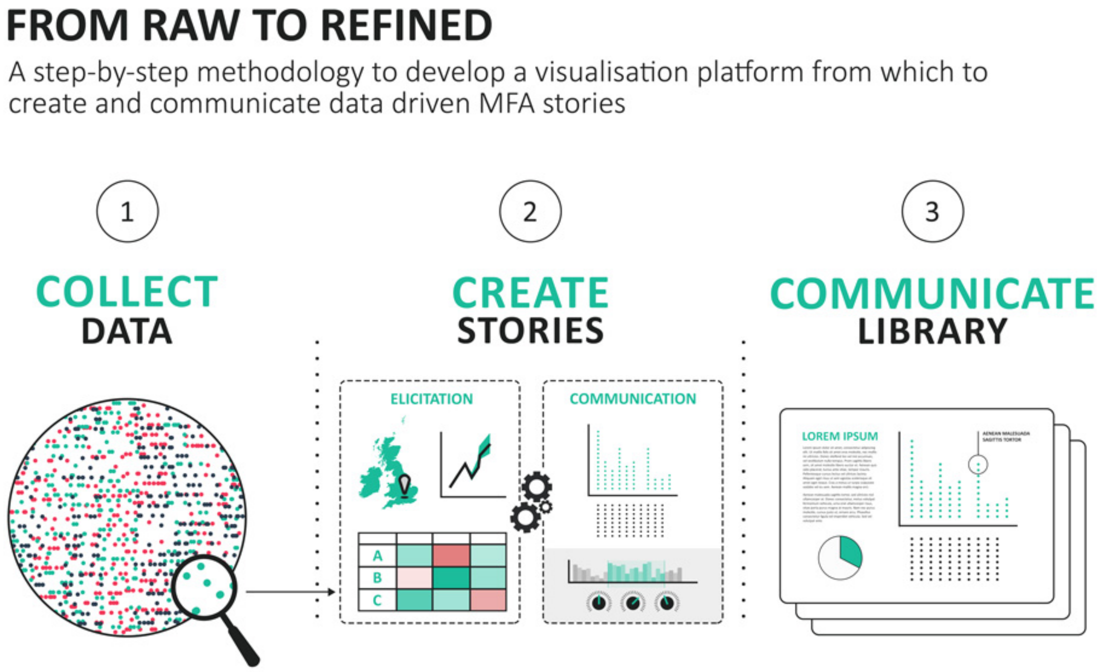


Figure 3: Graphical representation of MinFuture methodology for generating data driven stories and effective visualisation from MFA data.

1.4.4 Data

Collecting material data is the first stage of any MFA study. Several material databases exist, such as the detailed data collected by geological surveys, with much effort expended to collect data from companies involved in the mining and processing of materials. Collected data is cleaned, balanced and reported, typically on an annual basis, giving an important picture of changes across material sectors. However, the reporting of data in tables gives little insight into the structure of the materials system and can obscure the important areas to focus on, thus clouding decision making.

Trustworthy stories can only be created if the credibility of the MFA data can be verified. Users will want to know the answers to questions like: Where has the data been sourced from? Who has collected the data? How has the data been sorted, checked, formatted and verified? A well-structured database, including accurate recording of the data sources and cleaning processes is a good start. Visualisation tools at the data collection stage can assist users when comparing and integrating MFA data (i.e. from year to year) and provides a useful form of data transparency.

1.4.5 Stories

Building engaging data-driven stories involves two key components: to elicit selected portions of data; to create and communicate data stories.

Elicitation requires tools designed to sort and filter the data, based on selected parameters, and to isolate key data relevant to the story. Visual tools can be employed to assist the filtering process, ranging from sorting data columns through to complex big-data plots. The aim is to both speed up the elicitation process while ensuring data accuracy and a holistic view of the data is maintain.

Communication visuals are used to help tell the story in an engaging way. This can take the form of a static picture of the data (i.e. as a .svg, .png, .pdf) or a dynamic visual model including multiple data layers (i.e. the Google Map analogy). For dynamic interactive visuals the underlying data set must be accessible to enable user interactaction with the visualisation and base data. Much of this report is dedicated to describing how to create effective MFA visualisations.

1.4.6 Library

Data-driven stories can be communicated more widely using library collections. Each story can be read, compared and further investigated. Visuals help the reader to engage with the story on an aesthetic level and to understand the data in a logical way. A library should be carefully designed to promote consistency across data stories to enable easy comparison and the data should be traceable to ensure the library remains credible.

1.5 Aims and Objectives

The aims and objectives of this report are outlined below:

- To conduct a review of visualisation theory
- To create a catalogue of principles and features required for good visualisation
- To collate MFA visualisation examples and assess these against the catalogue above
- To construct a best-practice design guide for visualising material systems

2 Review of Visualisation Theory and Design Principles

Charles Joseph Minard's data map of the Napoleonic campaign into Russia from 1812-1813 (shown in Figure 4) is held up as an exemplar of visual design. This beautifully drawn data map demonstrates a clear narrative and with inherent simplicity brings meaningful insight into the ultimately disastrous Napoleonic invasion. Edward Tufte (2006), the visual information pioneer, states that the data map "… exemplifies many of the fundamental principles of analytical design." and believes that it is the "… best statistical drawings ever created."

The following section reviews these 'principles of analytical design' as they have evolved through history, through the writings of visualisation experts such as Edward Tufte, Jacque Bertin, Stephen Few, and Jock Mackinlay. Each has made significant contributions to define the foundational principles for understanding how visualisations impart meaning, information and bring insight to those reading them.

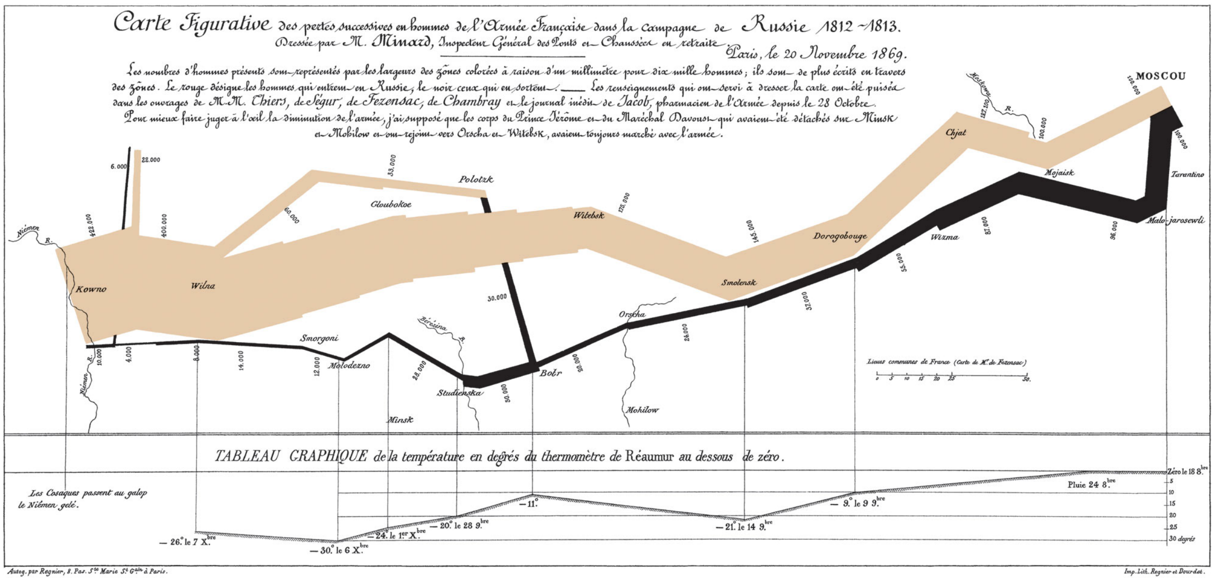


Figure 4: Visual depiction of the military conquest by Napoleon into Russia by Minard (1869) demonstrates the route and losses incurred by the French Army during the Russian campaign in 1812–13. The work combines many dimensions of data charts in a single map: advancing troops (beige), retreating troops (black), loss of life, time, location, temperature, geography, historical context, into one single graphic. These dimensions are shown with minimal text or labels to distract.

2.1 Principles of Analytical Design

Effective visualisation is found in simplicity, when data is visualised in its most naked or pure form, void of frivolous additions. Tufte (2001, 2006) takes a bold stance against 'chart junk' or 'unnecessary data-ink', which he describes as any ink used to display information that is superfluous to the core statistical data (essential) in communicating the data. He champions a minimalist approach, which focuses only on core information to be communicated to the audience.

Tufte (2006) presents six foundational principles of analytical design for communicating the essential information in visualisations, which are described below.

2.1.1 Principle 1: Show comparisons, contrasts, differences

In data analysis it is vital to be able to compare, contrast and ultimately ask questions of the data to infer detailed, meaningful responses. The reader should be able to ask the 'how does this compare to?' questions of the data and visually discern differences and similarities. Minard's data map (Figure 4) embodies this principle by including destination, temperature and troop losses to give a stark comparison between the start and the end of Napolean's military campaign. The map highlights the massive troop losses on the return march from Russia.

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

Data by itself can infer causality but without mechanism and explanation it is difficult to apply reason to the data and develop meaningful analysis and conclusions. When presenting data, it is therefore imperative to provide an explanation through linking data sets and addressing the 'why?' and 'how did?' questions.

2.1.3 Principle 3: Show multivariate data

Data is complex and multivariate and rarely has singular variables because we live in a complex multivariate world. Good visualisation goes beyond a two-dimensional data experience by exploring multiple variables. However, care must be taken to ensure the data does not become so complex as to overwhelm the reader, resulting in a loss of meaning or comprehension.

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

Making use of layered information improves the clarity of the data presented. This includes using multiple data sets or creating 'modes' of information. Tufte describes this importance of combining written narrative with statistical graphs and topographical maps. While different sources and modes of data should be explored to provide meaning and insight to support the narrative.

2.1.5 Principle 5: Describe the evidence

Documenting the evidence and sources which sit behind a visualisation are vital. Credibility is created when the reader can easily access the data sources behind the visualisation. Good visualisations include an informative title, accurate legends scales, detailed captions and a comprehensive list of data sources.

2.1.6 Principle 6: Content must be relevant, have integrity and quality

In the process of creating a visualisation the integrity of the data must be retained; data filtering and cleaning processes should be careful when removing data points as this will alter and degrade the presentation. The final audience and relevancy to the narrative must also be considered when sourcing and creating content.

Tufte's six principles of analytical design have been widely accepted in the field of visualisation theory. However, debate has arisen over Tufte's opposition to 'chart junk' and 'unnecessary data-ink'. Bateman et al. (2010), in contrast to Tufte, promote the use of chart junk within information presentation and identify a number of studies that encourage the use of chart junk to bring insight in visualisation. Their hypothesis is that chart junk can be an important addition to comprehension, aiding cognitive recall of the presentations. However, several issues in their study undermine this hypothesis. Firstly, the case studies selected for analysis are all well designed and constructed by seasoned graphic designers. The 'chart junk' identified in these examples is of high visual quality. Secondly, the number of case studies selected is small, and does not necessarily support the conclusions.

Few (2015) counters these arguments, stating that memorable visualisation is of less consequence than the comprehension of visuals and the communication of an idea or message. Creating visualisations that look 'attractive' (which Tufte describe as 'chart junk') is of secondary importance to the story the data is telling. A chart that uses vivid graphics and embellishments might be more memorable, as Few explains, but scarcely can one remember the specifics of a data visualisation amidst the daily bombardment of visual stimulus a person receives.

Few (2010) comments on the current state of information visualisation and the dilution of the field by the use of the term 'data visualisation', particularly in the context of modern digital-based visualisation mediums. He points out the flaws and pitfalls of several visualisations, where 'data visualised' does not always translate to 'information visualised'. Few's methodical process of extracting the core information from the data provides a guide for creating informative visuals which portray a strong data message, while avoiding artistic embellishment.

What is clear from the development of visualisation principles, by the likes of Tufte, Bertin, and Few, is that the field of information visualisation has been well documented and curated over considerable time. However, we often fail to apply this well-crafted knowledge to the scientific disciplines where data visualisation is important. This can result in poorly designed visuals, reduced insight and poor decision-making in these fields.

2.2 Gestalt Principles

The Gestalt principles of visual perception are based on the work of Wertheimer (1938) and have since been developed by a number of visualisation theorists. Gestalt is a psychology term which refers to the 'unified whole' and attempts to describe the basic visual groupings in human vision and how humans organise visual elements in simple, cohesive and ordered ways. Todorovic (2008) provides a comprehensive list of eight principles and summarises the causality of each: Figure-Ground Articulation, Proximity Principle, Common Fate Principle, Similarity Principle, Continuity Principle, Closure Principle, Good Gestalt Principle, and Past Experience Principle.

These principles should be kept in mind when understanding associations and context, such as alignment in visualisations. However, for the purposed of this report the Gestalt principles fall short, as they do not convey the differences between quantitative and qualitative information, required for MFA and material systems visualisation.

2.3 Retinal Variables

Whilst Tufte sought to build credible principles on which visualisations succeed or fail, other visualisation pioneers have focused on the retinal and cognitive interpretation of the fundamental attributes of design that form a visualisation. Jaques Bertin, the cartographer and visualisation theorist, is one such pioneer. His most formative book, 'Semiology of Graphics' Bertin (1983), originally published in 1967, outlines the foundational variables of graphical perception. The way we perceive information through sight is at the core of information visualisation. Through visual perception we are able differentiate, make comparisons, highlight and infer meaning.

Few (2004), Cleveland and McGill (1984) and Ware (2012) all provide scientific rational as to the construct of perception. The functionality of how and why this takes place is best described by Ware (2012) and Few (2004) where a distinction is made between pre-attentive processing and attentive processing. Pre-attentive attributes of visuals are subconsciously processed and can be perceived in parallel; attentive attributes require detailed focal attention and can only be processed in series. Triesman and Gelade (1980) describe this idea as 'feature integration theory', where focal attention and top-down processing are used to identify single objects. Similar items require more conscious focal attention to differentiate than visually distinct elements. Few (2004) proposes that by harnessing these pre-attentive, subconscious attributes in data presentation, visualisations can be better designed to inform and communicate key information.

2.3.1 Preattentive attributes

Bertin (1983) outlined a list of seven pre-attentive attributes that form the foundation of graphical perception: position, size, value, texture, colour, orientation and shape. Following on from this early list, information visualisers like Few (2004) and Mackinlay (1986) have supported and expanded upon the work of Bertin. Mackinlay's list mirrors Bertin's list but subdivides some of the categories, for example, size into area, length, volume and density. Few (2004) outlines a list of pre-attentive attributes which is collated into three categories: form, colour and spatial position. Both authors discuss the relative strengths of each approach and how they can be used in visual design, however Bertin and Mackinlay extend their approaches to give a perceptual ranking system for each attribute, against its ability to show qualitative and quantitative perpetual tasks.

For this study, we focus on Bertin's early list of seven pre-attentive variables, as shown in Figure 5. Bertin's list is divided into two distinct categories: planar variables (i.e. position) and retinal (or differential) variables (i.e. size, value, texture, colour, orientation and shape). The seven variables are discussed below, with particular attention paid to retinal variables that are used to differentiate or group data items regardless of position, as these are foundational to any visual diagram.

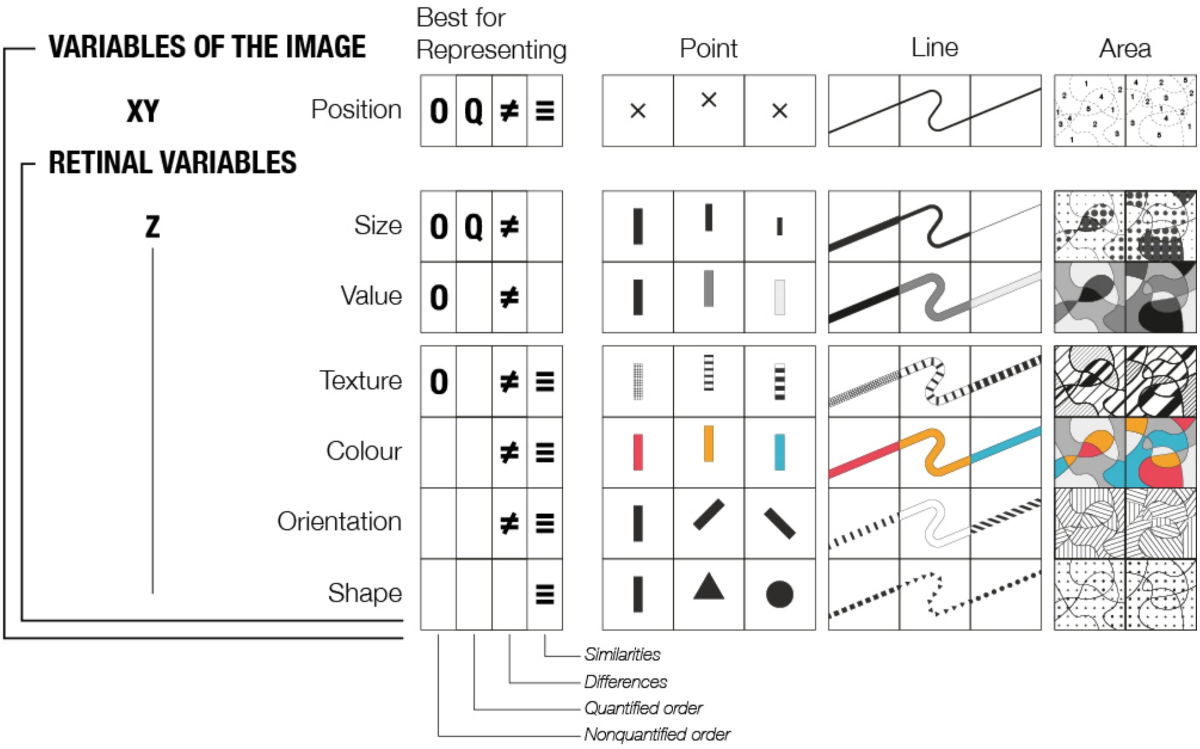


Figure 5: *Variables of an image, shows the retinal variables strengths, weaknesses and subsequent forms when displayed as a point, area and line. Adapted from Bertin (1983).*

2.3.2 Position

Position is a planar variable best used to demonstrate qualitative, nominal (for naming) and ordinal (for ordering) perceptual tasks. Bertin (1983) describes position as a preattentive attribute, but not a retinal (or differential) variable, as it requires a supporting scale and framework for position to be understood (i.e. an XY location is needed). Position is foundational to all charts and diagrams and is the base for all retinal variables; it is the primary layer on which all other layers are placed to communicate data. Position is the most accurate variable for conveying both quantitative and qualitative information.

2.3.3 Size

Size describes a change in length, area or repetition, and can also include volume and density as described by Mackinlay (1986). The bar chart provides an example of size used as a retinal variable, where the primary retinal variable is the height of the bar, which is proportional to the numeric quantity defined by the scale. It can be used to represent both quantitative (both discrete and continuous) and qualitative measures (differences, similarities, ordinal and nominal).

2.3.4 Value

Value describes changes from light to dark, most commonly as transition from black, through grey, to white. It is a common variable in print visualisation where colour print is not available or used. Value can be used to demonstrate quantitative changes but should only be used for integer scales where the number of possible values is small and discrete. It is more commonly used to show qualitative information (differences and nominal).

2.3.5 Texture

Texture is defined as the changes in coarseness of marks in an area, for example a pattern. Similar to value, this variable is often used for non-colour print articles to show qualitative information (similarities, differences, nominal). Texture can be used to show quantitative differences, but is only useful for small integer ranges, due to the visual complexity and possible confusion created by high levels of data ink in confined spaces. This use of texture for quantitative perceptual tasks is not encouraged as other retinal variables perform these tasks more effectively.

2.3.6 Colour

Colour (a change in hue) forms an essential aspect of how we perceive the world around us. We use colour to understand everything from objects to emotions. Culture attaches much meaning to colour, for example, in western culture we associate green with balance, positivity and nature. Colour theory and colour psychology are two highly developed and documented fields of study. Stone (2006) outlines the basic principles of colour design and how it can be used to occlude or facilitate data visibility in visualisation. The author presents guidelines for colour use focusing on contrast and analogy, where contrast should be used to differentiate key information and analogy should be used to group similar data or information. The recommendation is to use a prebuilt colour palette based upon the specific function you wish to achieve.

Many designers have proposed example colour schemes. Brewer (1994) describes a unique colour scheme topology that is targeted towards cartographic mapping and complex thematic maps, allowing the basic principles of qualitative differentiation and grouping to be applied. Light and Bartlein (2004) present a number of issues surrounding the use of colour schemes in data presentations. They describe how a spectral scale is not only redundant in communicating key information, but also presents issues for viewers who are colour deficient in some aspect. They highlight the need to adopt colour blind 'friendly' palettes. The authors provide links to a number of colour palettes which are suitable for people with colour deficiencies. Yau (2013) also provides suggestions for colour schema which use a wide colour span and adopt shades with high variation which are most suited to showing differences.

The complexities and nuances of colour use require that clear guidelines and principles are in place to communicate effectively. Colin Ware (2004), in his book Information Visualisation: Perception for Design, provides such a guide for colour use in visualisation, which is summarised in Table 1.

Colour should be used to present qualitative information (differences, similarities and nominal), and only sparingly for quantitative data, for example, to show specific groupings, to highlight extreme values, or to highlight key elements. It is always best to use a generated colour palette.

Colour use	• Colour is good for labelling and categorisation, significantly less so for representing shape, detail or space. • Colour effective when used as a nominal code • Use small set of colour codes. • Use only a few colours with distinct codes. Six are easy to choose, 10 become more difficult. • If showing variation is important, above and below 0, use a neutral value to represent 0. Then increasing saturation towards opposite colours.
Perceptual Factors	• Distinctiveness: Must be able to visually separate a single colour from the surrounding colours. • Unique Hues: Avoid using multiple shades of the same colour. • Black or white borders around colour can make them distinct by ensuring luminance contrast. • Colour contrast can cause large errors in representation of quantity. Errors can be reduced with borders or by using muted uniform backgrounds.
Relationship to background	• Colours used should contrast with background. • Items can become salient if they are similar to the background colour. • White should be used as a reference when judging other colours.
General considerations	• Colour coded objects should have at least half a degree of visual angle as a minimum size to perceive the coding. • When colour coding large areas use muted colours. • Smaller objects should have strong highly saturated colours for maximum discrimination. • There should be a significant luminance difference in addition to colour difference. • Colour Blindness: Use colour blind sensitive palettes • Colour conventions: Colour conventions differ in cultural contexts. • Be cautious of over saturating colour, especially for printed images.

Table 1: The effective use of colour in visualisation (adapted from Ware (2004)).

2.3.7 Orientation

Orientation describes the changes in alignment or variations in rotation of an object relative to a central axis. It is useful for demonstrating qualitative information (similarities) for grouping data. Orientation is used in flow maps (i.e. left to right in Sankey diagrams) and oceanic/weather forecasting due its good geospatial association. A good example is 'Project Ukko' (2016), developed as part of the EUPORIAS project, which uses orientation to compare wind speed relative to predicted changes, for a particular geographical area.

2.3.8 Shape

Shape is used to demonstrate qualitative information (similarities and nominal). However, change in the area of a shape can be difficult to interpret quantitatively. Shape is the weakest of the retinal variables and should only be used to show qualitative groupings for a small number of distinct groups within a data set. There are an infinite number of shapes available for use, however at small scale and with over-plotting differences in shape can become indistinguishable from each other. In general, there are more suitable variables that can demonstrate qualitative information.

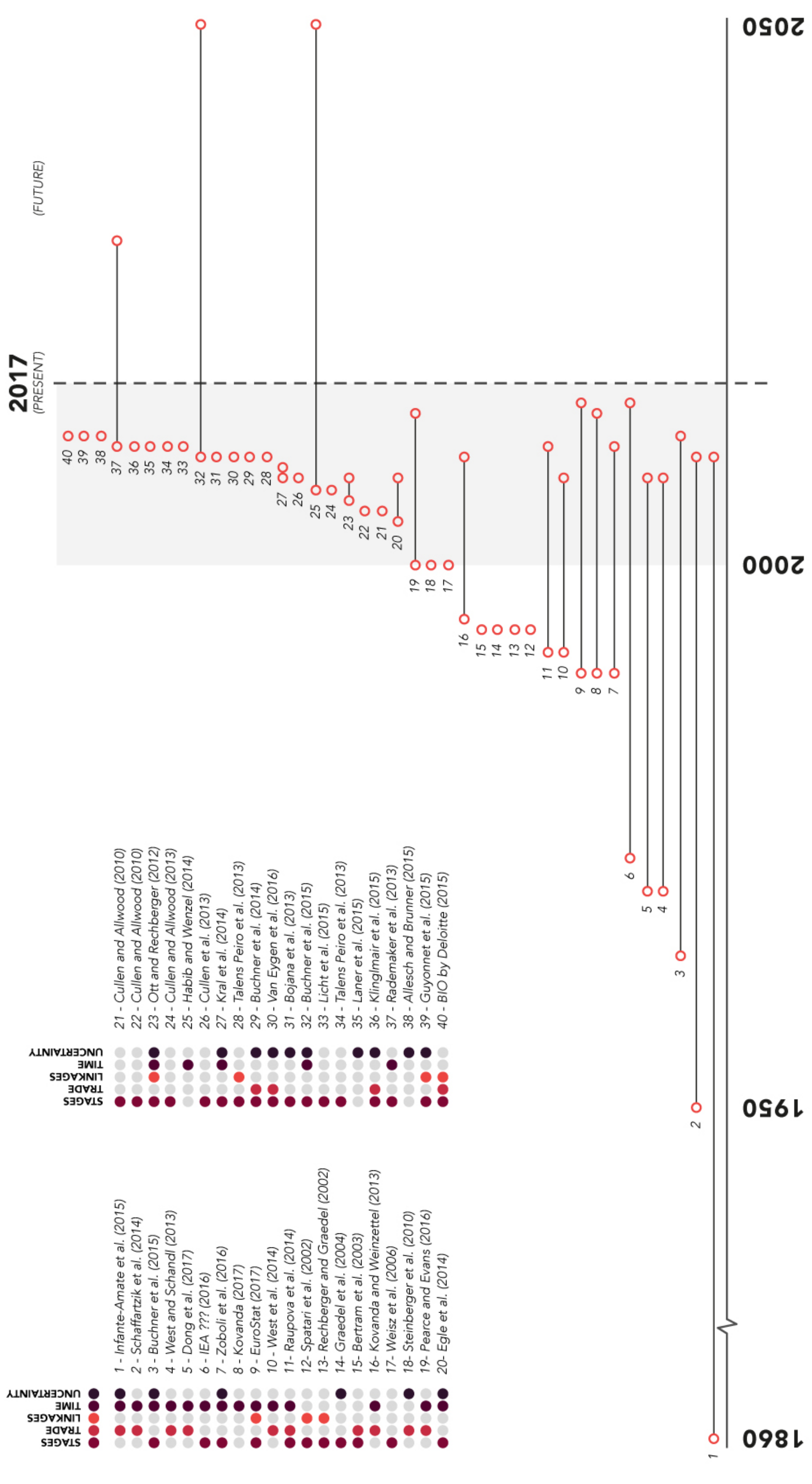
Good visualisation practice is characterised by the use of several retinal variables (size, value, texture, colour, orientation and shape) to reinforce position, conveying multiple layers of information to the reader without making the visual overly complex. Getting the correct balance between data complexity and visual clarity takes much effort and practice. In the following section, examples from the MFA literature are categorised by type and assessed against Bertin's retinal variables and the core dimensions from the MinFuture project.

3 Use of Visualisation in MFA

MFA is an essential tool for portraying material systems in economies and countries. Such studies, typically collate large amounts of data, filter and mass balance this data, and use visualisation tools to bring out the key points from the MFA data. In this chapter, we conduct a review of the types and forms of visualisation used across 48 individual MFA studies. Examples are sourced from MFA research publications, and a selection of online interactive models. Figure 6 provides a visual summary of 40 of the MFA studies collated for this study. This collection of studies is by no means complete, however, we believe it to be representative of the types of approaches employed to visualise MFA data. The figure shows the time period covered by each study, which includes single years MFA studies, historical MFA analysis over many years, and future dynamic predictions of a future material system. The studies are ordered according the start date of the MFA time period.

An initial characterisation of each MFA study by the MinFuture Core Dimensions is shown in Figure 6 (for more discussion on this see Section 3.2).

Figure 6 (next page): Summary of MFA studies, including core dimensions and time period.


1860
1950
2000
2050
2017
(PRESENT)
(FUTURE)
STAGES
TRADE
LINKAGES
TIME
UNCERTAINTY
1 - Infante-Amate et al. (2015)
2 - Schaffartzik et al. (2014)
3 - Buchner et al. (2015)
4 - West and Schandl (2013)
5 - Dong et al. (2017)
6 - IEA ??? (2016)
7 - Zoboli et al. (2016)
8 - Kovanda (2017)
9 - EuroStat (2017)
10 - West et al. (2014)
11- Raupova et al. (2014)
12- Spatari et al. (2002)
13- Rechberger and Graedel (2002)
14- Graedel et al. (2004)
15- Bertram et al. (2003)
16- Kovanda and Weinzettel (2013)
17- Weisz et al. (2006)
18- Steinberger et al. (2010)
19- Pearce and Evans (2016)
20- Egle et al. (2014)
21 - Cullen and Allwood (2010)
22 - Cullen and Allwood (2010)
23 - Ott and Rechberger (2012)
24 - Cullen and Allwood (2013)
25 - Habib and Wenzel (2014)
26 - Cullen et al. (2013)
27 - Kral et al. (2014)
28 - Talens Peiro et al. (2013)
29 - Buchner et al. (2014)
30 - Van Eygen et al. (2016)
31 - Bojana et al. (2013)
32 - Buchner et al. (2015)
33 - Licht et al. (2015)
34 - Talens Peiro et al. (2013)
35 - Laner et al. (2015)
36 - Klinglmair et al. (2015)
37 - Rademaker et al. (2013)
38 - Allesch and Brunner (2015)
39 - Guyonnet et al. (2015)
40 - BIO by Deloitte (2015)

In the remaining sections of this chapter we evaluate the visualisation in these MFA studies. The chapter is divided into three sections:

1. A review of the types of visuals commonly used in MFA and the key characteristics of each visual (Section 3.1)
2. An evaluation of each visualisation against the Core Dimensions of the MinFuture project, to assess the effectiveness of each visual form in portraying Stages, Trade, Linkages and Time (and Uncertainty and Stocks). (Section 3.2)
3. An assessment of each visualisation against Bertin's seven Retinal Variables to understand how Position, Size, Value, Texture, Colour, Orientation and Shape are employed to aid comprehension in MFA visualisation. (Section 3.3)

Appendix 4 provides a full table of the 48 individual MFA studies evaluated.

3.1 Review of Visual Forms Used in MFA Studies

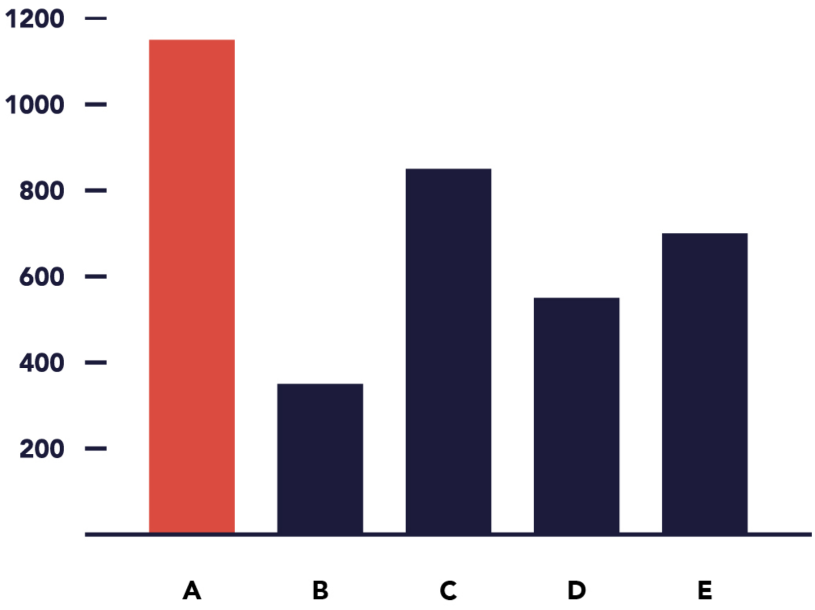
Most MFA studies include multidimensional variables, with heightened complexity, resulting in a broad range of diagrams being adopted. Many different visual forms are employed across the MFA studies, ranging from Sankey diagrams through to Bubble charts. Sankey diagrams, in different forms, are popular in providing a holistic overview of material systems, particularly for single year MFA studies. However, Sankey diagrams are less effective for visualising MFAs conducted over multiple years; traditional Line Charts, Bar Charts and Area Plots are more likely to be used to visualise the change in variables over time.

A range of retinal variables are employed to show qualitative information. However, these are applied with less consistency across the visualisations in each study, leading to some confusion. In some rare cases, the visualisation was so poor it provided no additional comprehension over and above a simple table. Unfortunately, there appears to be scant visual consistency across the range of MFA studies, which points to the need for more guidance on best practice design in MFA visualisation.

To follow is a review of the seven most commonly used visual forms in MFA studies: Bar Chart, Sankey Diagram, Table, Flow Diagram, Line Chart, Area Plot, and Pie Chart. For each visual form we have compiled a list of key characteristics and examples from literature.

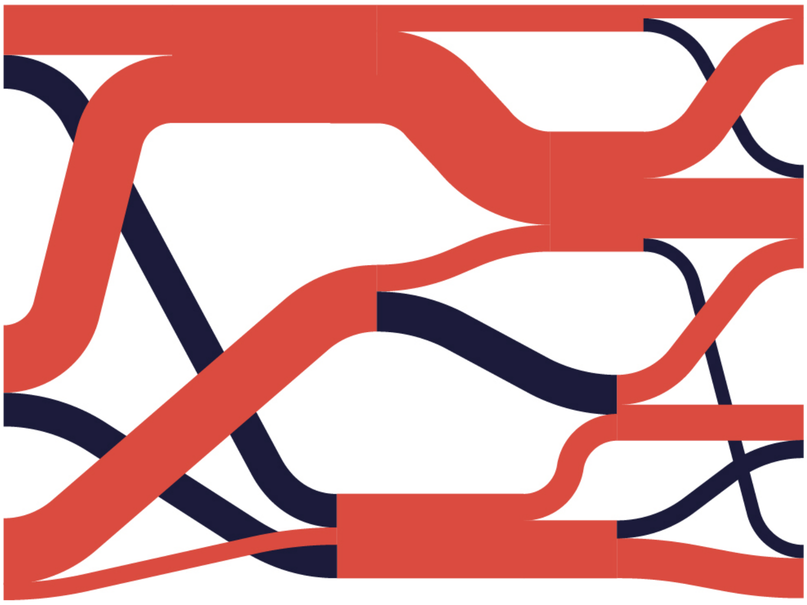
This is followed by an in-depth discussion of two exemplar visualisations chosen from the MFA studies. The first is a colour Sankey diagram of global steel flows for the year 2008 by Cullen et al. (2012) which makes good use of Position, Orientation, and Colour to visualise a complex MFA data set The second is a black and white Sankey Flow Diagram of an SFA (Substance Flow Analysis) model of phosphorus in the EU by Ott and Rechberger (2012) for 2008/09, which also uses Value and Orientation to convey a large amount of data in a compact form.

3.1.1 Bar Chart



Other derivatives	• Stacked Bar chart • Stacked Bar with Stacked Area • Stacked Bar with Lines • Grouped Bar chart • 3D Bar chart
Construct/ Purpose	• Used primarily for presenting comparisons within data • Constructed of horizontal/vertically oriented bars with a fixed baseline • Scale presented on the y axis with ordinal categories along the x axis. • Can be combined with area / line graphs, with a separate axis to show multivariate information
Retinal Variables	• Primary variables: Position and Shape • Secondary variables: Colour, Texture and Value (Secondary variables can be used to carry multivariate data or provide qualitative differentiation or similarities)
Core dimensions	• Can represent Stocks, Trade, and change any dimensions with time
Examples	• https://www.carbonbrief.org/mapped-the-global-coal-trade • Bertram et al. (2003) • Dong et al. (2017)

3.1.2 Sankey Diagram



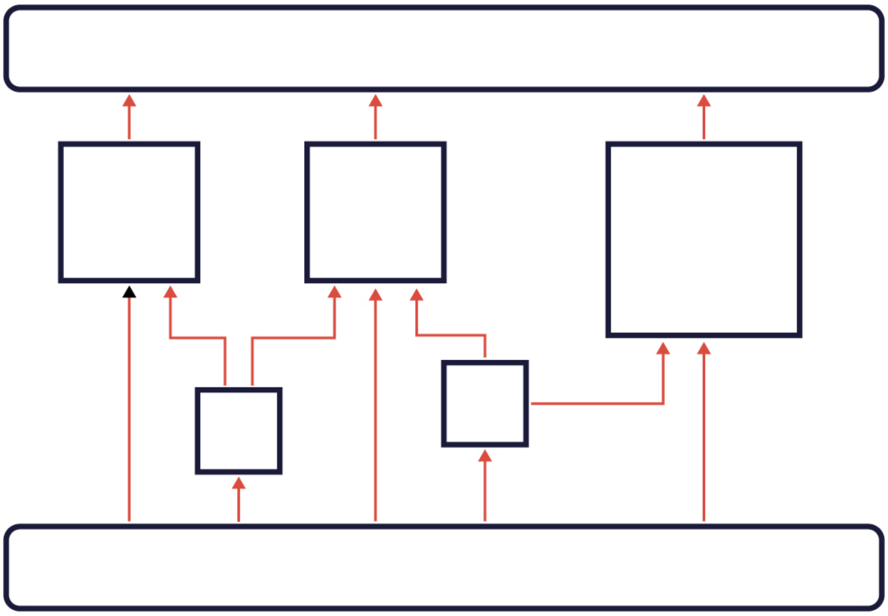
Other derivatives	• Sankey Diagram • Sankey Flow Diagram • Flow Map
Construct/ Purpose	• Used to show comparisons, relationships and overview of a system • Flow widths are proportional to the mass flowing between stages (Can be used to show energy, financial or material flows) • Derivatives, such as Flow Maps, show distributions and compare flows between geospatial sources and destinations
Retinal Variables	• Primary variables used: Position and Size • Secondary variables used: Colour, Value and Texture
Core Dimensions	• Stages, Trade and Linkages • Can be used to show Time, Stocks and Uncertainty
Examples	• Cullen and Allwood (2010) • Laner et al. (2015) • Lupton and Alwood (2017) • https://www.carbonbrief.org/mapped-the-global-coal-trade

3.1.3 Table

	X	Y
A	1200	✗
B	400	✓
C	1000	✓
D	200	✗

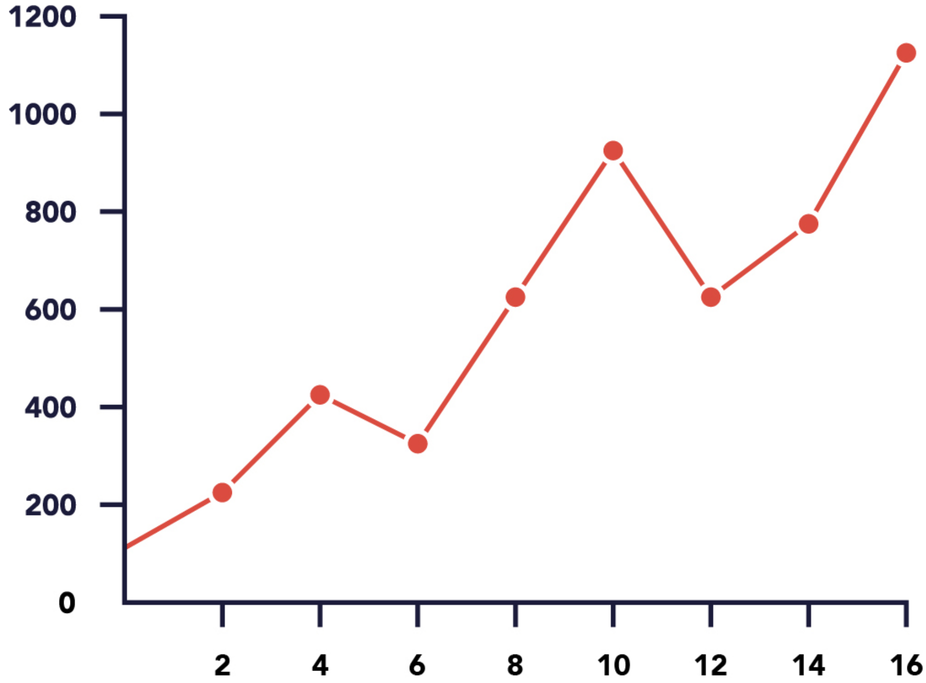
Construct/ Purpose	• Used to show comparisons of large bodies of data • Primarily used with complex data variables or large bodies of descriptive information and numeric data • Requires focused attention to serially perceive each column and row, and then compare across the table. • Commonly used to present information, including small quantities of information
Retinal Variables	• Primary variable: Position • Secondary variables: Colour and Value (Secondary variables applied to either the cell or the text and used for nominal data)
Core Dimensions	• Stages, Trade, Linkages, Time, Uncertainty and Stocks (note data patterns are difficult to identify or compare).
Examples	• Talens Peiro et al. (2013) • West et al. (2013) • Haas et al. (2015)

3.1.4 Flow Diagram



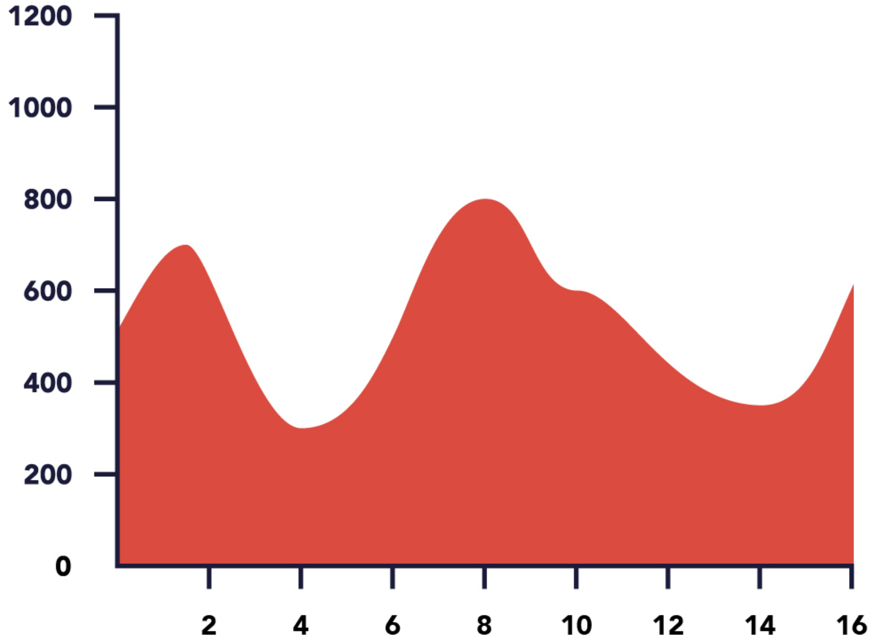
Other Derivatives	• Pictorial Flow
Construct/ Purpose	• Used to show system structure and network flows • Constructed from a series of shapes (nodes), with linking arrows (edges) used to denote the direction and flow of between nodes • Used to define complex system structures and hierarchies. • With added meta data they can be used to compare system models
Retinal Variables	• Primary variable: Position • Secondary variables: Size, Colour, Texture, Shape and Value
Core Dimensions	• Stages, Trade, Linkages, Uncertainty and Stocks
Examples	• Talens Peiro et al. (2013) • Buchner et al. (2015) • Zoboli et al. (2016)

3.1.5 Line Chart



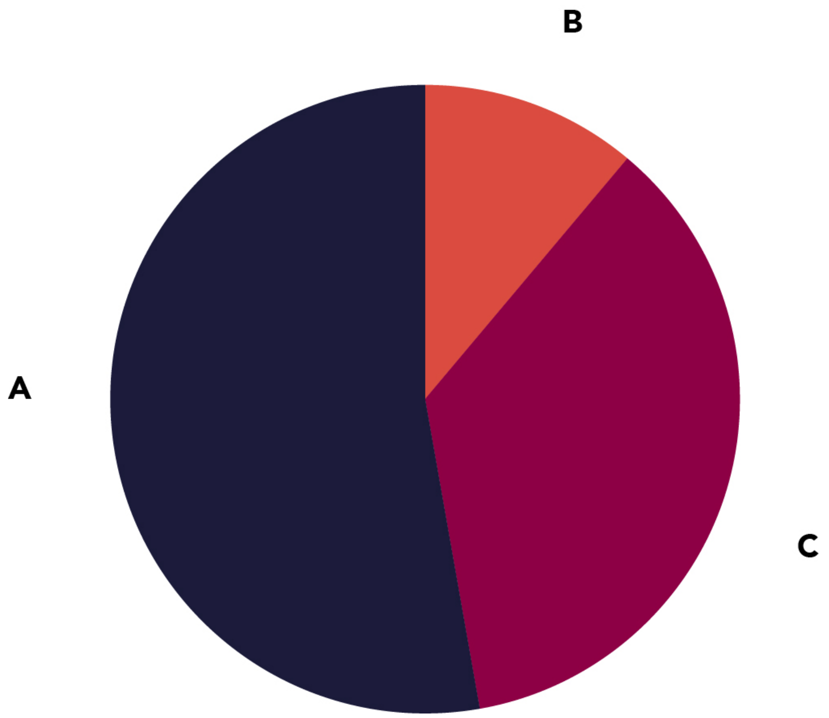
Other Derivatives	• Span • Fan
Construct/ Purpose	• Used to show changes over time and distribution of data by sectors • Multiple lines used for comparison of data • Constructed using data points with connecting lines
Retinal Variables	• Primary variables: position • Secondary variables: Colour, Value, Shape, and Texture
Core Dimensions	• Time, Uncertainty and Stocks
Examples	• Buchner et al. (2015) • Habib and Wenzel (2014) • Lee et al. (2012)

3.1.6 Area Plot



Other Derivatives	• Stack Area
Construct/ Purpose	• Built upon the same construct as a line graph • Uses a shaded lower section to present changes in size over time or distributions • Stacked area charts using multiple data sets can be plotted on the same graph • Used to compare, show time-based changes and show trends
Retinal Variables	• Primary variables: Position and Size • Secondary variables: Colour and Texture
Core Dimensions	• Trade, Time and Stocks
Examples	• Kovanda and Weinzettal (2013) • Lee et al. (2012) • https://www.carbonbrief.org/mapped-the-global-coal-trade

3.1.7 Pie Chart



Other Derivatives	• Donut • Stacked Donut
Construct/ Purpose	• Used to compare the parts which make up a whole • Measured by the arc length of each slice, which makes it difficult to accurately visually interpret the more slices are presented • Although commonly used in MFA, Tufte and Few argue strongly against the use of this visualisation
Retinal Variables	• Primary variable: Size • Secondary variables: Colour, Texture and Value
Core Dimensions	• Stock (as percentage), Stages (distribution of material flow)
Examples	• Dong et al. (2017) • Deloitte (2015) • https://www.iea.org/Sankey/

Many MFA studies cover large economies and time spans, tracing a single material as passes through different parts of the economy. The following section describes two common visualisation approaches have been selected to open up a discussion about different approaches for visualising MFAs.

3.1.8 Example 1 – Global Map of Steel Flows in 2008

Cullen et al. (2012) have produced a global map of steel from liquid metal to end use products and presented the model using a Sankey Diagram (shown in Figure 7). The source data is from the year 2008 and the purpose of the visualisation is to present a holistic picture of the global flow of steel, with interpretation and insight being discussed in the accompanying article. The Sankey diagram is complex requiring significant focal attention to understand and gain insight from the visualisation. The diagram conveys information about Stages from the MinFuture Core Dimensions.

In Sankey diagrams the width of each line is proportional to the mass flow of material. However, the length of each line bares no meaning. The visualisation can be read left to right, mirroring the material supply chain which tracks from iron ore, through liquid steel to final products. The largest material flows (and thickest lines) are organised to be as straight as possible.

The orientation of the flow lines provides some assistance in reading the diagram. All flows track from left to right, and between 0º to 180º (orientation), apart from the recycled scrap return flows (grey) which track from right to left, flowing back to the steel making process at the start of the supply chain.

Title labels are used to delineate vertical slices in the diagram (i.e. steelmaking, casting), while flows are labelled to indicate materials (i.e. pig iron, slab.) The complexity of the Fabrication to End-use products section is shown by the large number of crossing lines; in this case showing this degree of complexity is more important than being able to distinguish individual lines.

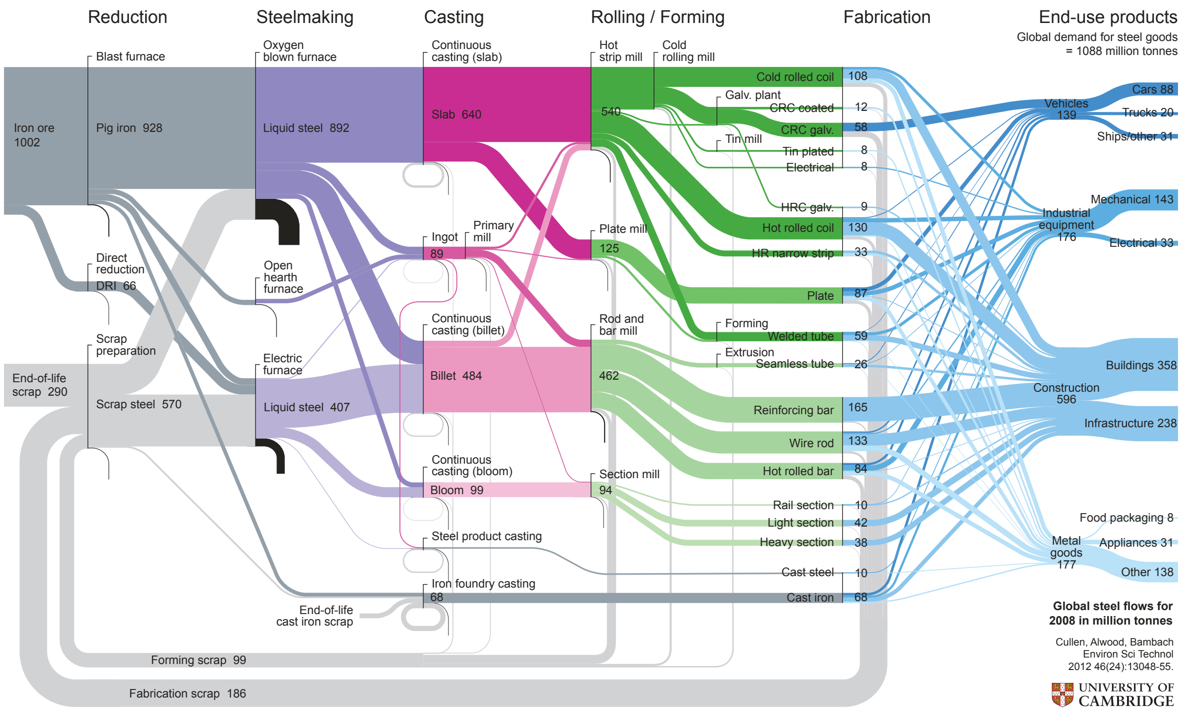


Figure 7: Sankey diagram showing the global steel flows in 2008, from Cullen et al. (2012)

The diagram uses colour to delineate Stages in the material supply chain for global steel, a form of qualitative information. Different hues within each colour are used differentiate between different product flows, in groups, each group graded from top to bottom. The salience of the colour 'pink' inadvertently draws immediate focus of the viewer, over and above the other muted tones.

Overall, this visualisation is presented with clear logic. The underlying MFA model is complex requiring a detailed visualisation. This can be taxing on the reader, requiring significant focal attention, however, such complexity is necessary given the topic nature. The diagram has proved an important MFA visualisation for decision making for the global steel industry.

3.1.9 Example 2 – EU Flow Chart of Phosphorus in 2008/09

Figure 8 shows an SFA (Substance Flow Analysis) model ofphosphorus in EU15 countries in 2008/09, created by Ott and Rechberger (2012). The visualisation is presented as a Sankey Flow Diagram, similar to a Flow Chart but with the added functionality of line thickness proportional to mass flow. The diagram conveys information about Trade, Stages, Uncertainty and Stocks, from the MinFuture Core Dimensions.

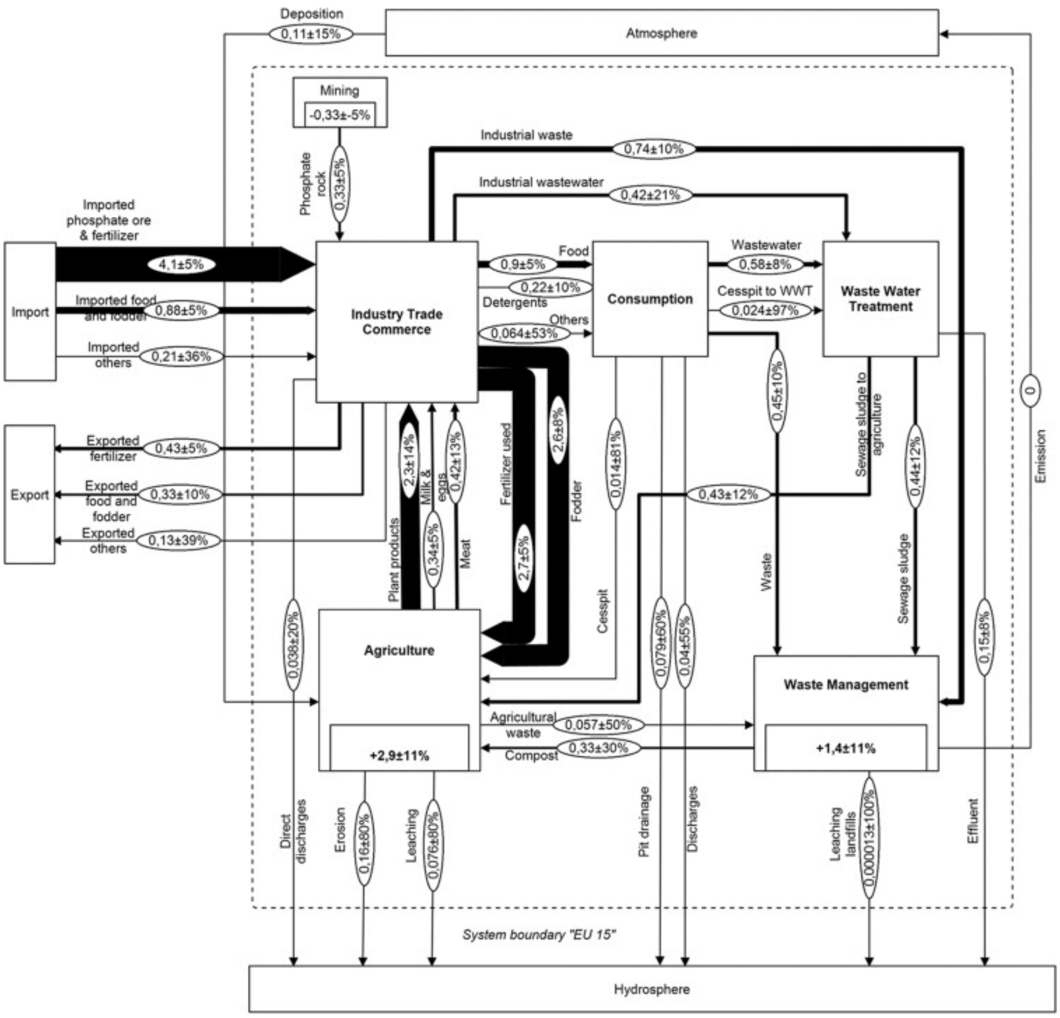


Figure 8: Sankey Flow Diagram from Ott and Rechberger (2012) demonstrating the SFA model of phosphorus in the EU15 countries.

This visualisation adopts the design of a traditional flow diagram with stages/processes defined as rectangles. The visualisation uses shape to differentiate between flows (arrows) and processes (boxes). Flow width is proportional to the mass of the flow between the stages, and the uncertainty for each flow is given in numerical form inside an elliptical shape. Arrowheads are used to denote the flow of material, which is important given the vertical and horizontal orientation of the flows. Smaller flows have pronounced arrow heads compared to the size of the flow to ensure visibility.

The system boundary is shown as a dotted outer line, providing a clear distinction between the system and external imports/exports. The visual adopts a neutral colour palette, using only black and white only, probably because of publication constraints. There are some areas of occlusion in the diagram as a result of the lack of space and alignment of the stages and text labels, and there is little consistency for the placement of labels in relation to the material flows. An improved approach would be to adopt rules for text in relation to features on the diagram. The study provides additional diagrams alongside the Flow Diagram, to further explains key elements of the SFA, including tables, bar charts, stacked bar charts and line graphs. All diagrams use a similarly neutral colour schema (grey scale) with various hues and textures.

In summary, this study adopts a technical style of Sankey Flow Diagram to present the topology of the material system. The study results are clear and the design simple, allowing the diagrams to work well in both print and online mediums. Some minor changes to improve the consistency of text placement would be welcome, but overall the diagrams are an example of good visualisations in MFA.

3.2 Core Dimensions Visualised in MFA Studies

The MinFuture project has identified four Core Dimensions for material systems (described in Section 1.2). Good visualisation approaches need to able to incorporate these four dimensions into the diagrams and figures used. In this section, we evaluate the visualisations from 48 MFA studies against the Core Dimensions of the MinFuture project: Stages, Trade, Linkages and Time, and two additional dimensions, Uncertainty and Stocks. Figure 9 shows the number of MFA studies, which incorporate the Core Dimensions in their visualisations. Note that each study can include more than one Core Dimension. The full results for each study are included in Appendix.

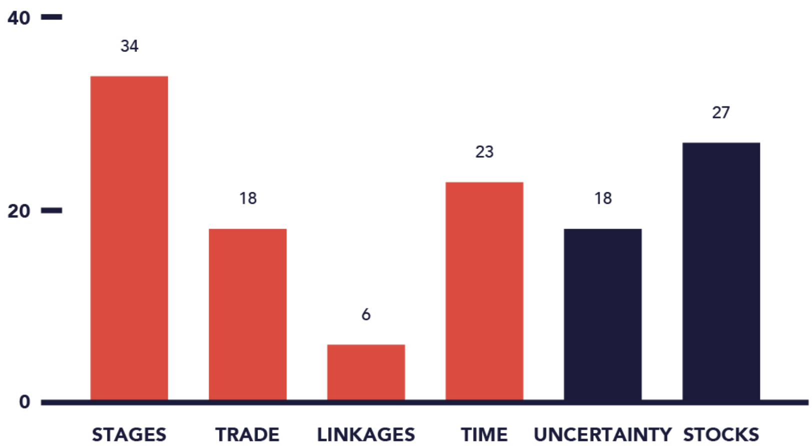


Figure 9: Number of MFA studies that demonstrated the Core Dimensions of MinFuture, and/or Uncertainty and Stocks.

3.2.1 Stages (34 Studies)

Most MFA models includes Stages to describe the various processing steps in a material supply chain. Stages are frequently presented in the form of a Sankey Diagram, a Sankey Flow Diagram or a Flow Diagram. It is important to note the distinction between the Sankey Diagrams and Sankey Flow Diagrams. While they both maintain the width of the line proportional to the mass flow, the structure and layout of the diagrams is different. Sankey diagrams have a linear directionality across the diagram. For example, the left to right flow of material in the aluminium diagram by Cullen and Allowed (2013) corresponds to the stages of the material supply chain. Whereas, Sankey Flow Diagrams have more in common with a traditional Flow Diagram, which use shapes to define processes/stages, connected by line flows. A good example can be found in the European study of phosphorus by Ott and Rechberger (2012). Sankey Flow Diagrams are more compact in design, often using a 4:3 aspect ratio. The size of the process boxes carries no quantitative data. These diagrams, are often used more to show uncertainty or stocks for MFA models, as these dimensions are more difficult to show in a Sankey Diagram.

3.2.2 Trade (18 Studies)

Trade is analysed in 18 of the MFA studies reviewed and is visualised using many different diagram types. For example, import and export data can be identified using colour in a Bar Chart, shown as a cross-boundary flow in a Sankey Diagram or Sankey Flow Diagram, or included in a Flow Diagram or Chord Chart. Using a Chord Chart (a circular ring divided into countries, with trade lines crossing through the circle) can be problematic, as the scale and proportions of the data are difficult to distinguish (i.e. Dong et al. (2015)). In most cases, a simple bar chart provides the best options for visualising trade.

3.2.3 Linkages (6 Studies)

The inclusion of linkages in MFA visualisation is still novel, with Tables of alloy composition or material purity being the main examples found. However, Talens Peiro et al. (2013) created a dedicated Flow Diagram to illustrate 'hitch hiker' materials within their MFA study. Further research is required to develop effective visualisation for clearly communicating linkages to readers.

3.2.4 Time (23 Studies)

Many MFA studies track material flows and stocks over man years, creating visualisations, which included the Core Dimension of Time. Temporal data is predominantly displayed using Line Graphs and Bar Charts. Interactive online Sankey Diagram models have been used to display time via the use of animation (a video-clip or slider) that steps through a sequence of annual Sankey diagrams over a time period, for example the energy balance flow map created by Eurostat (2016). This method is beneficial to see changes in material flows over time, however, it relies heavily on the readers short term memory to make comparisons with previously displayed Sankey Diagrams. The International Energy Agency (IEA) (2015) resolves this problem by showing a secondary Line Graph of the material flow with time, below the animated Sankey Diagram. Presenting time-based data on a single graph enables accurate comparisons and information to be obtained. However, this technique can only display, at most, a few key flows on a Line Graph, in contrast to the many material flows displayed on a Sankey Diagram.

3.2.5 Uncertainty (18 Studies)

MFA studies frequently involve the collation of data from multiple sources, with varying degrees of uncertainty. MFA studies in recent years have begun including uncertainty analysis alongside their models. Visualising uncertainty quantitively in diagrammatic form is challenging, hence most studies employ 'meta data' labels attached to material flows in Sankey Flow Diagrams and Flow Diagrams. For example, Klinglmair et al. (2015) display mass flow and percentage uncertainty in an elliptical shape next to the flow.

Lupton and Allwood (2017) employ an alternative approach using a colour scale to show uncertainty, with flows colour coded according to their percentage variance. This approach gives immediate retinal feedback to differentiate and categorise flows according to their uncertainty. Their Sankey diagram shows higher levels of uncertainty in the earlier stages of the material flow model. The major drawback of this approach is the inability of the viewer to attribute a numeric value to a change across the colour spectrum. Without 'meta data' labels, or another visualisation technique (i.e. error bars) it is difficult to accurately interpret uncertainty from a range of colours. The diagrams may also be difficult for colour blind readers to interpret.

3.2.6 Stocks (27 Studies)

A total of 27 studies included some assessment of Stocks in their MFA models. These were typically visualised using shapes (i.e. boxes) and numerical values, attached to the flows in Sankey type diagrams. For example, Laner et al. (2015) uses rectangular boxes containing the stock mass, attached to a parent process in a Sankey Flow Diagram. Stocks can also be visualised using a Line Chart or Bar Chart showing changes in the stock value over time.

This analysis of the MinFuture Core Dimensions across a 48 MFA studies reveals the diversity of models and visualisation formats currently being used. The inconsistency in quality across these diagrams points to a lack of clear guidance for visualising material systems.

3.3 Retinal Variables Used in MFA Studies

In Section 2.3 of this report we introduced Bertin's seven Retinal Variables: Position, Size, Value, Texture, Colour, Orientation and Shape. These variables describe the way humans perceive information through sight and the deliberate use of these variable is a key element of good visual design. In this section we evaluate visualisations from the 48 MFA studies against six of the Retinal Variables to understand which variable are most important in MFA visualisation. The seventh variable, Position is excluded as it is a planar preattentive variable which is present in all visualisations.

This is followed by an in-depth discussion of the retinal variables in two example visualisations chosen from the MFA studies. The first is a Sankey diagram by Lupton and Allwood (2017) which uses colour to indicate uncertainty in the MFA model. The second is a complex colour Sankey Diagram of global petrochemical flows for 2013 by Levi and Cullen (2018) which is used to discuss options for colour-blind readers.

Figure 10 shows the number of MFA studies, which incorporate the Retinal Variables (excluding Position) in their visualisations. The full results for each study are included in Appendix A4.

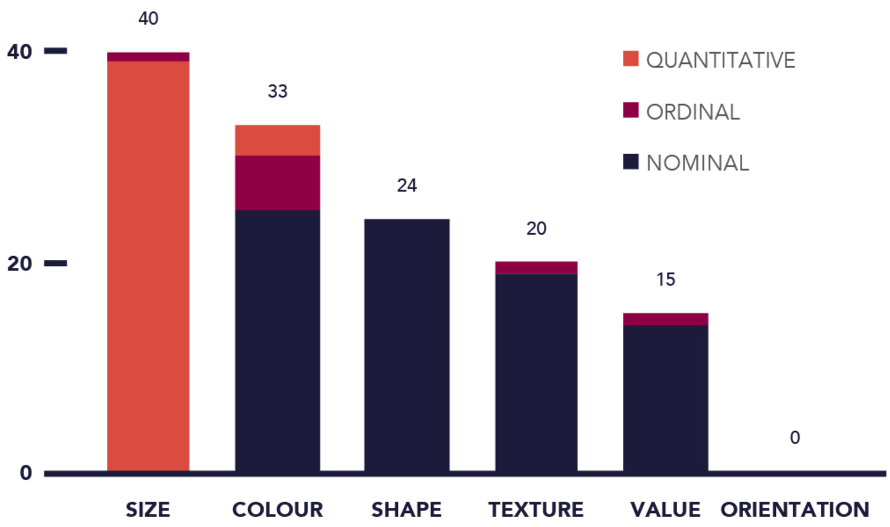


Figure 10*:* Bar chart showing the total numbers of MFA studies that adopted retinal variables in their visualisations, matched alongside the data type that was being shown.

Quantitative information is predominantly passed via the size variable, which is fundamental to many common visualisations such as Bar, Line and Pie Charts. Line Charts use position and marks to denote quantitative information. Overall, 39 MFA studies used size to show quantitative change in their visualisations; the only other variable used to show quantitative data is colour.

Qualitative information, including both nominal (naming) and ordinal (order), are mostly presented using Colour. A total of 30 studies used colour in this way (25 nominal and 5 ordinal). Many visualisations in MFA studies combine retinal variables to show nominal differentiation and similarities. For example, Raupova et.al (2014) combine both Colour and Shape on a Line Graph. The combination of two retinal variables has little benefit, as the stronger retinal variable (in this case Colour) will dominate. Changing the Shape of the data point is unnecessary, particularly as the diagram aims to focus attention towards the shapes of the lines, not the individual points on the line. Using multiple retinal variables to display a single feature goes against Tufte's philosophy of minimising 'data ink' to create the most simple and clear visualisations.

The use of shape is surprisingly common within MFA visualisation with 24 MFA studies choosing to use this retinal variable. The most common misuse of shape in MFA visualisation is the application of marker points within line charts, where each data set has a unique shape. One factor which may contribute to this trend is that many software packages provide shape as a base option and automatically apply shapes visualisations. Mackinlay (1986) ranks shape as the most ineffective retinal variable. Hence, many MFA visualisations could be improved by avoiding shape and instead using other retinal variable like colour or value. The exception is Flow Diagrams, where different outlined shapes (i.e. boxes, circles, ovals) are used to distinguish between types of stages or processes in the diagram, with text labels placed inside the shapes.

Texture and Value are primarily used for nominal qualitative presentation, except for the study by Buchner et al. (2015) where they were both used for ordinal purposes. Within MFA visualisation, Texture (20 studies) is used more than Value (15 studies) due to publication of print articles in grayscale in which lines or areas in the charts need to be distinguished. The use of Texture in preference to Value is surprising, as Value is considered a stronger retinal variable. For example, Laner et al. (2011) have adopted the use of texture (dotted and dashed lines) for nominal differentiation in their line graphs.

However, the breaks in the trend lines can sometimes be misinterpreted as missing data, and for this reason, Texture is not normally recommended as a retinal variable for distinguishing or comparing data.

The use of Orientation as a retinal variable was not found in any of the MFA studies investigated, perhaps because most design tools for visualising data do not use Orientation as a default option.

To finish this section we provide two examples of MFA visualisation which make use of the retinal variables in unique ways.

3.3.1 Example 3 – Use of Colour to Show Uncertainty

Overview: The purpose of study is to present new model for presenting uncertainty within MFA using Bayesian Interference

Types of Visualisation: Uses Sankey diagram for uncertainty mapping using the Bayesian Inference methodology developed by the authors. Supporting charts to outline theory includes, line, area and histograms

Retinal Variables: Size is used to present quantitative data for the mass of the flow. Colour is used to represent mass uncertainty in the flows as a quantitative measure scale (dark blue through to light turquoise). Colour shows the general uncertainty trends but does not provide specific values.

Core Dimensions: Stages and Uncertainty

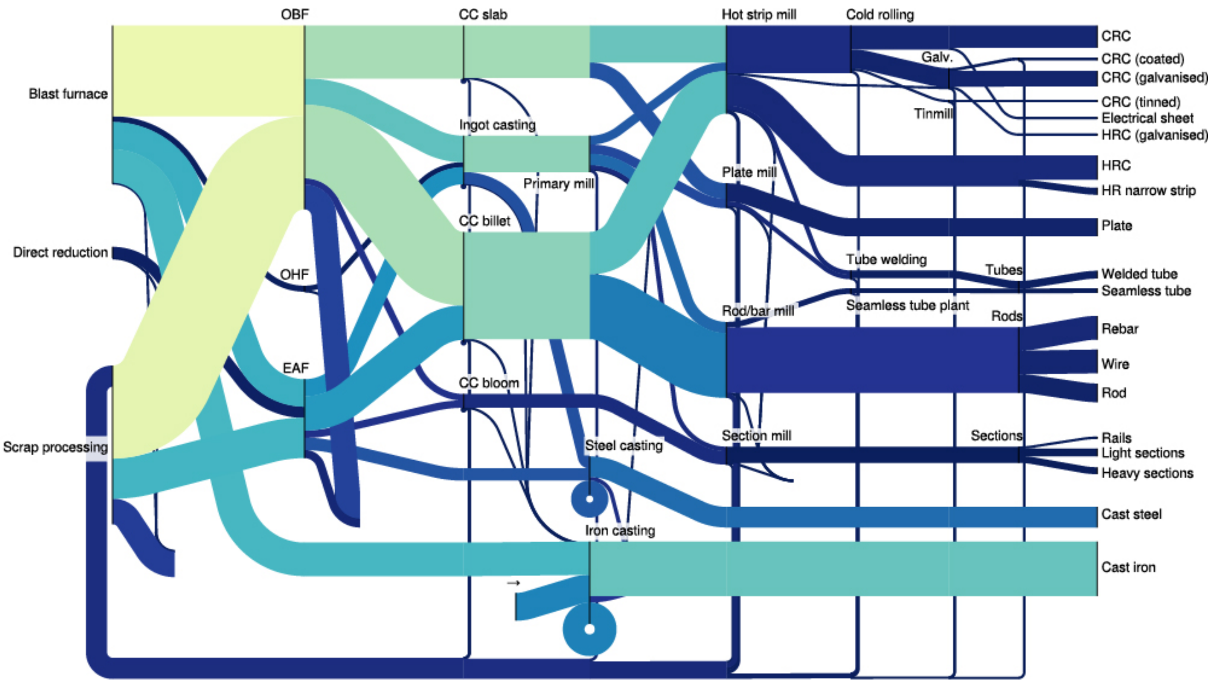


Figure 11: Sankey diagram created by Lupton and Allwood (2017) to demonstrate the use of colour as a quantitative measure to show uncertainty.

Design Comments: The use of colour adheres to colour blind sensitive palettes and is suitable for comparison and communicating the uncertainty in flows. The structure of the Sankey is generally well laid out with clear delineation between stages in appropriate columns. Labelling on the diagram is difficult to identify consistency and to match to the appropriate flow or stage. Consistent positioning of labels i.e. above the corresponding flow would be one option to improve this. Another would be to use line pointers to identify the flow. This method has been adopted in other studies such as Levi and Cullen (2018). There are some flows in the diagram that are unlabelled and provide little information to the audience.

One design concern is the rotation of flows against the vertical. There are a number of flows that rotate past 180 degrees, which visually detracts and is contrary to the left to right flow across the visualisation. The only flows that should appear to flow backwards are return flows such as scrap recycling. There is also come occlusions of flows, which makes it impossible to identify the source and destination of the flow. This should be improved by the layering of flows, to place the larger flows behind the smaller flows. Abbreviations on flows should be replaced with full titles to enable the visualisation to be read in isolation from the full paper.

3.3.2 Example 4 – Use of Colour in Sankey Diagrams

Overview: The purpose of study is to map global flows of fossil fuel feedstocks through to end use chemical products, based on data collected from the year 2013.

Types of Visualisation: A Sankey Diagram is used for the global map. Supporting information is presented using a bar chart to display the sensitivity of the flows.

Retinal Variables: Size is used to present quantitative data for the mass of the flow. Colour and Value hold only nominal qualitative data. Gradient’s are used within the Sankey to demonstrate the transformation process between chemical input and final products. Colour is used to group with sub-types following hues of the parent colour. Colours have more balanced saliency and work well together to provide differentiation but is not immediately obvious without reading the supporting text as to the categorisation and nominal coding of colours.

The colours used however do not conform to a colour-blind sensitive palette. Figure 13 shows a representation of what a person with deuteranopia would see. The colours become muted and mixed, especially for reds and greens, resulting in an apparent similarity and grouping of these flows.

Core Dimensions: Stages

Design Comments: In some areas, the text is occluded due to the size and density of colour behind the text. Labelling is generally consistent in relation to the flows with connecting line used to link labels where they are placed outside of the flow. Consistent font weight and size used across the diagram. However, the title and sub heading are visually hidden due to placement (left bottom corner) and small size. The flows on the right-hand side of the diagram are presented in descending order, but the flows on the left-hand side do not follow the same pattern.

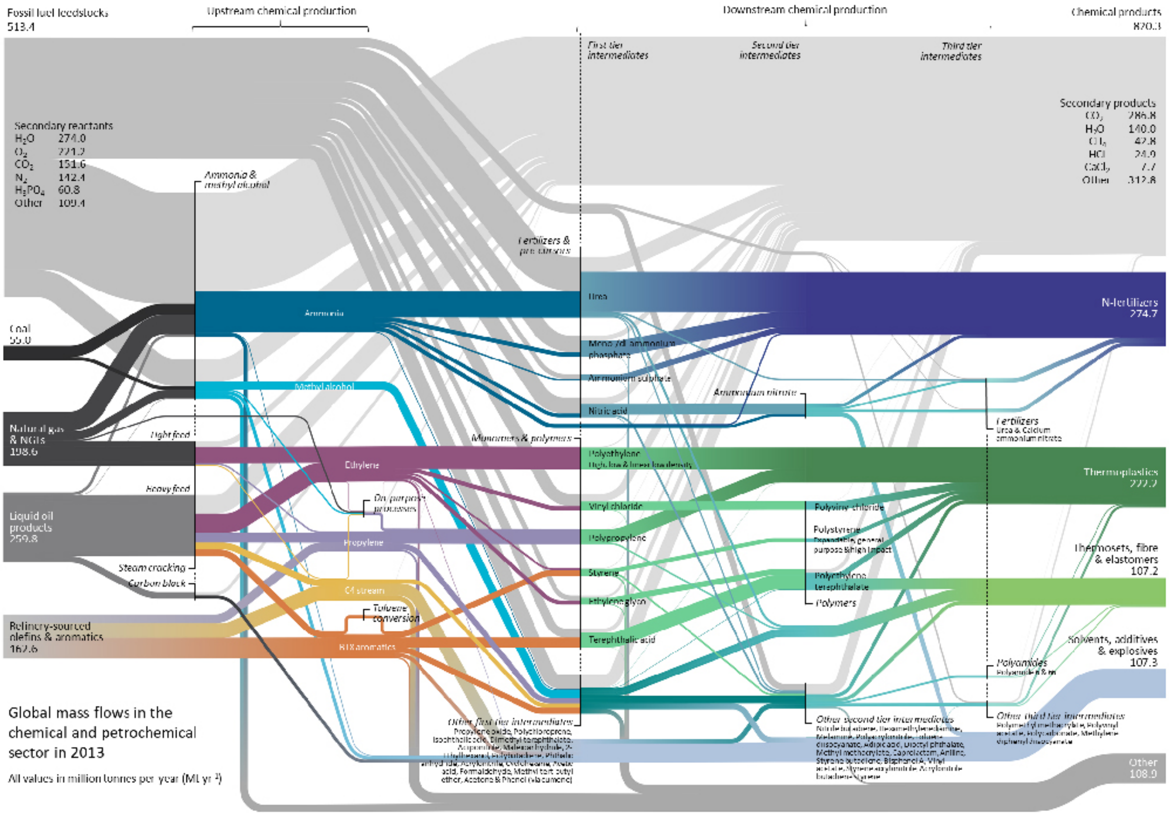


***Figure 12:* Sankey diagram created by Levi and Cullen (2018) to demonstrate the global mass flow of chemical and petrochemical flows in 2013.**

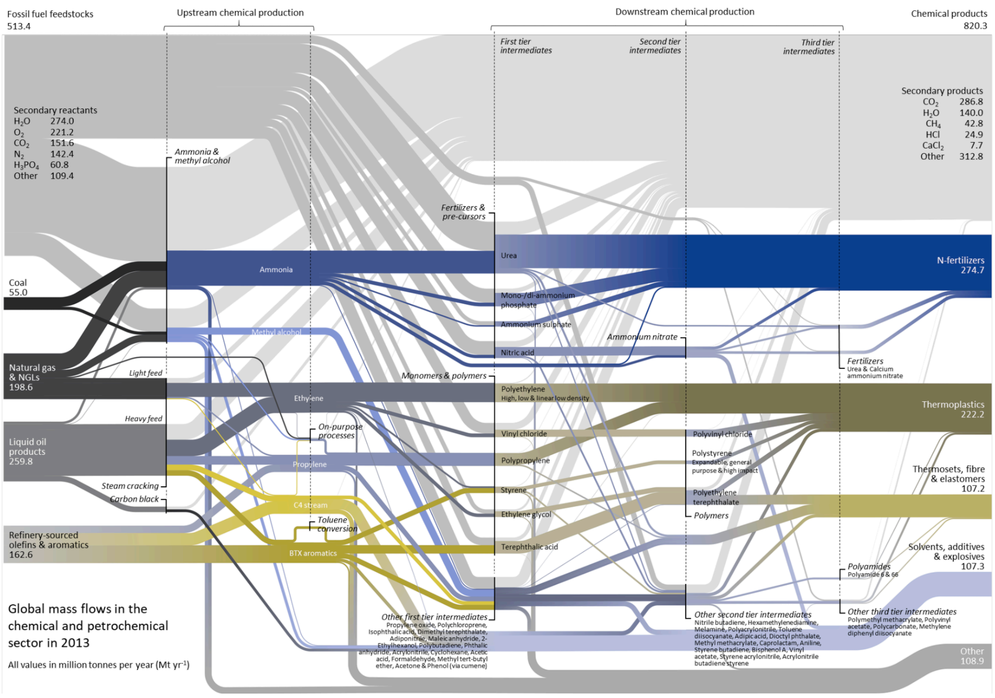


Figure 13: Sankey diagram created by Levi and Cullen (2018), coloured to show how a reader with deuteranopia would see it.

3.4 Discussion

In this section, we have conducted a review of visualisation in MFA studies and evaluated these studies against the four MinFuture Core Dimensions and the six Bertin Retinal Variables. The analysis found that many visualisations used in MFA studies fall below the level of quality required for communicating clearly the messages with in the data. We found that:

- Visualisations lack labels that correspond to marks or features on the visualisation. More 'meta data' could be included.
- Missing axis labels and the over-use of tick marks on the axes of graphs.
- Over-plotting was common, where multiple lines are occluded by similar data sets.
- Captions for diagrams are often missing or incomplete.
- Many line-graphs use multiple retinal variables to show the same qualitative grouping or feature.
- Many visualisations use colour schemes that are not colour-blind sensitive.

Those engaged in analysing and visualising MFA data would benefit from a well-constructed set of design principles and guidelines, a Best Practice Guide for Visualisation in MFA, aimed at improving the clarity and design of MFA visualisations. Better visualisation would in-turn improve the communication of MFA data to readers. Designers of MFA visuals should work to remove 'data ink' from their diagrams (i.e. tick marks on axes), to provide consistency throughout journal papers (i.e. font weightings and alignment), to use pre-selected colour palettes, and to design with a clear narrative in mind.

Online interactive models and visualisations offer enormous potential for displaying MFA data, allowing the reader to interrogate and manipulate the MFA data to create their own data stories. With digital interactivity comes the opportunity to zoom and layer information over one diagram in the same digital landscape, with immediate visual feedback given to aid short-term recall of comparative data. A good example of this is country level aluminium flow models hosted online by the International Aluminium Institute (nd), in which the user has the option to scroll through several years of data and see the Sankey Diagram updating in real time. A short animation can also be viewed which traverses the years of data updating the Sankey in chronological sequence. However, creating MFA visualisations on digital platforms still requires the implementation of good design practice. The added complexity in digital online visualisations, and the increased volume of data that can be visualised, can result in diagrams, which are even more confusing and muddled. Good design should be practiced equally for visualisations in print and online.

3.4.1 Elicitation and Communication

There is a clear difference between visualisations intended for elicitation and visualisations created for communication. The analysis in this report focuses mostly on the communication tools used for MFA visualisation. Commenting on the elicitation visualisation is much more challenging, as the methods used by the authors to collate, filter and balance the data are rarely published. Tables and matrices are used primarily for the elicitation process. While sparklines, line charts and bar charts, within a matrix, serve to identify the patterns in the data. Comparative visualisations such as tree maps, tables, histograms, scatter plots, line charts and bar charts are fundamental for identifying gaps or anomalies in the data and for spotting trends within the data, which in most cases will not be communicated.

Elicitation visualisation seeks to show a holistic view of the data set. Its purpose is not to tell a narrative or communicate with the reader, rather elicitation visualisations should allow the designer to investigate the data and draw out the narratives for communication.

4 Best Practice Guide for Visualising MFA

In this section, we outline a Best Practice Guide for visualising MFA data. The views here are based on the evidence collated for this report, alongside our own thoughts on what makes for effective visualisation.

4.1 Basic Framework

We believe that the Sankey Diagram is best suited for communicating the Core Dimensions which are listed in the MinFuture project: Stages, Trade Linkages and Time, as well as Uncertainty and Stocks. Sankey Diagrams and Sankey Flow Diagrams are the most used visuals in MFA studies, because they convey the structure of the material system. Other diagrams, such as Bar and Line Charts are unable to show how materials flow through the material supply chain. Sankey Diagrams are good at displaying multivariate data, which is a common requirement in MFA studies. They provide a holistic view of the whole material system and indicate the relative weightings of individual material flows.

Supplementary visualisations should be used to support the primary Sankey visualisation. An interactive online MFA model is ideal, allowing the user to interrogate the primary Sankey visualisation, present more detailed multivariate data as 'meta data' labels, and provide a link to a secondary 'pop-up' visual. Secondary visuals are particularly useful for displaying the Time, Stock and Uncertainty dimensions, where these dimensions would clutter the primary Sankey visual. Moving to an interactive layered approach (i.e. the Google Maps analogy) allows multiple data sets to be overlaid onto a common framework (stages) vastly increasing the information available to the user.

Whatever the visual approach taken, the importance of the information narrative remains paramount. Knowing what you want to communicate is key to creating effective and informative visualisations.

4.2 Visualisation of the Core Dimensions

In the following section, we discuss the best visualisation approaches to use for each of the MinFuture Core Dimensions: Stages, Trade, Linkages, and Time, as well as for Uncertainty and Stocks. Each visualisation approach is illustrated with a simple sketch, creating a catalogue of diagram types to use when visualising material systems.

4.2.1 Stages

Sankey diagrams are the most popular visual form for conveying the Stages in a material system, and in our view are the best diagram for this purpose. They are widely adopted due to their ability to provide a complete and holistic system map. Good Sankey Diagram design involves two steps: the careful and accurate visualisation of the material system stages, and the connecting the material flows between stages in a way which maintains linear readability.

The careful definition of Stages in a material system is key component of any MFA study. This is recognised within the MinFuture project. When Stages are presented as a Sankey Diagram they form a framework which allows other information and layers to be added. Dimensions, such as Linkages, Time and Trade, can all be mapped onto the stages framework.

4.2.2 Trade

Trade can be visualised in a Sankey diagram as materials flowing in or out of the material system boundary. Trade can also be applied as an added layer to the stages in a Sankey Diagram as Chord, Bar and Sankey diagrams visuals. For example, Bar Charts can be used to show a target country and its imports from and exports to other countries in the study. Dong et al. (2017) use this approach using Stacked Bar Charts with a positive and negative y-scale to show trade imports and exports, in a simple and clear form.

Figure 14 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.

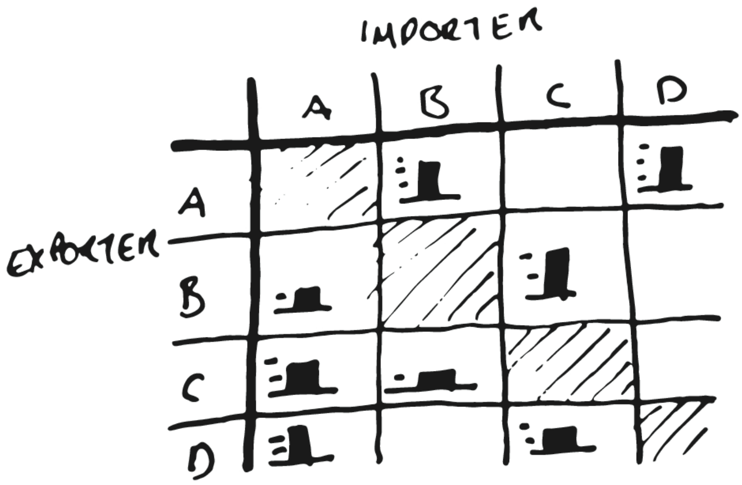


Figure 14: A trade matrix of countries, used primarily for elicitation purposes.

Figure 15 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, but not the source of target countries for trade flows.

Figure 15: Imports and exports for an individual flow on a Sankey diagram.

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 16. 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 can also be adapted to show just the imports and exports from a specific country.

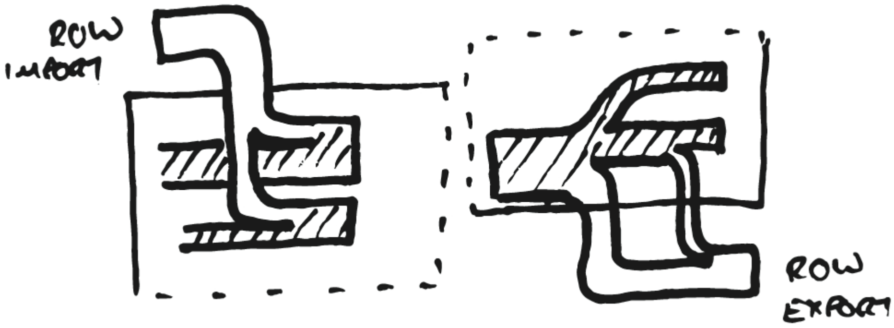


Figure 16: Trade shown on a Sankey diagram, with imports coming from the top and exports leaving at the bottom.

Figure 17 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.

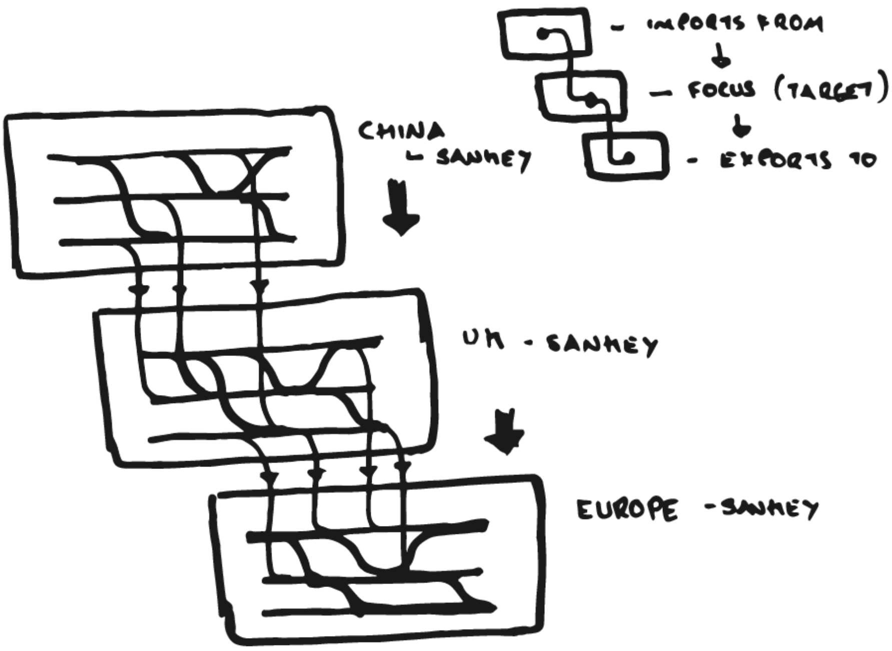


Figure 17: Multiple Sankey Diagrams with trade flows shown between each.

Figure 18 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.

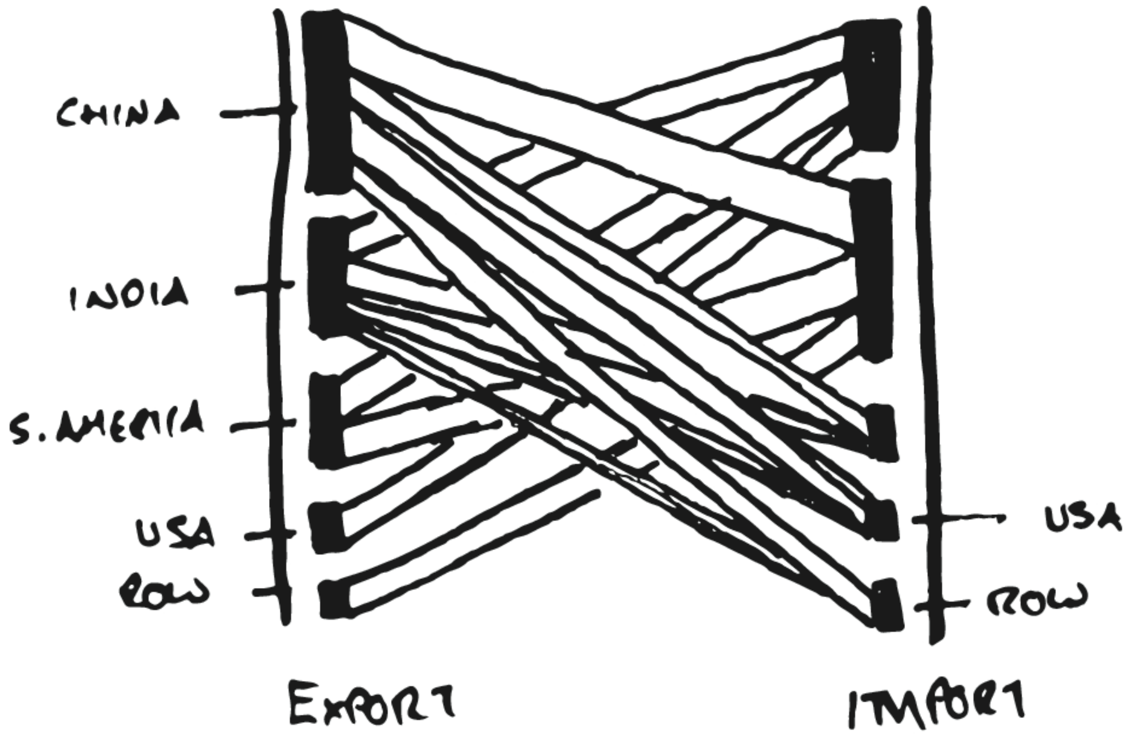


Figure 18: Trade shown as a parallel coordinate plot for a group of countries, with exporters on left and importers on the right.

4.2.3 Linkages

Linkages provide information about associative flows (energy, value etc.) and the composition of material flows, and can be mapped onto the Stages in a material system. Two options for visualisation are proposed.

The simplest method is to present the linkages for each stage as a bar chart, as shown in Figure 19. Linkages such as cost, carbon emissions or percentage composition can be reported on the basis of per tonne of material or as mass percentages.

The second more complicated visualisation option displays the Linkages within the material flow in the Sankey diagram, as demonstrated in Figure 20. 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.

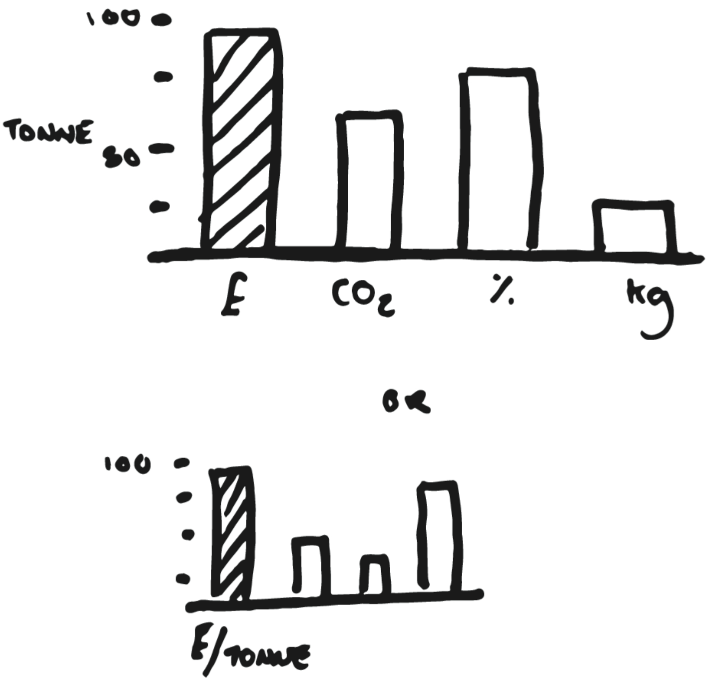


Figure 19: Linkages presented in Bar Chart form with different scales.

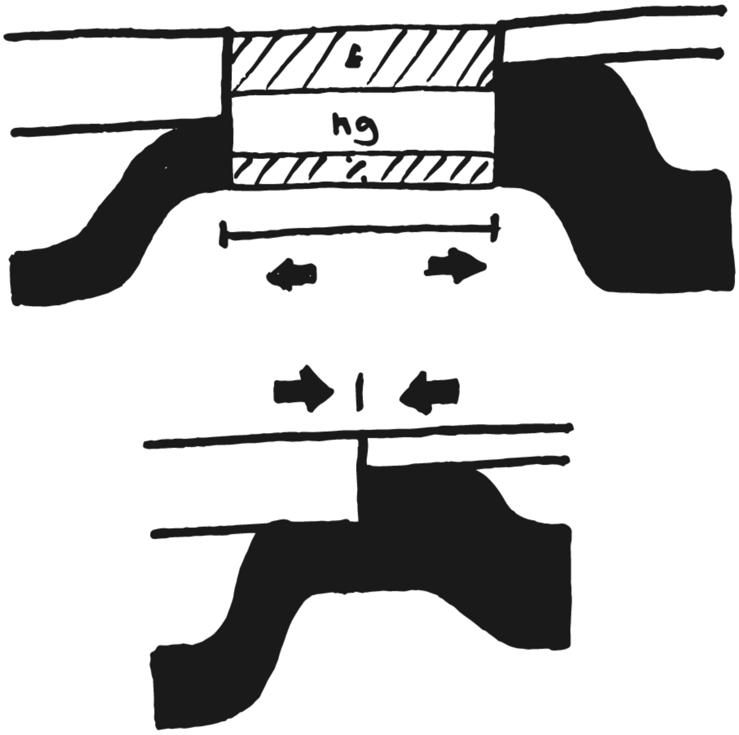


Figure 20: Linkages presented in Sankey Diagram format, expanded (top) and collapsed (bottom)

4.2.4 Time

All of the Dimensions can be viewed through the lens of Time. For example, one can visualise the change in trade with time or the change in the structure/stages of a material system, over time. Visualisations of Time are used to understand historical trends and inform decisions about the future. However, visualising MFA data over many years increases the amount of data required and can lead to more complex diagrams.

Visualising stages over time can be achieved through a Multiples Matrix (similar to trade in Figure 14). This is beneficial only in the elicitation stage of MFA, for identifying trends and assessing the data. Multiples Matrices provide a holistic view of the data but fail to show relationships between stages: the main advantage of using Sankey diagrams.

Using an interactive Sankey model is useful for interrogating the change in material flows and stages over time, however displaying the collective change poses more analytical challenges. An option adopted by International Energy Agency (IEA) is to animate changes in the Sankey model over time as a video-clip, however, this requires the reader to recall the previous Sankey shapes.

Stream graphs are 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 21.

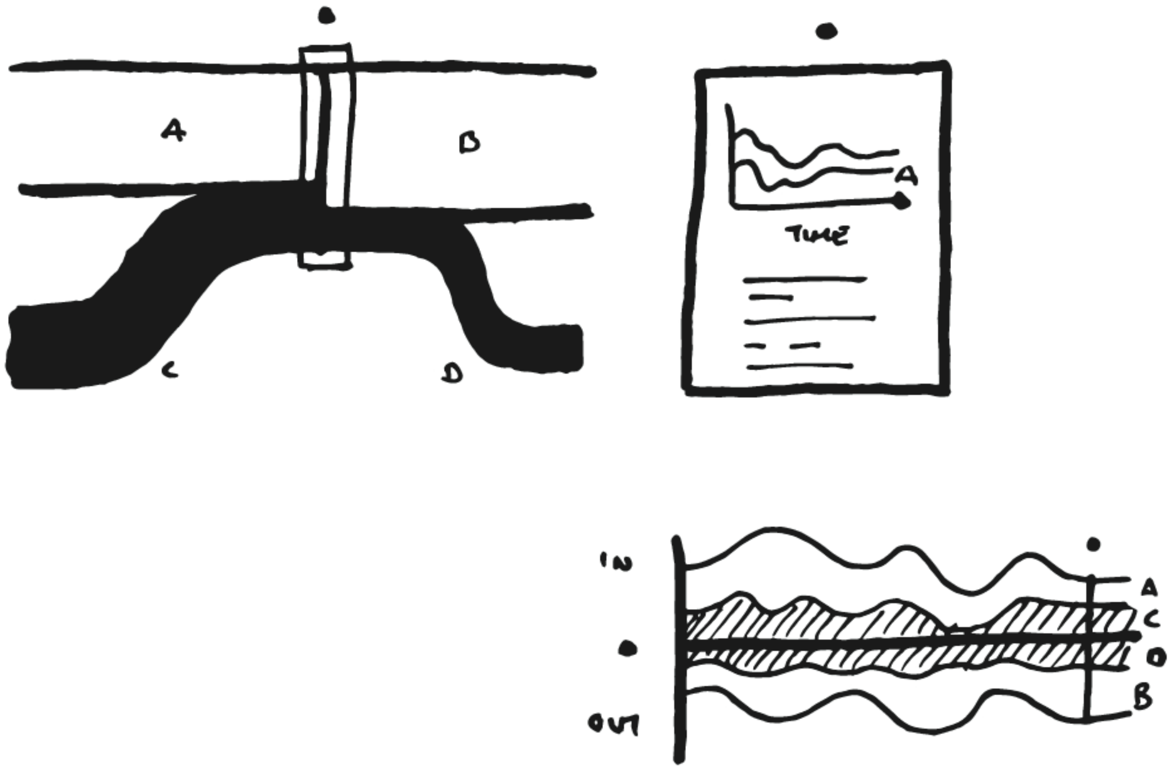


Figure 21: Stages changing over time, presented on line chart or as a stream graph in pop out tab or side menu.

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 data driven stories can be formed. Examples are shown in Figure 22.

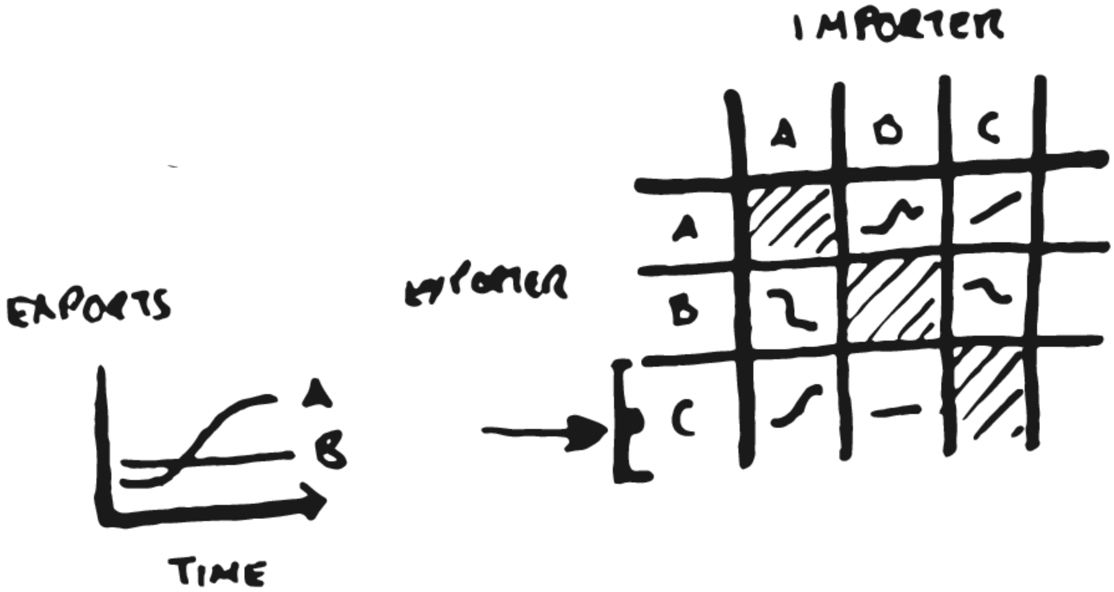


Figure 22: Trade changes over time, presented on line chart or as small multiples in matrix form for elicitation purposes.

Individual exports or imports for a country or region can be plotted on a line graph, as shown in Figure 23. 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.

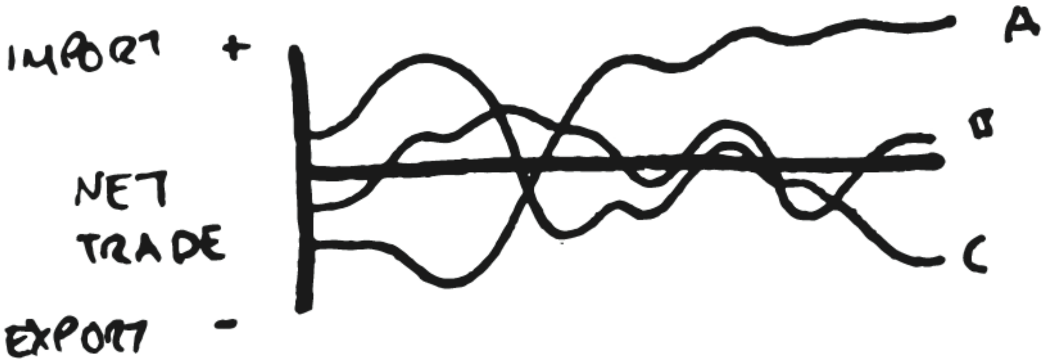


Figure 23: Trade over time as presented on line chart with net trade.

Changes in Linkages can be visualised using Line Graphs over time, as shown in Figure 24.

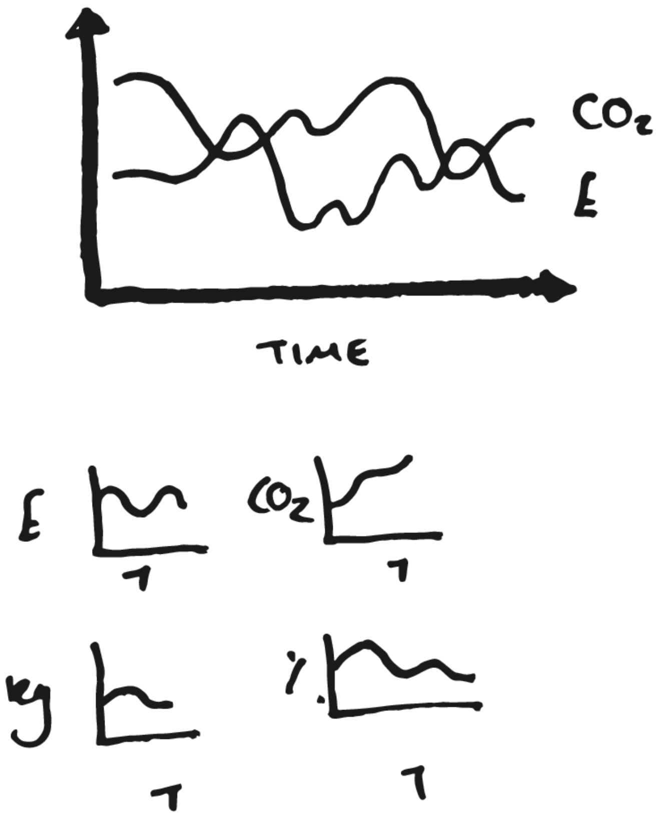


Figure 24: Linkages over time as presented on line chart or as small multiples.

4.2.5 Uncertainty

For elicitation, uncertainty can be presented as numeric values in tabular form or using colour to provide quantitative retinal differentiation. Sankey diagram which include meta-data can supplement this tabular view of data uncertainty.

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 25.

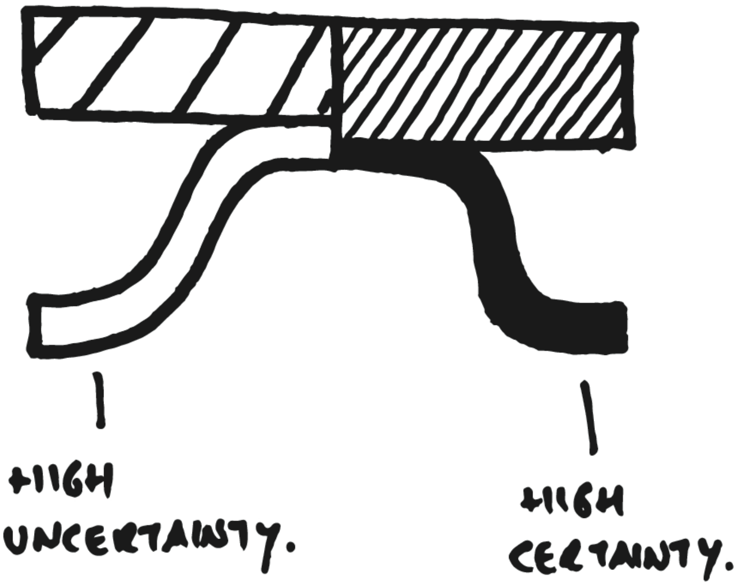


Figure 25: Uncertainty on Sankey diagram, with texture is used to symbolise colour hues.

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 26.

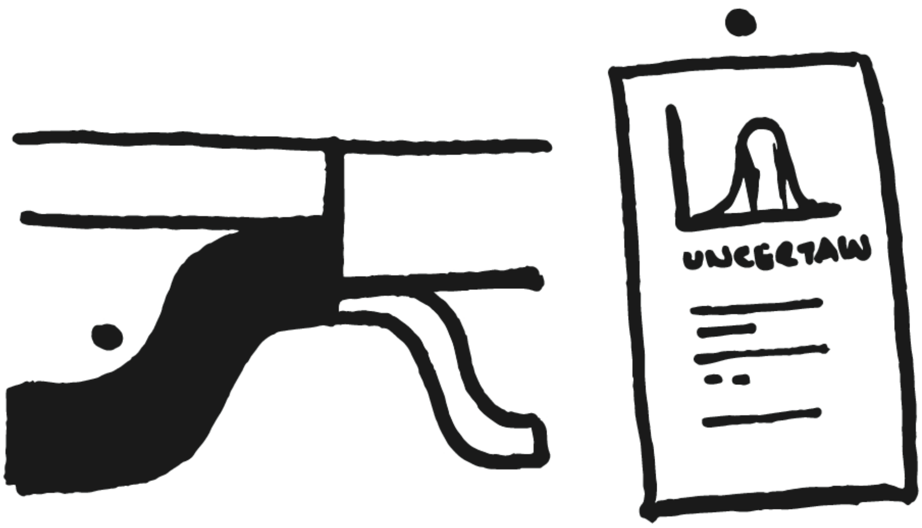


Figure 26*:* Uncertainty shown using a histogram for flow in a Sankey Diagram.

4.2.6 Stocks

We present two options for visualising material stocks in Sankey Diagrams, which is a relatively new concept. Figure 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.

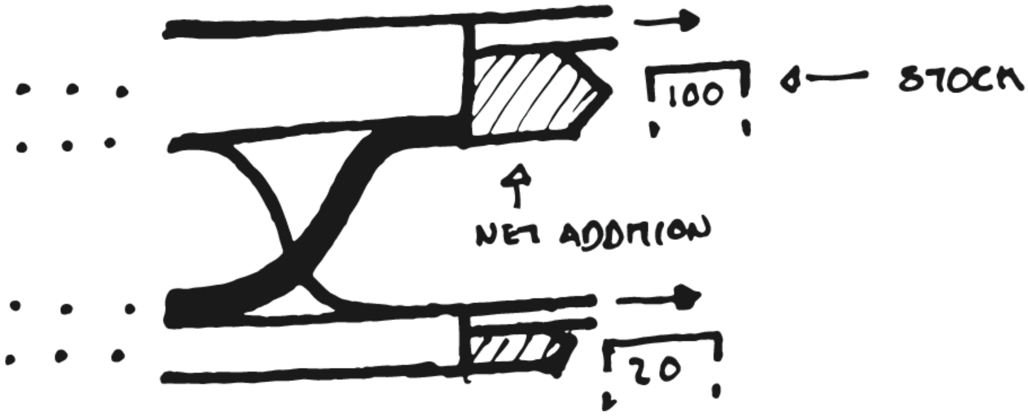


Figure 27: Stocks on Sankey diagram at stages as icon with net addition flow.

Figure 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.

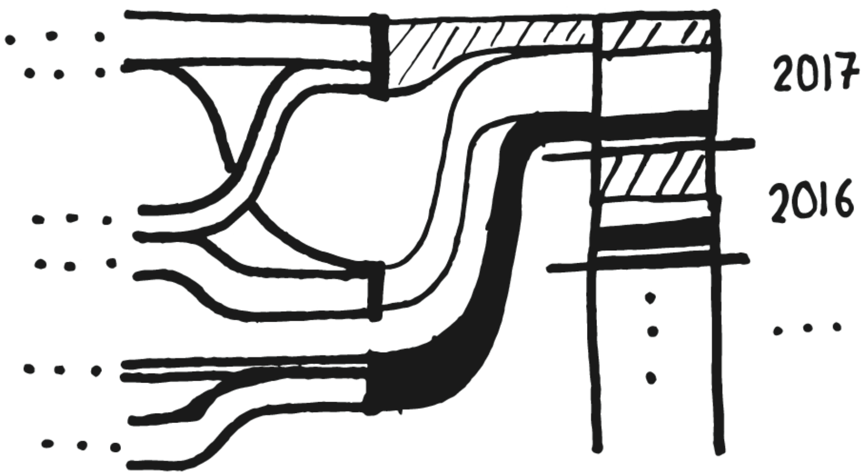


Figure 28: In-use *stocks* on Sankey diagram as a stacked bar chart with line widths proportional to the flow of each year/time period.

4.3 Design Guidelines and Visualisation Principles

The previous section provides a catalogue of 'best-practice' visual forms for visualising MFA data and the Core Dimensions from the MinFuture project. This allows designers of MFA visuals to select the most appropriate visual form to use. However, design guidelines and visualisations principles are still required to ensure the chart or diagram is simple, clear and informative.

General guidelines for visualisation design in scientific disciplines is not a new concept. Cleveland (1984) outlines many common errors within scientific disciplines in relation to graphical presentations and presents a list of guidelines for both journals and for authors. Similarly, Kelleher and Wagener (2011) outline ten guidelines that they believe would lead to better visualisation within scientific publications:

1. Create the simplest graph that conveys the information that you want to convey.
2. Consider the types of encoding objects and attributes used in the plot.
3. Focus on visualising patterns or on visualising details, depending on the purpose of the plot.
4. Select meaningful axis ranges.
5. Data transformations and carefully chosen graph aspect ratios can be used to emphasise rates of change for time series data.
6. Plot overlapping points so that density differences become apparent in scatter plots.
7. Use lines when connecting sequential data in a time series plot.
8. Aggregate larger datasets in meaningful ways.
9. Keep axis ranges as similar as possible across multiple plots, to allow comparison.
10. Select an appropriate colour scheme based on the data.

These guidelines for scientific publications are built on the more fundamental design principles described by Tufte (2006), discussed in more detail in Section 3.1:

- 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.

Many more visualisation designers have sought to provide practice guidance for creating effective visualisation.

Cleveland and McGill (1984) discuss the foundation elements of graphical perception and provide a theory and provide a framework to build upon. They describe the building blocks of perception and evaluate their impact on visual perception and provide a ranking system for visuals for different graph types.

Jason Pearson founder of Truth Studio has sought to refine and draw out the essential aspects of creating good visualisations. He presents his foundational elements in the form of a poster. Whilst Pearson (2011) does not explicitly reference his sources, it is clear from the vocabulary that much of his work and design philosophy has been influenced by Tufte and Bertin. His 10 principles demonstrate a methodical systematic approach to information design. What is clear in his methodology is the emphasis on the core information to be communicated in the visualisation.

Yau (2011, 2013) outlines the need for good visualisation that tells stories and has good narration. Yau believes that good narration is critical to the way in which we present data and suggests that visual hierarchy, the logical and sequential order created through using colour and size to promote visual distinction in the visualisation, is important.

Few (2016) investigates the encoding of the width, length and spacing of bars in bar charts and then applies guideline rules to the relationship of width, length and spacing.

4.3.1 Workflow for creating good visualisations

So how does this apply to MFA studies and material systems? Based on the work by Tufte and others, we present the following questions which can be used as a framework for creating communication visuals. This list of questions can be applied to any visualisation but is particularly applicable to the types of complex data-rich MFA diagrams which form a part of the MinFuture project.

What is it for?

Why do we need a visualisation? What is the reason behind making this visualisation? What is it essential to present this information in a visual form? The reasoning behind making a visualisation should never be: 'because it is required or asked for'. The purpose of the visualisation must be to impart new information that could not otherwise be presented within the literature. Although good aesthetic design is important, it is not the defining aspect; a beautiful chart or graph can contain little information of importance or significance. What is important is the story the data tells and therefore the information it imparts. This question covers both the first and second of Tufte's principles.

What is the best way to represent the information?

The Data Viz Project by Ferdio (2017) provides a catalogue of visual diagrams which can provide inspiration when choosing the best way to represent data. The project categorises visualisations by their purpose and what application they are best used for. The Data Viz Catalogue by Ribecca (2018) lists a variety of diagrams and describes the attributes and the composition of each diagram. This is useful for understanding how a specific visualisation should be read and what it can be used for. The Graphic Continuum - Schwabish and Ribecca (2014) gives some examples of purpose of diagrams, for example, showing relationships, geospatial information, time, part-to-whole and comparisons.

Choosing an appropriate visualisation involves understanding what the visualisation needs to accomplish. Few (2004) describes seven quantitate relationships for selecting the right graph to communication a message from a set of data. Few's detailed discussion on Dimensions for Visualisation, is a great place to start when seeking to understand the best visual forms to use.

How should I display multivariate information?

"*Show multivariate data*"

Bertin (1983) provides a hierarchical structure for prioritising retinal variables in visual diagrams. Some variables prove better for conveying certain information than others and using higher-level encodings aids visual clarity for multivariate data. It is important to decern whether qualitative or quantitative elements are required from the data, as certain retinal variables (size and position) are superior for presenting quantitative data.

What does the data look like? Sketch a wire frame

"*mechanism and systematic structure"*

Get to know the data! Elicitation processes are important for sanitising and interpreting data. Small Multiples and Sparklines are useful diagrams for assessing the holistic shape of the data. Matrices are good at showing comparisons across the data and spotting trends in large data sets. Keep the first attempts simple (e.g. a wire frame). Iteration through design is common and should be expected in chart design; it is rare to find that the first attempt at a graph is the best version.

Have I included titles and captions?

"*describe the evidence*"

"*Integrate words, numbers, images, diagrams*"

Is there a consistent vocabulary and are the terms clearly defined? Are any abbreviations explained in the caption or a key. A good visualisation should be able to stand alone, away from the text, and still make sense. Check the titles, labels, captions and key are all clear and provide sufficient detail

How could the diagram be simplified? What is essential?

Maximise the data-ink ratio; Erase non-data-ink; Erase redundant data-ink and Revise and edit. Tufte (2001)

Visual diagrams can quickly become overly complex and confusing. Adding more ideas to a visualisation can quickly degrade the original intent and communication outcome. Tufte (2001) has a ruthless view when it comes to simplification, arguing for stripping away any superfluous information. Whilst the extremes of this approach are seldom called for, the ideal to refine and draw out only the essential messages in a diagram is important.

'Keep the one thing the one thing.' If an outsider struggles to understand the core message of a visualisation then the diagram has failed. If necessary, use more than one diagram to tell parts of the message. Few (2018) publishes a blog called 'Perceptual Edge' which is a good source practical information on how to make the most of visualisations and how to refine them. Yau (2013) suggests that having a clear visual hierarchy assists greatly in understanding what is essential in a visualisation and what can be removed.

Does it support the literature, is it consistent with other visualisations?

Consistency in design is key, and variability distracts from the message. One should ask: do all the visualisations in a study have a common form and language? Are the same fonts, colours, structures, and message hierarchy employed?

Does the visualisation tell a narrative?

Few (2009) puts forward a tentative list of principles and practices to support statistical narration with good visualisation. The author openly discusses the limitations of the list as non-exhaustive, however, the foundational elements proposed are widely applicable. Few draws out the elements that contribute to a 'successful' narrative using Hans Rosling's interactive of family size verses life expectancy as an example. His list of principles and practices is: Simple, Seamless, Informative, True, Contextual, Familiar, Concrete, Personal, Emotional, Actionable, and Sequential. What is pertinent to reiterate is the words of Tufte: *"Above all else show the data" Tufte (2001)*

Can the visualisation be made interactive?

Interaction can be a powerful tool as it gives the audience the opportunity to interrogate and further study the data. The design guidelines and visualisation principles described above, for the most part, translate well to interactive online platforms. However, Few (2009) describes many added capabilities from switching to interactive visuals. For example, brushing enables the user to 'scrub' through the data quickly and highlight specific portions of the data set, which can then be loaded into visualisation; meta-data can be tagged to specific stages and flows in a diagram, and crucially hidden/exposed to avoid cluttering the diagram.

Robertson et al. (2008) discuss the effectiveness of using animation to visualise trends in the data, although animation also requires considerable cognitive recall from the viewer. Using small multiples is sometimes a more appropriate means of providing comparison.

Practice makes perfect

Our final word is a plea that more time be given to creating visuals in MFA research. For many academics involved in MFA, the collection of data takes many months, and the write-up takes several weeks, yet it is considered lucky if more than a few days are devoted to visualising the MFA data. In contrast, when we read articles and reports, it is the titles, abstracts and the diagrams that we first examine.

Good visualisation takes time and requires multiple iterations and feedback cycles to perfect. When we allocate more time to creating visuals, we not only communicate our message more effectively, we also gain valuable skills and techniques for creating better visuals in the future.

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James West, Heinz Schandl, Material use and material efficiency in Latin America and the Caribbean, Ecological Economics, Volume 94, October 2013, Pages 19-27, ISSN 0921-8009, http://doi.org/10.1016/j.ecolecon.2013.06.015.

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6 Appendices

6.1 Appendix 1 – Examples of Data Driven Stories

A Day in the Life of Americans
http://flowingdata.com/2015/12/15/a-day-in-the-life-of-americans/

A Spacecraft for all
http://spacecraftforall.com/a-new-orbit

A World of Oil
http://www.gsmlondon.ac.uk/global-oil-map/#1995-importers

Crime in Context
https://www.themarshallproject.org/2016/08/18/crime-in-context#.b18C7Pe0q

Data story authors
https://shorthand.com/#featured-clients
http://davidmccandless.com
http://fivethirtyeight.com

Death on the roads
http://www.who.int/violence*injury*prevention/road*traffic/death-on-the-roads/en/#intro*

Digital Divide
http://scidev.live.kiln.digital/digitaldivide/

GEDVIZ
https://viz.ged-project.de/

Global Education Monitoring Report
http://www.education-inequalities.org/indicators/edu4/countries/niger#?dimension=allandgroup=allandagegroup=|edu420andyear=|2006

Maps
https://ghemawat.com/data-viz/area-map?country=United%20Statesandindicator=m.exportsandindicatorFilePrefix=m.exportsandindicatorFullName=Merchandise%20ExportsandyearStart=2005andyearEnd=2015anddistortion=scaleandcolor=shareandcolorOptionMax=falseandcolorOptionBlending=falseandcountryCompTooltip=false

Memory Underground
http://memoryunderground.com/

Project Ukko
http://project-ukko.net/map.html#

Resources Future
http://resourcesfutures.org/#!/more-more-and-more

Resource Trade .Earth
https://resourcetrade.earth/data?year=2001andunits=value

The Atlantic Slave Trade in Two Minutes
http://www.slate.com/articles/life/the*history*of*american*slavery/2015/06/animated*interactive*of*the*history*of*the*atlantic*slave*trade.html*

The Fallen of World War 2
http://www.fallen.io/ww2/#

The Globe of Economic Complexity
http://globe.cid.harvard.edu/?mode=gridSphereandid=PY

The Interactive U.K. Energy Consumption Guide
http://www.evoenergy.co.uk/uk-energy-guide/

The Missing Migrants Map
https://www.behance.net/gallery/34680727/THE-MISSING-MIGRANTS-MAP-Corriere-della-Sera

The Refugee Project
http://www.therefugeeproject.org/#/2016

The State of the polar bear
http://www.periscopic.com/our-work/pbsg

World Food Clock
http://worldfoodclock.com/

6.2 Appendix 2 – Current Visualisation Software

Microsoft Word - *Licensed* - https://products.office.com/en-gb/word

Microsoft Excel - *Licensed* - https://products.office.com/en-gb/excel

Microsoft Powerpoint - *Licensed* - https://products.office.com/en-gb/powerpoint

Microsoft Visio - *Licensed* - https://products.office.com/en-gb/visio/flowchart-software?tab=tabs-1

Raphael - *MIT License* - http://dmitrybaranovskiy.github.io/raphael/

MATLAB - *Licensed* - https://uk.mathworks.com/products/matlab.html

R - *Open Source* -https://www.r-project.org

Python - *Open Source* - https://www.python.org

D3 - *Open Source* - https://d3js.org

floWeaver (D3) - *Open Source* - https://github.com/ricklupton/d3-sankey-diagram

Circular Sankey - Open Source - http://www.visualisation.industrialecology.uni-freiburg.de

Sankey matic - *Open Source* - http://sankeymatic.com

Forseer - *Licensed* - https://www.foreseer.group.cam.ac.uk

E!Sankey - *Licensed* - https://www.ifu.com/e-sankey/

Adobe Illustrator - *Licensed* - http://www.adobe.com/uk/products/illustrator.html?promoid=PGRQQLFSandmv=other

Adobe Photoshop - *Licensed* - http://www.adobe.com/uk/products/photoshop.html?promoid=PC1PQQ5Tandmv=other

Inkscape - *Open Source* - https://inkscape.org/en/

Plotly - *Licensed* - https://plot.ly

Tableau - *Licensed* - https://www.tableau.com

Infovis - *MIT License* - https://philogb.github.io/jit/

Crossfilter - *Apache License* - http://square.github.io/crossfilter/

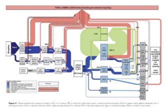
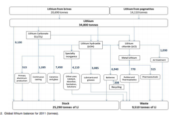
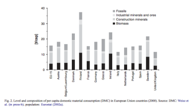
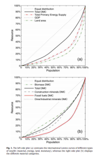
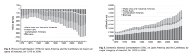
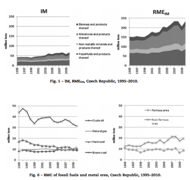
6.3 Appendix 3 – Software requirements

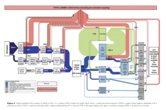
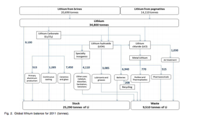
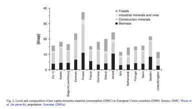
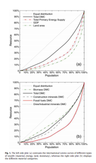
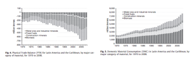
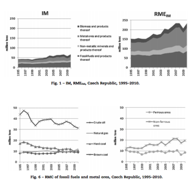
Ideal software should be able to:

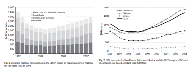
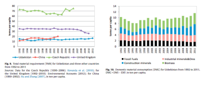
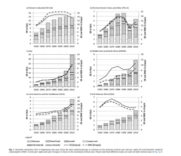
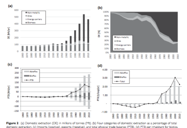
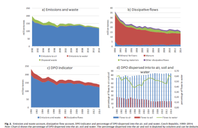
- Generate foundational Sankey diagram with the core dimensions
    - Presented online with the Best Practice guide for dimensions of MinFuture
- Provide elicitation tools to interrogate and see the data
    - This requires a broad spectrum of visualisation options
    - Tables, bars, line graphs etc. Should allow freedom of expression to see the data.
- Provide communication tools
    - These are outlined in Section D for each core dimension
    - Should promote the use of Sankey diagram as the default
    - Other supplementary visualisations should be provided
- Provide Interactivity to zoom, and layers, aggregate and transform the sales of visualisations.
    - This is typical of software like Excel.
- Ability to generate data driven stories
    - A platform for which a narrative piece can be written along with the visualisations which can be accessed in an online repository.
    - After creation must allow reader to interrogate the data to see the source information and interact with the data (Evans and Pearce (2016))
- Must be able to export visualisations to editable vector graphic format for editing in Adobe suites (or equivalent) or by a Graphic Designer.
    - Also export for print and web publications
    - Default aspect ratio for all visualisations should be 16:9
- Must generate visual hierarchy and include space for headings, titles captions and labels where appropriate.
- Must adopt the use of colour spectrums and theories.
    - This could be linked to colour palette generators, similar to those used by Adobe in their products.

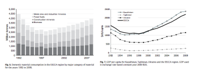
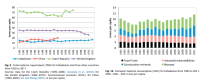
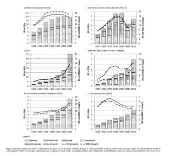
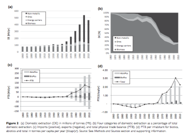
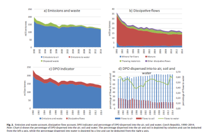
6.4 Appendix 4 – MFA studies analysed

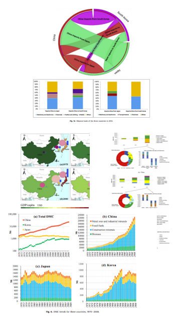
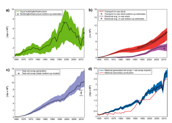
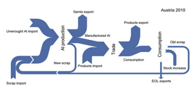
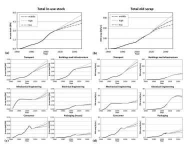
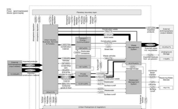
The following table provides information on the 48 MFA studies which were evaluated for this study.

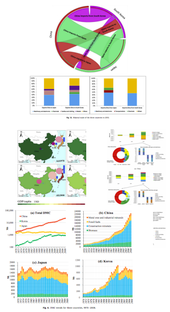
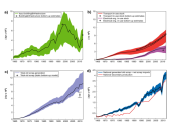
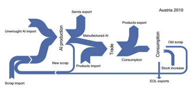
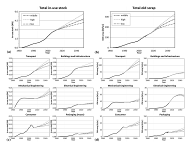
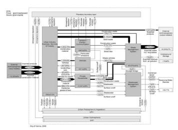
Entry No.	Source information						Type of diagram(s)
	Preview Image	*Publication*	*Author(s)*	*Date (source data)*	*Publication Summary*	*Purpose*	
1		Licht, C; Talens, L.; Villalba, G. (2015) Global Substance Flow Analysis of Gallium, Germanium, and Indium – Quantification of Extraction, Uses, and Dissipative Losses within their Anthropogenic Cycles. Journal of Industrial Ecology 19(5): 890-903. DOI: 10.1111/jiec.12287	Christina Licht, Laura Talens Peiro, and Gara Villalba	2011	*This study provides a global substance flow analysis for gallium (Ga), germanium (Ge), andindium (In) for 2011, quantifying the amount of metal lost during extraction, beneficia-tion/smelting/refining, manufacturing of intermediate products, and the amount embodiedin end-use products. Thus far, studies illustrating their cradle to end-use life cycle on a globalscale are either missing or outdated, and thus opportunities to increase their supply remainunknown and/or not quantified. The results illustrate the losses and inefficiencies stages,thereby identifying potential additional supply by process improvement, recovery, and recy-cling. Results show that there are significant opportunities to meet future demand of Ga andGe by concentrating recovery efforts in the extraction and beneficiation/smelting/refiningstages. Further, 1.4% Ga, 0.7% Ge, and 54% In of the theoretical available amount inthe attractor ores are extracted to meet the primary refined demand in 2011. Of the9,065 tonnes (t) of Ga embodied in the Bayer liquor (from aluminum production), only263 t are refined. This is owing to low capacities of Ga refining, combined with a refiningefficiency of 60%. Ge presents a similar case for the same reasons, in which only 43 t ofGe of the 7,636 t of Ge available from zinc leach residue are refined. Meeting future Indemand, on the other hand, will require greater efforts in increasing end-of-life recycling.Process efficiencies for Ga (46%), Ge (56%), and In (78%) demonstrate further potential.We quantify the flows into use by distinguishing among dissipative and nondissipative enduses, as well as the recyclable fraction for each metal for 2011.*	To evaluate recovery potential in various life cycle stages, to quantify use-stock, end-of-life stock, future demand versus supply	Sankey
2		Talens Peiro, L., Villalba, G., Ayres, R. (2013). "Material flow analysis of scarce metals: sources, functions, end-uses and aspects for future supply." Environmental Science & Technology, 47 (6), pp 2939–2947.26. DOI: 10.1021/es301519c	Laura Talens Peiro, Gara Villalba Mendez, and Robert U. Ayres	2010	*A number of metals that are now important to the electronic industry (and others) will become much more important in the future if current trends in technology continue. Most of these metals are byproducts (or hitch-hikers) of a small number of important industrial metals (attractors). By definition, the metals in the hitch-hiker group are not mined by themselves, and thus their production is limited by the demand for the major attractors. This article presents a material flow analysis (MFA) of the complex inter-relationships between these groups of metals. First, it surveys the main sources of geologically scarce (byproduct) metals currently considered critical by one or other of several recent studies. This is followed by a detailed survey of their major functions and the quantities contained in intermediate and end-products. The purpose is to identify the sectors and products where those metals are used and stocked and thus potentially available for future recycling. It concludes with a discussion of the limitations of possible substitution and barriers to recycling.*	To illustrate the industrial metabolism from sources to products, and potential future recycling	Flow Diagram / table
3		Talens Perio, L, Villalba G., Ayres, R. (2013) Lithium: sources, production, uses and recovery outlook. The Journal of The Minerals, Metals & Materials Society. 65 (8) 986-996. DOI: 10.1007/s11837-013-0666-4	Laura Talens Peiro, Gara Villalba Mendez, and Robert U. Ayres	2011	*The demand for lithium has increased significantly during the last decade as it has become key for the development of industrial products, especially batteries for electronic devices and electric vehicles. This article reviews sources, extraction and production, uses, and recovery and recycling, all of which are important aspects when evaluating lithium as a key resource. First, it describes the estimated reserves and lithium production from brine and pegmatites, including the material and energy requirements. Then, it continues with a description about the current uses of lithium focusing on its application in batteries and concludes with a description of the opportunities for recovery and recycling and the future demand forecast. The article concludes that the demand of lithium for electronic vehicles will increase from 30% to almost 60% by 2020. Thus, in the next years, the recovery and recycling of lithium from batteries is decisive to ensure the long-term viability of the metal.*	To describe the estimated reserves and production (including the material and energy requirements), the current uses, and opportunities for recovery and recycling and the future demand forecast.	Flow Diagram / table
4		Helga Weisz, Fridolin Krausmann, Christof Amann, Nina Eisenmenger, Karl-Heinz Erb, Klaus Hubacek, Marina Fischer-Kowalski, The physical economy of the European Union: Cross-country comparison and determinants of material consumption, Ecological Economics, Volume 58, Issue 4, 1 July 2006, Pages 676-698, ISSN 0921-8009, http://doi.org/10.1016/j.ecolecon.2005.08.016	Helga Weisz, Fridolin Krausmann, Christof Amann, Nina Eisenmenger, Karl-Heinz Erb, Klaus Hubacek, Marina Fischer-Kowalski	2000	*In this paper we investigate what determines observed differences in economy-wide material use among the EU-15 member states. The empirical basis for our analysis is an extended and revised material flow data set for each of the EU-15 countries in time series from 1970 to 2001. This data set comprises consistent data for domestic extraction, imports and exports as well as for derived material flow indicators, broken down by 12 types of materials. We compare the level and composition of domestic material consumption (DMC) in the EU-15 member states and identify determinants of the observed differences. Across the European Union member states overall DMC per capita varies by a factor of three ranging between 12 tonnes per capita in Italy and the United Kingdom and 37 tonnes per capita in Finland. This variability of DMC in the EU-15 is in a similar order of magnitude as the variability of GDP per capita or total primary energy supply per capita. Linear correlation analysis reveals that national income and final energy consumption relate to material use but cannot fully account for the observed differences in material consumption. By breaking down overall material flow indicators into 12 categories of materials and analysing their use patterns in detail, we identified a number of factors, socio-economic and natural, that influence the level and composition of economy-wide material use. Many of these factors are specific for certain types of materials, others are more general, and quite some driving factors counteract each other regarding the direction of their influence. Concluding we summarize the most important driving factors for domestic material consumption stressing population density as largely neglected but important explanatory variable for material use patterns, discuss issues of environmental significance, aggregation and the use of different denominators in material flow accounting and suggest a re-interpretation of DMC.*	Material extraction, material consumption, physical trade balance, material efficiency, assessment of determinants of material use	stacked bar chart, tables, grouped bar
5		Julia K. Steinberger, Fridolin Krausmann, Nina Eisenmenger, Global patterns of materials use: A socioeconomic and geophysical analysis, Ecological Economics, Volume 69, Issue 5, 15 March 2010, Pages 1148-1158, ISSN 0921-8009, http://doi.org/10.1016/j.ecolecon.2009.12.009.	Julia K. Steinberger, Fridolin Krausmann, Nina Eisenmenger	2000	*Human use of materials is a major driver of global environmental change. The links between materials use and economic development are central to the challenge of decoupling of materials use and economic growth (dematerialization). This article presents a new global material flow dataset compiled for the year 2000, covering 175 countries, including both extraction and trade flows, and comprising four major material categories: biomass, construction minerals, fossil energy carriers and ores/industrial minerals. First, we quantify the variability and distributional inequality (Gini coefficients) in international material consumption. We then measure the influence of the drivers population, GDP, land area and climate. This analysis yields international income elasticities of material use. Finally, we examine the coupling between material flows, and between income and material productivity, measured in economic production per tonne material consumed. Material productivity is strongly coupled to income, and may thus not be suitable as an international indicator of environmental progress — a finding which we relate to the economic inelasticity of material consumption. The results demonstrate striking differences between the material groups. Biomass is the most equitably distributed resource, economically the most inelastic, and is not correlated to any of the mineral materials. The three mineral material groups are closely coupled to each other and economic activity, indicating that the challenge of dematerializing industrial economies may require fundamental structural transformation. Our analysis provides a first systematic investigation of international differences in material use and their drivers, and thus serves as the basis for more detailed future work.*	Material extraction, material consumption, physical trade balance, material efficiency, assessment of determinants of material use	line, tables, scatter
6		James West, Heinz Schandl, Material use and material efficiency in Latin America and the Caribbean, Ecological Economics, Volume 94, October 2013, Pages 19-27, ISSN 0921-8009, http://doi.org/10.1016/j.ecolecon.2013.06.015.	James West, Heinz Schandl	1970-2008	*Different world regions have followed very different trajectories for natural resources use over the recent decades. Latin America has pursued a development path based largely on exports of primary resources. Adopting this path has characteristic environmental and social impacts. In this paper, we provide the first broad based estimate of material use and material efficiency for the region, beginning in 1970 and extending to the onset of the global financial crisis in 2008. The results show a region with rapidly growing primary materials consumption, which is simultaneously becoming less efficient at converting those resources into national income. Using an IPAT framework, we found that population growth and rising per-capita incomes made comparable contributions to growing material use, while technological change as reflected in material intensity, did not moderate consumption. Increasing materials intensity, observed for the region as a whole, is also observed for most individual countries. This contrasts with some other world regions, and implies that many countries in Latin America and the Caribbean will confront higher environmental pressures than expected when expanding their extractive industries to take advantage of new demand from other world regions, while simultaneously supplying the requirements for their own domestic industrial transformations and urbanization.*	Material extraction, material consumption, physical trade balance, material efficiency, assessment of determinants of material use	Line / stacked bar / table
7		Jan Kovanda, Jan Weinzettel, The importance of raw material equivalents in economy-wide material flow accounting and its policy dimension, Environmental Science & Policy, Volume 29, May 2013, Pages 71-80, ISSN 1462-9011, http://doi.org/10.1016/j.envsci.2013.01.005.	Jan Kovanda, Jan Weinzettel	1995-2010	*This article presents a comparison of indicators based on an economy-wide material flow analysis, namely imports, exports, domestic material consumption, raw material equivalents of imports, raw material equivalents of exports and raw material consumption. These indicators were calculated for the Czech Republic for 1995–2010 using, besides an economywide material flow analysis, the hybrid input–output life cycle assessment method, which allows for a calculation of raw material equivalents of imports and exports. The results show that a calculation of indicators, which include raw material equivalents, is useful, as it provides some important information which is not obvious from imports, exports and domestic material consumption indicators. We have proved that the latter group of indicators provide the incorrect information regarding the environmental pressure trend related to material flows, underestimate the overall pressure related to foreign trade and provide incorrect information on the importance of various material categories in particular indicators. Consequently, in the case ofthe Czech Republic, the implications stemming from these points such as the very high dependency of the Czech production system on metal ores from abroad and a rather unequal distribution of environmental pressures between the Czech Republic and its trading partners have not been more thoroughly addressed by Czech economic, environmental and sustainability policies so far and present unresolved issues which will have to be dealt with in the future.*	Material extraction, material consumption, physical trade balance, material efficiency, calculation of raw material equivalents, assessment of determinants of material use	Stacked area, line

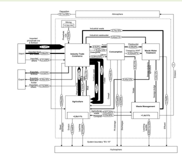
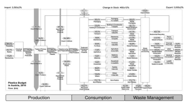
Entry No.	Preview Image	Publication	Author(s)	Core Dimensions: Stages	Trade	Linkages	Time	Uncertainty	Stocks	Retinal Variables: Colour	Shape	Orientation	Size	Texture	Value	Comments
1		Licht, C; Talens, L.; Villalba, G. (2015) Global Substance Flow Analysis of Gallium, Germanium, and Indium – Quantification of Extraction, Uses, and Dissipative Losses within their Anthropogenic Cycles. Journal of Industrial Ecology 19(5): 890-903. DOI: 10.1111/jiec.12287	Christina Licht, Laura Talens Peiro, and Gara Villalba	y					y	nominal (groupings in sankey)	nominal (Rounded polygons denote flows, rectangles denote stages)		quantitative (uses width to denote the size of flow)	nominal (uses texture alongside colour to provide groupings)		Mixed scale of flows in sankey diagram so interpretation of diagram could be erronous. Layout and alignment could be improved as there is overlap of node and flow which is not necessary. Losses should be the bottom horizontal of the diagram.
2		Talens Peiro, L., Villalba, G., Ayres, R. (2013). "Material flow analysis of scarce metals: sources, functions, end-uses and aspects for future supply." Environmental Science & Technology, 47 (6), pp 2939–2947.26. DOI: 10.1021/es301519c	Laura Talens Peiro, Gara Villalba Mendez, and Robert U. Ayres	y		y			y	nominal & ordinal (uses colour minimally to differentiate text groupings)	nominal (uses rectangles to define substances, uses arrows to denote process links and directionaility)					Would be beneficial to see more consistent alignment within each of the diagrams and even spacing between nodes. Uses colour to highlight specific figures against grey colour palette
3		Talens Perio, L, Villalba G., Ayres, R. (2013) Lithium: sources, production, uses and recovery outlook. The Journal of The Minerals, Metals & Materials Society. 65 (8) 986-996. DOI: 10.1007/s11837-013-0666-4	Laura Talens Peiro, Gara Villalba Mendez, and Robert U. Ayres	y				y	y		nominal (flow diagram uses shape to differentiate process / stage and flow)					Simple use of differential variable, consitent alignement and layout.
4		Helga Weisz, Fridolin Krausmann, Christof Amann, Nina Eisenmenger, Karl-Heinz Erb, Klaus Hubacek, Marina Fischer-Kowalski, The physical economy of the European Union: Cross-country comparison and determinants of material consumption, Ecological Economics, Volume 58, Issue 4, 1 July 2006, Pages 676-698, ISSN 0921-8009, http://doi.org/10.1016/j.ecolecon.2005.08.016	Helga Weisz, Fridolin Krausmann, Christof Amann, Nina Eisenmenger, Karl-Heinz Erb, Klaus Hubacek, Marina Fischer-Kowalski	y									quantitative (length of bars)		nominal (Uses value to differentiate groupings)	Good consistency in design although alignmet and layout of axis could be improved specifically in the second grouped bar chart. Good use of value as primary differential variable for nominal data
5		Julia K. Steinberger, Fridolin Krausmann, Nina Eisenmenger, Global patterns of materials use: A socioeconomic and geophysical analysis, Ecological Economics, Volume 69, Issue 5, 15 March 2010, Pages 1148-1158, ISSN 0921-8009, http://doi.org/10.1016/j.ecolecon.2009.12.009.	Julia K. Steinberger, Fridolin Krausmann, Nina Eisenmenger		y			y		nominal (groupings in line chart)				nominal (Uses value to differentiate groupings)		As colour is already used in the line chart it should be the primary retinal variable above shape and texture for nominal categorisation. There is good consistency in the small multiples in regards to design and scale
6		James West, Heinz Schandl, Material use and material efficiency in Latin America and the Caribbean, Ecological Economics, Volume 94, October 2013, Pages 19-27, ISSN 0921-8009, http://doi.org/10.1016/j.ecolecon.2013.06.015.	James West, Heinz Schandl		y		y				nominal (Uses shape as markers on line graph to show qualitative grouping)		quantitative (length of bars)	nominal (Uses value to differentiate groupings)	nominal (Uses value to differentiate groupings)	Good use of constistent alignment and asthetics, more consistent scales would improve ease of comparison. Removal of the shapes and texture on the line as diferential variables and making the value the primary differential variable would improve differentiation.
7		Jan Kovanda, Jan Weinzettel, The importance of raw material equivalents in economy-wide material flow accounting and its policy dimension, Environmental Science & Policy, Volume 29, May 2013, Pages 71-80, ISSN 1462-9011, http://doi.org/10.1016/j.envsci.2013.01.005.	Jan Kovanda, Jan Weinzettel		y		y				nominal (Uses shape as markers on line graph to show qualitative grouping)		quantitative (area in area chart)		nominal (Uses value to differentiate groupings)	Good use of constient scales when comparing charts and statistics. Extra tick marks could be removed to reduce the data ink ratio. Removal of the shapes on the line as a diferential variable and making the value the primary differential variable would improve differentiation.

Entry No.	Preview Image	Publication	Author(s)	Date (source data)	Publication Summary	Purpose	Type of diagram(s)
	Source information						
8		James West, Heinz Schandl, Fridolin Krausmann, Jan Kovanda, Tomas Hak, Patterns of change in material use and material efficiency in the successor states of the former Soviet Union, Ecological Economics, Volume 105, September 2014, Pages 211-219, ISSN 0921-8009, http://doi.org/10.1016/j.ecolecon.2014.06.013.	James West, Heinz Schandl, Fridolin Krausmann, Jan Kovanda, Tomas Hak	1992-2008	*The successor states of the former Soviet Union present a unique opportunity to study the changes in the socio-metabolic profile of a cohort of nations which underwent a radical and contemporaneous shift in economic system. That change was from being regions within an economically integrated, centrally planned whole, to being independent nations left to find their own place in the global economic system. The situation of these nations since the dissolution of the Soviet Union provides a rare experiment, in which we might observe the influence of the different starting conditions of each nation on the development path it subsequently followed, and the attendant socio-metabolic profiles which resulted. Here we take the opportunity to examine patterns for the region as a whole, and for three individual countries. We also examine the relative importance of three different drivers of material consumption using a version of the IPAT framework. Finally, an area for follow-on investigation was suggested by a significant positive correlation observed between the economic growth of individual successor states, and the degree to which they improved their material productivity. This latter is of potential importance in assessing whether dematerialization acts primarily to accelerate or retard economic growth.*	Material extraction, material consumption, physical trade balance, material efficiency, assessment of determinants of material use	Line / stacked bar / table
9		Ozoda Raupova, Hirotsugu Kamahara, Naohiro Goto, Assessment of physical economy through economy-wide material flow analysis in developing Uzbekistan, Resources, Conservation and Recycling, Volume 89, August 2014, Pages 76-85, ISSN 0921-3449, http://doi.org/10.1016/j.resconrec.2014.05.004.	Ozoda Raupova, Hirotsugu Kamahara, Naohiro Goto	1992-2011	*In this paper, we assess the physical dimensions of Uzbekistan's economy during 1992–2011 by using the economy-wide material flow analysis (EW-MFA) method, which is an internationally recognized tool for such assessments. There have been a number of studies using methodological standardization of EW-MFA, but to the best of our knowledge, it has never been used to assess the metabolism of Central Asian economies, especially, in this case, the Republic of Uzbekistan.* *Our analysis strives to empirically evaluate macroscopic economic activities by considering the accounting of material flows. The material flows data-set comprises of consistent data for domestic extraction, imports, and exports, as well as other derived MFA-based indicators. The derived indicators are internationally compared for further evaluation of national economic development performance in a given period. The indicators of direct material input (DMI) and total material requirements (TMR) showed a slight increase in 1992–2011 with an average annual increase of 2.79% and 2.34%. The trends of TMR, DMI, domestic material consumption (DMC) and material efficiency, which is indicated by GDP/DMI, displayed lower values than other industrialized countries referenced in the international comparison. Although national economic performance data showed particularly remarkable success, indicators measuring material inputs and DMC reveal an insignificant increase during the period of study. During the second decade of study period, relative decoupling has occurred which indicated that the economic indicator (GDP) grows faster than DMC and other macro indicators grow.*	Material extraction, material consumption, physical trade balance, assessment of determinants of material use	Line / stacked bar / grouped bar / stacked area / table
10		Anke Schaffartzik, Andreas Mayer, Simone Gingrich, Nina Eisenmenger, Christian Loy, Fridolin Krausmann, The global metabolic transition: Regional patterns and trends of global material flows, 1950–2010, Global Environmental Change, Volume 26, May 2014, Pages 87-97, ISSN 0959-3780, http://doi.org/10.1016/j.gloenvcha.2014.03.013.	Anke Schaffartzik, Andreas Mayer, Simone Gingrich, Nina Eisenmenger, Christian Loy, Fridolin Krausmann	1950-2010	*Since the World War II, many economies have transitioned from an agrarian, biomass-based to an industrial, minerals-based metabolic regime. Since 1950, world population grew by factor 2.7 and global material consumption by factor 3.7–71 Gigatonnes per year in 2010. The expansion of the resource base required by human societies is associated with growing pressure on the environment and infringement on the habitats of other species. In order to achieve a sustainability transition, we require a better understanding of the currently ongoing metabolic transition and its potential inertia. In this article, we present a long-term global material flow dataset covering material extraction, trade, and consumption of 177 individual countries between 1950 and 2010. We trace patterns and trends in material flows for six major geographic and economic country groupings and world regions (Western Industrial, the (Former) Soviet Union and its allies, Asia, the Middle East and Northern Africa, Latin America and the Caribbean, and Sub-Saharan Africa) as well as their contribution to the emergence of a global metabolic profile during a period of rapid industrialization and globalization. Global average material use increased from 5.0 to 10.3 tons per capita and year (t/cap/a) between 1950 and 2010. Regional metabolic rates range from 4.5 t/cap/a in Sub-Saharan Africa to 14.8 t/cap/a in the Western Industrial grouping. While we can observe a stabilization of the industrial metabolic profile composed of relatively equal shares of biomass, fossil energy carriers, and construction minerals, we note differences in the degree to which other regions are gravitating toward a similar form of material use. Since 2000, Asia has overtaken the Western Industrial grouping in terms of its share in global resource use although not in terms of its per capita material consumption. We find that at a sub-global level, the roles of the world regions have changed. There are, however, no signs yet that this will lead to stabilization or even a reduction of global resource use.*	Material extraction, material consumption, physical trade balance, material efficiency, assessment of transition from agrarian to industrial regimes	line / stacked bar
11		Infante-Amate, J., Soto, D., Aguilera, E., García-Ruiz, R., Guzmán, G., Cid, A. and González de Molina, M. (2015), The Spanish Transition to Industrial Metabolism: Long-Term Material Flow Analysis (1860–2010). Journal of Industrial Ecology, 19: 866–876. doi:10.1111/jiec.12261	Juan Infante-Amate, David Soto, Eduardo Aguilera, Roberto Garc´ıa-Ruiz, Gloria Guzman, ´ Antonio Cid, and Manuel Gonzalez de Molina	1860-2010	*The aim of this work is to reconstruct the main economy-wide/material flow accounting indicators for the Spanish economy between 1860 and 2010. The main results indicate that from 1960 onward, the country saw a very rapid industrial transition based on the domestic extraction of quarry products and the impor t of fossil fuels and manufactured goods. Direct material consumption rose from 58.7 million tonnes (Mt) in 1860 to 570.2 Mt in 2010. In per capita terms, it rose from 2.76 tonnes per capita per year (t/cap/yr) to 11.61 t/cap/year. Of the decennial years studied in this ar ticle, a peak of 15.23 t/cap/yr occurs in the year 2000; the subsequent fall is explained by the crisis of 2008. Until 1930, Spain was a net exporter of resources, but since that year, and especially since 1960, it began to depend heavily on overseas resources. The physical trade balance per inhabitant in Spain was –0.01 t/cap/year in 1860 and today it is 2.45 t/cap/year. This process also reveals the change in consumption patterns, which became increasingly dependent on abiotic resources. In 1860, 98.1% of resources consumed was biomass, whereas today the figure is 16.2%. In all events, this ar ticle shows how, although the great transformation did not occur until 1960, before that date the country saw significant qualitative transformation, which did not involve relevant changes in the mobilization of resources.*	Material extraction, material consumption, physical trade balance, assessment of transition to transition from agrarian to industrial regimes	Line / stacked bar / grouped bar / stacked area / table
12		Jan Kovanda, Total residual output flows of the economy: Methodology and application in the case of the Czech Republic, Resources, Conservation and Recycling, Volume 116, January 2017, Pages 61-69, ISSN 0921-3449, http://doi.org/10.1016/j.resconrec.2016.09.018.	Jan Kovanda	1990-2014	*The article goes beyond standard emission and waste statistics and elaborates upon total residual output flows of economies based on economy-wide material flow accounting and analysis (EW-MFA). This concept allows for evaluation of total environmental pressures related to material output flows and assessing the potential trade-offs if environmental policies are more successful in some fields than in others. We provide basic information on EW-MFA and its output accounts and indicators and describe in detail the methodology of their compilation. The methodology is then applied to the Czech Republic for the period 1990–2014. All major components of residual output flows, i.e. emission and waste flow, dissipative use flow and unused domestic extraction accounts, as well as domestic processed output (DPO) and total domestic output (TDO) indicators, went down in the monitored period. We identified a few major driving forces behind this decrease, including changes in the structure of the economy, changes in the structure of TPES, technological change, advances in waste management, and changes in the agricultural system of the Czech Republic. The results further indicate that another decrease in DPO and TDO indicators is at stake, as Czech economic policies are aimed at maintaining the current relatively high proportion of manufacturing industries in the economy.*	Emission flows, dissipative flows, unused domestic extraction, assessment of determinants of output material flows	Line / stacked area / grouped bar

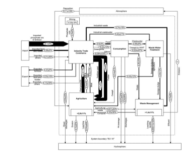
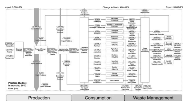
Entry No.				Core Dimensions						Retinal Variables						
	Preview Image	Publication	Author(s)	Stages	Trade	Linkages	Time	Uncertainty	Stocks	Colour	Shape	Orientation	Size	Texture	Value	Comments
8		James West, Heinz Schandl, Fridolin Krausmann, Jan Kovanda, Tomas Hak, Patterns of change in material use and material efficiency in the successor states of the former Soviet Union, Ecological Economics, Volume 105, September 2014, Pages 211-219, ISSN 0921-8009, http://doi.org/10.1016/j.ecolecon.2014.06.013.	James West, Heinz Schandl, Fridolin Krausmann, Jan Kovanda, Tomas Hak		y		y				nominal (Uses shape as markers on line graph to show qualitative grouping)		quantitative (area in area chart)		nominal (Uses value to differentiate groupings)	Reasonable level fo consitency within overall report. Non-consotent fort typeface, weighting and size used whoich if matched would improve the report. Sahpes on lines could be removed to leave value as the differential variable on the line graphs. removing the key and labelling the lines would reinforce the groupings.
9		Ozoda Raupova, Hirotsugu Kamahara, Naohiro Goto, Assessment of physical economy through economy-wide material flow analysis in developing Uzbekistan, Resources, Conservation and Recycling, Volume 89, August 2014, Pages 76-85, ISSN 0921-3449, http://doi.org/10.1016/j.resconrec.2014.05.004.	Ozoda Raupova, Hirotsugu Kamahara, Naohiro Goto	y	y		y			nominal (groupings in stacked bar, grouped bar and line)	nominal (Uses shape as markers on line graph to show qualitative grouping)		quantitative (length of bars and area)	nominal (Uses texture in the stacked area chart to differentiate categories)	nominal (Value used in the line charts alongside texture to provide differenitation of categories)	Stacked are chart could be improved by using value or colour to differentiate nominal groupings. Line charts could be improved bu removing spae as a nominal variable for differentiation and simply have as line with colour as differential variable. Overplotting in a number of the line graphs could be reduced by using a different scale, small multiples or a secondary plot removing the larger categories and pltting those that fall below a certain range. A more consitent colour pallete would add improve the consistency across the report
10		Anke Schaffartzik, Andreas Mayer, Simone Gingrich, Nina Eisenmenger, Christian Loy, Fridolin Krausmann, The global metabolic transition: Regional patterns and trends of global material flows, 1950–2010, Global Environmental Change, Volume 26, May 2014, Pages 87-97, ISSN 0959-3780, http://doi.org/10.1016/j.gloenvcha.2014.03.013.	Anke Schaffartzik, Andreas Mayer, Simone Gingrich, Nina Eisenmenger, Christian Loy, Fridolin Krausmann		y		y						quantitative (length of bars)	nominal (stacked bar charts and in lines on line chart to differentiate categories)	nominal (Value used in the line charts alongside texture to provide differenitation of categories)	Use of texture in stacked bar could be improved if value was used in its place. Scales are inconsisten across the small multiples making comparisons difficult. There is also a major issue with one of the scales of the stacked bar with line in that the zero (origin) does not match up. Alignment could also be improved within the scales and design of each chart.
11		Infante-Amate, J., Soto, D., Aguilera, E., García-Ruiz, R., Guzmán, G., Cid, A. and González de Molina, M. (2015). The Spanish Transition to Industrial Metabolism: Long-Term Material Flow Analysis (1860–2010). Journal of Industrial Ecology, 19: 866–876. doi:10.1111/jiec.12261	Juan Infante-Amate, David Soto, Eduardo Aguilera, Roberto Garc´ıa-Ruiz, Gloria Guzman,´ Antonio Cid, and Manuel Gonzalez de Molina		y		y	y			nominal (Uses shape as markers on line graph to show qualitative grouping data points)		quantitative (length of bars)	nominal (line charts on lines)	nominal (Value used in the line charts alongside texture to provide differenitation of categories)	Uses a mixture of texture and value on line graph to differentiate groupings. This method has a number of issues in that for complex lines and shapes, texture loses defenition on crucial markes and points due to the segementation of the line.
12		Jan Kovanda, Total residual output flows of the economy: Methodology and application in the case of the Czech Republic, Resources, Conservation and Recycling, Volume 116, January 2017, Pages 61-69, ISSN 0921-3449, http://doi.org/10.1016/j.resconrec.2016.09.018.	Jan Kovanda				y			nominal (groupings in stacked area grouped bar and line)			quantitative (area on stcaked area graph and length on bar charts)			The high saliency of the colour choice could be improved to a less satuated scheme which would improve the visual appeal. The ue of mixed axis can quiet easily be misread in the grouped bar with line graph and alternatives should be considered,

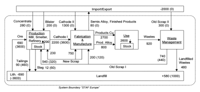
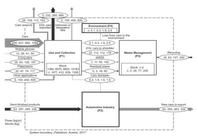
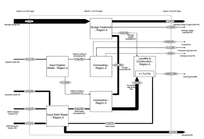
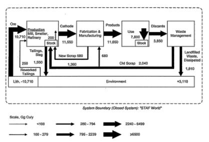
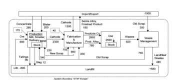
Entry No.	Source information						Type of diagram(s)
	Preview Image	*Publication*	*Author(s)*	*Date (source data)*	*Publication Summary*	*Purpose*	
13		Liang Dong, Ming Dai, Hanwei Liang, Ning Zhang, Nabeel Mancheri, Jingzheng Ren, Yi Dou, Mingming Hu, Material flows and resource productivity in China, South Korea and Japan from 1970 to 2008: A transitional perspective, Journal of Cleaner Production, Volume 141, 10 January 2017, Pages 1164-1177, ISSN 0959-6526, http://doi.org/10.1016/j.jclepro.2016.09.189.	Liang Dong, Ming Dai, Hanwei Liang, Ning Zhang, Nabeel Mancheri, Jingzheng Ren, Yi Dou, Mingming Hu	1970-2008	*China, Japan and South Korea are the important East Asian countries and being paid intensive attentions to their economic miracle, while their environmental performance is less discussed together. These three countries are in different level of developmental stages from emerging economy to matured developed economy. We hereby provide a laboratory idea to investigate the socio-economic metabolism under typical development stages, so that enlightenment on global resource management policy making can be made. This study is based on a long-time series data on the material flow analysis on China, South Korea and Japan, applied with up-to date standardized methodologies of material flow accounting. Material flows, resource productivity data, indicators as well as Environmental Kuznets Curve are presented and compared from 1970 to 2008. Driving forces for the material flow change were further investigated with IPAT approach. Obvious differences of resource efficiency, productivity and consumption patterns were verified. Japan presented the trend of dematerialization and technology effects made significant contribution; China was highlighted with surging resource consumption stage, mainly driven by the economic and population factors, even though the resource efficiency was significantly enhanced in the past three decades. South Korea presented the combined features of China and Japan in different stages. Based on the analytical results, information and insights behind results, like the industrial structure, value chain position in the global supply-demand chain and how they had impacts on the resource efficiency and productivity were discussed in-depth. The research results provide critical insights to future effective and efficient global resource management policy making.*	Material extraction, material consumption, physical trade balance, material efficiency, assessment of determinants of material use	bubble chart / bar / line / stacked bar / donut / scatter / chord / grouped bar / bubble & line map / table
14		Buchner, H., Laner, D., Rechberger, H., and Fellner, J. (2015): Dynamic Material Flow Modeling: An Effort to Calibrate and Validate Aluminum Stocks and Flows in Austria. Environmental Science & Technology 49: 9 5546-5554.	Hanno Buchner, David Laner, Helmut Rechberger, and Johann Fellner	1964-2012	*A calibrated and validated dynamic material flow model of Austrian aluminum (Al) stocks and flows between 1964 and 2012 was developed. Calibration and extensive plausibility testing was performed to illustrate how the quality of dynamic material flow analysis can be improved on the basis of the consideration of independent bottom-up estimates. According to the model, total Austrian in-use Al stocks reached a level of 360 kg/capita in 2012, with buildings (45%) and transport applications (32%) being the major in-use stocks. Old scrap generation (including export of end-of-life vehicles) amounted to 12.5 kg/capita in 2012, still being on the increase, while Al final demand has remained rather constant at around 25 kg/capita in the past few years. The application of global sensitivity analysis showed that only small parts of the total variance of old scrap generation could be explained by the variation of single parameters, emphasizing the need for comprehensive sensitivity analysis tools accounting for interaction between parameters and time-delay effects in dynamic material flow models. Overall, it was possible to generate a detailed understanding of the evolution of Al stocks and flows in Austria, including plausibility evaluations of the results. Such models constitute a reliable basis for evaluating future recycling potentials, in particular with respect to application-specific qualities of current and future national Al scrap generation and utilization.*	To develop a calibrated dynamic model of Austrian Al flows from 1964 to 2012 for determining in-use stocks and scrap flows	flow / stacked area / table / line / fan chart
15		Buchner, H., Laner, D., Rechberger, H., and Fellner, J. (2014): In-depth analysis of aluminum flows in Austria as a basis to increase resource efficiency", Resources, Conservation and Recycling. Resources, Conservation and Recycling 93: 112-123.	Hanno Buchner, David Laner, Helmut Rechberger, Johann Fellner	2010	*Based on the method of material flow analysis (MFA), a static model of Austrian aluminum (Al) flows in 2010 was developed. Extensive data research on Al production, consumption, trade and waste management was conducted and resulted in a detailed model of national Al resources. Data uncertainty was considered in the model based on the application of a rigorous concept for data quality assessment. The model results indicated that the growth of the Austrian "in-use" Al stock amounts to 11 ± 3.1 kg yr−1 cap−1. The total "in-use" Al stock was determined using a bottom-up approach, which produced an estimate of 260 kg Al cap−1. Approximately 7 ± 1 kg of Al yr−1 cap−1 of old scrap was generated in 2010, of which 20% was not recovered because of losses in waste management processes. Quantitatively, approximately 40% of the total scrap input to secondary Al production originated from net imports, highlighting the import dependency of Austrian Al refiners and remelters. Uncertainties in the calculation of recycling indicators for the Austrian Al system with high shares of foreign scrap trade were exemplarily illustrated for the old scrap ratio (OSR) in secondary Al production, resulting in a possible range of OSRs between 0 and 66%. Overall, the detailed MFA in this study provides a basis to identify resource potentials as well as resource losses in the national Al system, and it will serve as a starting point for a dynamic Al model to be developed in the future.*	To establish the Austrian Al budget for the year 2010 as a basis for anthropogenic resource management.	Sankey, Sankey flow, pie, grouped bar / table / 3d bar
16		Buchner, H., Laner, D., Rechberger, H., and Fellner, J. (2015b): Future Raw Material Supply: Opportunities and Limits of Aluminium Recycling in Austria. Journal of Sustainable Metallurgy 1: 1-10.	Hanno Buchner, David Laner, Helmut Rechberger, Johann Fellner	2010-2050	*In order to promote sustainable production by using secondary raw material from existing material stocks, complementary to primary raw material, information about the future availability of secondary resources constitutes a prerequisite. In this study, a dynamic material flow model of historic aluminium (Al) flows in Austria is combined with forecasts on future Al consumption to estimate the development of old scrap generation and in-use stocks until 2050. In-use stocks are estimated to increase by 60 % to 515 kg/cap. by 2050 assuming a scenario of moderate economic growth. Old scrap generation in 2050 would thereby more than double (up to 30 kg/cap.) in comparison to the 2010 amounts. Despite this substantial increase in old scrap generation, industrial self-supply from old scrap will probably not exceed 20 %, and final consumption self-supply of Al will not exceed 40 % given present conditions. Opportunities and limits of increasing self-supply through higher collection rates and lower scrap export levels are investigated in this study as the European Raw Material Initiative considers enhanced recycling to be a key measure to ensure future resource supply. Based on these analyses, a self-sustaining Al supply from post-consumer Al is not expected if current trends of Al usage continue. Therefore, comprehensive resource policy should be based on a profound understanding of the availability of primary and secondary resources potentials and their dynamics.*	To promote sustainable production by using secondary raw material from existing material stocks, complementary to primary raw material, information about the future availability of secondary resources constitutes a prerequisite	Flow, table / fan chart
17		Kral, U., Lin, C.-Y., Kellner, K., Ma, H.-W., and Brunner, P. H. (2014): The Copper Balance of Cities. Journal of Industrial Ecology 18: 3 432-444.	Ulrich Kral, Chih-Yi Lin, Katharina Kellner, Hwong-wen Ma, and Paul H. Brunner	2008/2009	*Material management faces a dual challenge: on the one hand satisfying large and increasing demands for goods and on the other hand accommodating wastes and emissions in sinks. Hence, the characterization of material flows and stocks is relevant for both improving resource efficiency and environmental protection. This article focuses on the urban scale, a dimension rarely investigated in past metal flow studies. We compare the copper (Cu) metabolism of two cities in different economic states, namely, Vienna (Europe) and Taipei (Asia). Substance flow analysis is used to calculate urban Cu balances in a comprehensive and transparent form. The main difference between Cu in the two cities appears to be the stock: Vienna seems close to saturation with 180 kilograms per capita (kg/cap) and a growth rate of 2% per year. In contrast, the Taipei stock of 30 kg/cap grows rapidly by 26% per year. Even though most Cu is recycled in both cities, bottom ash from municipal solid waste incineration represents an unused Cu potential accounting for 1% to 5% of annual demand. Nonpoint emissions are predominant; up to 50% of the loadings into the sewer system are from nonpoint sources. The results of this research are instrumental for the design of the Cu metabolism in each city. The outcomes serve as a base for identification and recovery of recyclables as well as for directing nonrecyclables to appropriate sinks, avoiding sensitive environmental pathways. The methodology applied is well suited for city benchmarking if sufficient data are available.*	To analyze and evaluate the Cu flows and stocks on an urban scale, present and compare the results for two cities	Sankey Flow / grouped bar / stacked bar / table

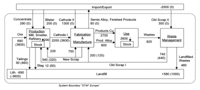
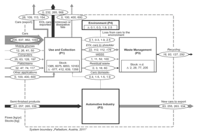
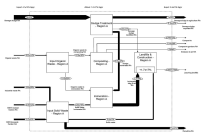
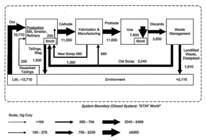
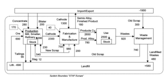
Entry No.				Core Dimensions						Retinal Variables						
	Preview Image	*Publication*	*Author(s)*	*Stages*	*Trade*	*Linkages*	*Time*	*Uncertainty*	*Stocks*	*Colour*	*Shape*	*Orientation*	*Size*	*Texture*	*Value*	*Comments*
13		Liang Dong, Ming Dai, Hanwei Liang, Ning Zhang, Nabeel Mancheri, Jingzheng Ren, Yi Dou, Mingming Hu, Material flows and resource productivity in China, South Korea and Japan from 1970 to 2008: A transitional perspective, Journal of Cleaner Production, Volume 141, 10 January 2017, Pages 1164-1177, ISSN 0959-6526, http://doi.org/10.1016/j.jclepro.2016.09.189.	Liang Dong, Ming Dai, Hanwei Liang, Ning Zhang, Nabeel Mancheri, Jingzheng Ren, Yi Dou, Mingming Hu		y		y			nominal (in most of the bar, line, stcked bar, scatter, chord, grouped bar charts). Quantitative use in bubble, line, choropleth.			quantitative (changes in magnitude represented by length on bar charts, area on donut graph and area in bubble map and bubble chart ordinal data on bubble chart for sizes grouped categroies of dsicrete data.)			There is very little consitency in the design of the charts across the paper. Scales are lacking in some of the diagrams and are incossisntent or misplaced in a number of others. The highly salient colour palette makes differentiation difficult in places. Alignment and oreientation of text could be significantly improved. The 'line' charts that are eally plot graphs would be improved by a simple line graph as all the data points are not neccessary and incrase the data ink ratio. Overplotting in the scatter grph could be reduced by the use of opacity. The chloropeth could be replaced by a series of grouped bar charts for each of the categories as the disparate nature of the charts makes interpretation difficult and a lack of consitency between the key and chart provides more obscurity.
14		Buchner, H., Laner, D., Rechberger, H., and Fellner, J. (2015): Dynamic Material Flow Modeling: An Effort to Calibrate and Validate Aluminum Stocks and Flows in Austria. Environmental Science & Technology 49: 9 5546-5554.	Hanno Buchner, David Laner, Helmut Rechberger, and Johann Fellner	y			y	y	y	nominal (groupings in flow, stacked area, fan and line charts)	nominal (Uses shape as markers on line graph to show qualitative grouping data points)		qualitative (length on bar charts, area graph)	nominal (line graph alongside using colour to provide differentiation		Use of opacity to show unceratinty in data are difficult to visually distinguish and provide no insight into the data. Overplotting on final line graph could be minimised by changing the scale in the y axis. Highly salient colour palette used.
15		Buchner, H., Laner, D., Rechberger, H., and Fellner, J. (2014): In-depth analysis of aluminum flows in Austria as a basis to increase resource efficiency", Resources, Conservation and Recycling. Resources, Conservation and Recycling 93: 112-123.	Hanno Buchner, David Laner, Helmut Rechberger, Johann Fellner	y	y			y	y	nominal (groupings in pie, bar and stacked bar and 3d bar and sankey flow	nominal (uses shape to differentiate process / stage and flow in Sankey flow)		quantitative (width in sankey to denote magnitude. Length in bar (3d and grouped) chart . Area in pie charts)			Uneccessary use of pie chart and 3d bar which could both be presented more effectively with a bar or grouped bar, stacked bar chart. Sankey flow diagrams show some good consitiency but could be improved in alignement of flows and nodes and boxes in the diagram
16		Buchner, H., Laner, D., Rechberger, H., and Fellner, J. (2015b): Future Raw Material Supply: Opportunities and Limits of Aluminium Recycling in Austria. Journal of Sustainable Metallurgy 1: 1-10.	Hanno Buchner, David Laner,Helmut Rechberger, Johann Fellner	y			y	y	y		nominal (flow diagram uses shape to differentiate process / stage and flow)			ordinal (line graph alongside using value to provide differentiation)	ordinal (fan & line charts to differentiate categories)	Good use of small multiples to impart insight into change over time. Could be improved by using value instead of value and texture for the line graphs.
17		Kral, U., Lin, C.-Y., Kellner, K., Ma, H.-W., and Brunner, P. H. (2014): The Copper Balance of Cities. Journal of Industrial Ecology 18: 3 432-444.	Ulrich Kral, Chih-Yi Lin, Katharina Kellner, Hwong-wen Ma, and Paul H. Brunner	y			y	y	y		nominal (uses shape to differentiate process / stage and flow in Sankey flow)		quantitative (width in sankey to denote magnitude. Length in bar (grouped and stacked) chart .)	nominal (Uses texture in one of the stacked bar charts to differentiate categories.)	nominal (uses value to categorise flows / stages etc. in Sankey flow. Uses value to categorise in grouped and stacked)	Consitency in alignment and arrangement internally within sankey diagram to be improved. Flows in/out should be assigned to two sides of process/stage box. arrangement and orientation of labels should be to the horizontal in sankey flow

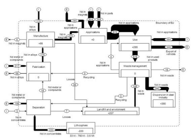
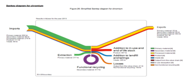
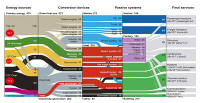
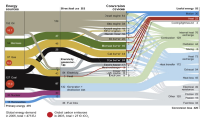
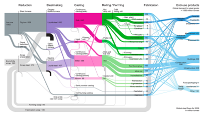
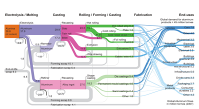
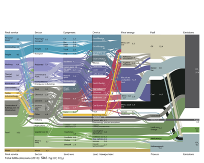
Entry No.	Preview Image	Publication	Author(s)	Date (source data)	Publication Summary	Purpose	Type of diagram(s)
18		Ott, C. and Rechberger, H. (2012): The European phosphorus balance. Resources, Conservation and Recycling 60: 159-172.	Christian Ott, Helmut Rechberger	2006-2008	*Phosphorus (P) is considered a potentially critical resource because reserves are limited; it is required by all creatures, and it cannot be substituted. In this paper a substance flow analysis of phosphorus for the former 15 member states of the European Community (EU15) is presented. In order to consider the heterogeneity of the database with regard to quantity and quality all data are considered with uncertainty ranges. Error propagation and data reconciliation are performed applying the software STAN. Comparing basic and reconciled data shows that the result is reliable enough to allow the following conclusions: the system of the EU15 is largely dependent on imports of phosphorus. Net per capita consumption in the EU15 is 4.7 kgP/yr of which only 1.2 kgP/yr reach the consumer. The main losses are a net accumulation in agricultural soils (2.9 kgP/yr), followed by losses to landfills (1.4 kgP/yr) and to the hydrosphere (0.55 kgP/yr). Only 0.77 kgP/yr are recycled. Optimizing phosphorus fertilization, collecting and recycling of phosphorus-rich wastes, increasing the connection of households to sewer systems, and implementing tertiary wastewater treatment comprehensively could reduce Europe's import dependence on phosphorus significantly.*	To develop an SFA model for the EU15 and adopt it to the special requirements for an EU15 wide analysis	Sankey Flow / stacked bar with line / table. / flow / grouped bar
19		Van Eygen, E., Feketitsch, J., Laner, D., Rechberger, H., and Fellner, J. (2016): Comprehensive analysis and quantification of national plastic flows: The case of Austria. Resources, Conservation and Recycling1-12.	Emile Van Eygena, Julia Feketitscha, David Laner, Helmut Rechberger, Johann Fellner	2010	*Plastics have been increasingly used in a wide range of applications, generating important waste streams, but overall information on their flows through society is generally not available. Therefore, the national plastic flows in Austria were analyzed and quantified from the production stage up to the waste management stage, for the reference year of 2010. To achieve this, material flow analysis was used to set up a model quantitatively describing the Austrian plastics budget, and the quality of the data sources was assessed using uncertainty characterization. The results show that about 1.1 million tonnes (132 kg/cap·a ±2%) of primary plastics were produced in Austria, whereas about 1.3 million tonnes (156 kg/cap·a ±5%) of plastics products were consumed. Roughly one third of the consumed amount contributed to net stock increase in all consumption sectors, and about half of this increase occurred in building and construction, whereas packaging waste constituted approximately half of total post-consumer wastes (70 kg/cap·a ± 4%). Of the total waste amount (including traded and production waste, 91 kg/cap·a ± 3%), the majority was incinerated in waste-to-energy plants or in the cement industry (46% and 21% respectively), whereas the rest was mainly recycled mechanically or chemically (21% and 10% respectively). The results identify the major national flows and processes of plastics, and evaluate the overall data availability for quantifying these flows. Furthermore, the increasing amounts of plastic wastes, due to large stocks having been built up in sectors with long product lifetimes, necessitate assessing which processing capacities are needed and which treatment priorities are to be set in waste management.*	To connect the sources (e.g. imports), the pathways (e.g. transfer coefficients from manufacturing to consumption) and the intermediate (e.g. consumption) and final sinks (e.g. waste management) of materials	Flow / table / Sankey Flow / candlestick / grouped bar
20		Zoboli, O., Laner, D., Zessner, M., and Rechberger, H. (2016b): Added Values of Time Series in Material Flow Analysis: The Austrian Phosphorus Budget from 1990 to 2011. Journal of Industrial Ecology 20: 6 1334-1348.	Ottavia Zoboli, David Laner, Matthias Zessner, Helmut Rechberger	1990-2011	*Material flow analysis is a tool that is increasingly used as a foundation for resource management and environmental protection. This tool is primarily applied in a static manner to individual years, ignoring the impact of time on the material budgets. In this study, a detailed multiyear model of the Austrian phosphorus budget covering the period 1990–2011 was built to investigate its behavior over time and test the hypothesis that a multiyear approach can also contribute to the improvement of static budgets. Further, a novel method was applied to investigate the quality and characteristics of the data and quantify the uncertainty. The degree of change between the budgets was assessed and showed that approximately half of the flows have changed significantly and, at times, abruptly since 1990, but it is not possible to distinguish unequivocally between constant and moderately changing flows given their uncertainty. The study reveals that the phosphorus transported in waste flows has increased more rapidly than its recovery, which accounted for 55% to 60% of the total waste phosphorus in 1990 and only 40% in 2011. The loss ratio in landfills and cement kilns has oscillated in the range of 40% to 50%. From a methodological point of view, the multiyear approach has broadened the conceptual model of the budget, making it more suitable as a basis for material accounting and monitoring. Moreover, the analysis of the data reconciliation process over a long period of time proved to be a useful tool for identifying systematic errors in the model.*	To identify and assess the extent of the temporal changes that occurred in the system during the last two decades	Flow / line / range area / Sankey Flow
21		Egle, L., Zoboli, O., Thaler, S., Rechberger, H., and Zessner, M. (2014): The Austrian P budget as a basis for resource optimization. Resources, Conservation and Recycling 83: 152-162.	L. Eglea, O. Zoboli, S. Thaler, H. Rechberger, M. Zessner	2004-2008	*Phosphorus (P) is a finite and non-substitutable resource that is essential to sustaining high levels of agricultural productivity but is also responsible for environmental problems, e.g., eutrophication. Based on the methodology of Material Flow Analysis, this study attempts to quantify all relevant flows and stocks of phosphorus (P) in Austria, with a special focus on waste and wastewater management. The system is modeled with the software STAN, which considers data uncertainty and applies data reconciliation and error propagation. The main novelty of this work lies in the high level of detail at which flows and stocks have been quantified to achieve a deeper understanding of the system and to provide a sound basis for the evaluation of various management options. The budget confirms on the one hand the dependence of mineral P fertilizer application (2 kg cap−1 yr−1), but it highlights on the other hand considerable unexploited potential for improvement. For example, municipal sewage sludge (0.75 kg cap−1 yr−1) and meat and bone meal (0.65 kg cap−1 yr−1) could potentially substitute 70% of the total applied mineral P fertilizers. However, recycling rates are low for several P flows (e.g., 27% of municipal sewage sludge; 3% of meat and bone meal). Therefore, Austria is building up a remarkable P stock (2.1 kg P cap−1 yr−1), mainly due to accumulation in landfills (1.1 kg P cap−1 yr−1) and agricultural soils (0.48 kg P cap−1 yr−1).*	To develop a national P balance	line / table / flow / Sankey flow
22		Allesch, A. and Brunner, P. H. (2015): Material Flow Analysis as a Decision Support Tool for Waste Management - A Literature Review. Journal of Industrial Ecology 19: 5 753-764.	Astrid Allesch, Paul H. Brunner	2012	*This article reviews, categorizes, and evaluates the objectives, means, and results of the application of material flow analysis (MFA) in waste management. It identifies those areas where MFA methodologies are most successful in supporting waste management decisions. The focus of this review is on the distinction between MFA on the level of goods and on the level of substances. Based on 83 reviewed studies, potentials, strengths, and weaknesses are investigated for the two levels of MFA when applied for analysis, evaluation, and improvement of waste management systems. The differences are discussed in view of effectiveness, applicability, and data availability. The results show that MFA on the level of goods are instrumental for understanding how waste management systems function, facilitating the connections of stakeholders, authorities, and waste management companies. The substance level is essential to assess qualitative aspects regarding resources and environment. Knowledge about the transformation, transport, and storage of valuable and hazardous substances forms the base for identifying both resource potentials and risks for human health and the environment. The results of this review encourage the application of MFA on both levels of goods and substances for decision making in waste management. Because of the mass balance principle, this combination has proven to be a powerful tool for comprehensively assessing if a chosen system reaches designated waste management goals.*	To demonstrate how MFA can be used as tool to design WM-systems, to point out how MFA can be applied as a base for assessment o in view of given objectives	table / stacked bar / pie
23		Spatari, S., Bertram, M., Fuse, K., Graedel, T. E., and Rechberger, H. (2002): The contemporary European copper cycle: 1 year stocks and flows. Ecological Economics 42: 1–2 27-42.	S. Spatari, M. Bertram, K. Fuse, T.E. Graedel, H. Rechberger	1994	*Substance flow cycles can provide a picture of resource uses and losses through a geographic region, allowing us to evaluate regional resource management and estimate gross environmental impacts. This paper traces the flow of copper as it enters and leaves the European economy over 1 year and provides the numerical accounting of copper flows that are further analyzed in a companion paper in this issue. We examine the major flows of copper from ore, as it is extracted from the earth, transformed into products, and discarded or recycled. A regional material flow model was developed to estimate patterns of copper use in the early 1990s in select European countries. Successive mass balance calculations were used to determine copper flows, including the amount of metal that enters use in society and is deposited in waste repositories. A database that records temporal and spatial boundary conditions and data quality was developed for continental substance flow analysis. The majority of copper is mined, smelted, and refined outside of Europe. Across the life cycle, a net total of 1900 Gg/year of copper is imported into Europe. About 40% of cathode copper produced within the system is made from old and new scrap. It is estimated that approximately 8 kg of copper per person enters use in society, largely in infrastructure, buildings, industry, and private households. The majority of copper in finished products is contained in pure form (70%), the remainder in alloy form. The waste management system in Europe recycles about 60% of the copper from waste. The copper discard flow from post-consumer waste is roughly five times higher than that from copper production waste. This ratio would decrease if we consider production wastes generated outside of the European system boundary. The net addition of copper to the stock in society in the system is about 6 kg/person. Given the in-service lifetime of the applications of copper identified in this model, most of the copper processed during the last few decades still resides in society, mostly in non-dissipative uses.*	To capture at least 80% of relevant copper movement and use within continental Europe	Flow / table

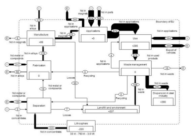
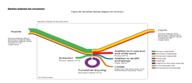
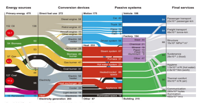
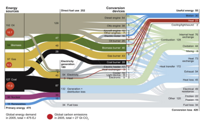
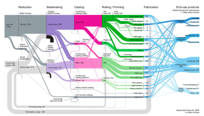
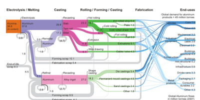
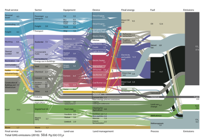
Source information

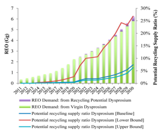
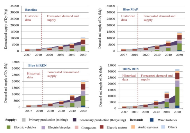
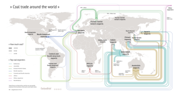
Entry No.				Core Dimensions						Retinal Variables						
	Preview Image	*Publication*	*Author(s)*	*Stages*	*Trade*	*Linkages*	*Time*	*Uncertainty*	*Stocks*	*Colour*	*Shape*	*Orientation*	*Size*	*Texture*	*Value*	*Comments*
18		Ott, C. and Rechberger, H. (2012): The European phosphorus balance. Resources, Conservation and Recycling 60: 159-172.	Christian Ott, Helmut Rechberger	y		y	y	y	y		nominal (uses shape to differentiate process / stage and flow in Sankey flow)		quantitative (width in sankey to denote magnitude. Length in bar (grouped and stacked) chart .)	nominal (bar chart to differentiate categories only in relation to the line elements on the graph)	nominal (stacked bar char)	Arrangement and orientation of labels should be to the horizontal in sankey flow. Lack of consistency in sizes of labels also. In / out flows from each stage should be arranged and grouped appropriatey to one side of the process box in the sankey. Use of multiple scales on grouped bar infers incorrect information.
19		Van Eygen, E., Feketitsch, J., Laner, D., Rechberger, H., and Fellner, J. (2016): Comprehensive analysis and quantification of national plastic flows: The case of Austria. Resources, Conservation and Recycling1-12.	Emile Van Eygena, Julia Feketitscha, David Laner, Helmut Rechberger, Johann Fellner	y	y			y	y		nominal (uses shape to differentiate process / stage and flow in Sankey flow)		quantitative (width in sankey to denote magnitude. Length in bar (grouped) and candlestick chart .)	Nominal (grouped bar chart)		bar chart would be better served to use value to show nominal data. Good alignement and consitency in distribution in sankey flow.
20		Zoboli, O., Laner, D., Zessner, M., and Rechberger, H. (2016b): Added Values of Time Series in Material Flow Analysis: The Austrian Phosphorus Budget from 1990 to 2011. Journal of Industrial Ecology 20: 6 1334-1348.	Ottavia Zoboli, David Laner, Matthias Zessner, Helmut Rechberger	y			y	y	y	ordinal (Uses colour in the Sankey Flow to demonstrate grouped quantitative change over time.)	nominal (uses shape to differentiate process / stage and flow in Sankey flow. Uses shape in line graph to differentiate categroies)		quantitative (width in sankey)	nominal (line graph)	nominal (area chart)	One of the main issues here is that the colour has no real meaning to the change over time as it simply categroises the change as a lot, some, or none. No indication as to trend or overall change (positive or negative). Good consistency within line chart. Line charts that use shape for nominal groupings are ineffective when occlusion occurs.
21		Egle, L., Zoboli, O., Thaler, S., Rechberger, H., and Zessner, M. (2014): The Austrian P budget as a basis for resource optimization. Resources, Conservation and Recycling 83: 152-162.	L. Eglea, O. Zoboli, S. Thaler, H. Rechberger, M. Zessner	y			y	y	y		nominal (differentiate process / stage and flow in Sankey flow.)		quantitative (width in sankeys)	nominal (line graph)		Consitency in alignment and arrangement internally within sankey diagram to be improved. Flows in/out should be assigned to two sides of process/stage box.
22		Allesch, A. and Brunner, P. H. (2015): Material Flow Analysis as a Decision Support Tool for Waste Management - A Literature Review. Journal of Industrial Ecology 19: 5 753-764.	Astrid Allesch, Paul H. Brunner					y	y				quantitative (Uses area in pie and length in stacked bar)		nominal (in both bar and pie)	Arrangement of labels needs to be improved and given more space. Pie charts should be replaced with bar charts for vount information.
23		Spatari, S., Bertram, M., Fuse, K., Graedel, T. E., and Rechberger, H. (2002): The contemporary European copper cycle: 1 year stocks and flows. Ecological Economics 42: 1–2 27-42.	S. Spatari, M. Bertram, K. Fuse, T.E. Graedel, H. Rechberger	y		y			y		nominal (Uses shape to differentiate flows from stages)			nominal (texture for grouping and association)		Arrangement of in/out flows needs to be adjusted and made consistent.

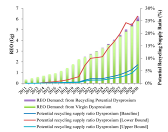
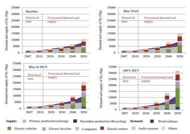
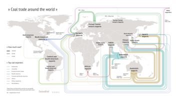
Entry No.	Source information						Type of diagram(s)
	Preview Image	Publication	Author(s)	Date (source data)	Publication Summary	Purpose	
24		Rechberger, H. and Graedel, T. E. (2002): The contemporary European copper cycle: statistical entropy analysis. Ecological Economics 42: 1–2 59-72.	H. Rechberger, T.E. Graedel	1994	*The copper flows and stocks of the European economy are investigated and evaluated over a 1-year period in the early 1990s. The method applied is statistical entropy, which quantifies the distribution pattern of a substance (e.g. copper) caused by a system (e.g. political economy). Contemporary copper management can be defined as a simple chain of four processes: production of refined copper from ore; manufacture and fabrication of products and goods; consumption, utilization and storage (infrastructure) of goods; and separation of copper from waste for recycling and finally, landfilling (waste management). Relevant recycling streams (new and old scrap) within or between production, manufacture, and waste management processes also characterize the system. Throughout the life cycle of copper the statistical entropy varies considerably among the above-mentioned processes and covers about 50% of the possible range between total dissipation and maximal concentration of the total throughput of copper. Nevertheless, present copper management does not show a clear entropy trend across its life cycle. The system as a whole neither dissipates nor concentrates copper significantly with regard to the original ore. Even a more optimized waste management system with higher recycling efficiency could not significantly change this finding since today's copper flows into waste management are small compared to the consumption of copper. The relatively limited impact on the entropy trend of contemporary waste management may increase in the future because the infrastructure, which has been established over the last few decades, will be continuously renewed and replaced. As a result of these larger waste streams, decreasing overall entropy trends will be realizable, provided efficient recycling technologies are applied. This indicates the possibility for long-term feasible (perhaps sustainable) copper management. The entropy approach improves our understanding of industrial metabolism and is a useful decision support and design tool, since complex systems can thereby be quantified by a single metric per substance.*	To introduce an alternative and useful method(statistical entropy analysis) for evaluating material flows only.	flow / bar / line
25		Laner, D.; Rechberger, H.; Astrup, T. (2015) „Applying Fuzzy and Probabilistic Uncertainty Concepts to the Material Flow Analysis of Palladium in Austria", Journal of Industrial Ecology, 19, 0, p. 1-15, ISSN 1088-1980. DOI: 10.1111/jiec.12235	David Laner, Helmut Rechberger, Thomas Astrup	2011	*Material flow analysis (MFA) is a widely applied tool to investigate resource and recycling systems of metals and minerals. Owing to data limitations and restricted system understanding, MFA results are inherently uncertain. To demonstrate the systematic implementation of uncertainty analysis in MFA, two mathematical concepts for the quantification of uncertainties were applied to Austrian palladium (Pd) resource flows and evaluated: (1) uncertainty ranges expressed by fuzzy sets and (2) uncertainty ranges defined by normal distributions given as mean values and standard deviations. Whereas normal distributions represent the traditional approach for quantifying uncertainties in MFA, fuzzy sets may offer additional benefits in relation to uncertainty quantification in cases of scarce information. With respect to the Pd case study, the fuzzy representation of uncertain quantities is more consistent with the actual data availability in cases of incomplete databases, and fuzzy sets serve to highlight the effect of uncertainty on resource efficiency indicators derived from the MFA results. For both approaches, data reconciliation procedures offer the potential to reduce uncertainty and evaluate the plausibility of the model results. With respect to Pd resource management, improved formal collection of end-of-life (EOL) consumer products is identified as a key factor in increasing the recycling efficiency. In particular, the partial export of EOL vehicles represents a substantial loss of Pd from the Austrian resource system, whereas approximately 70% of the Pd in the EOL consumer products is recovered in waste management. In conclusion, systematic uncertainty analysis is an integral part of MFA required to provide robust decision support in resource management.*	To investigate the effect of a rigorous uncertainty analysis on the evaluation of the Austrian Pd resource system	table / flow / Sankey flow / line
26		Klinglmair, M.; Lemming, C.; Jensen, L.S.; Rechberger, H.; Astrup, T.F., Scheutz, Ch. (2015) "Phosphorus in Denmark: National and regional anthropogenic flows", Resources, Conservation and Recycling, Vol. 96, p. 311-324, dx.doi.org/10.1016/j.resconrec.2015.09.019, ISSN 0921-3449	Manfred Klinglmair, Camilla Lemming, Lars Stoumann Jensen, Helmut Rechberger, Thomas Fruergaard Astrupa, Charlotte Scheutz	2011	*Substance flow analyses (SFA) of phosphorus (P) have been examined on a national or supra-national level in various recent studies. SFA studies of P on the country scale or larger can have limited informative value; large differences between P budgets exist within countries and are easily obscured by country-wide average values. To quantify and evaluate these imbalances we integrated a country-scale and regional-scale model of the Danish anthropogenic P flows and stocks. We examine three spatial regions with regard to agriculture, as the main driver for P use, and waste management, the crucial sector for P recovery. The regions are characterised by their differences in agricultural practice, population and industrial density. We show considerable variation in P flows within the country. First, these are driven by agriculture, with mineral fertiliser inputs varying between 3 and 5 kg ha−1 yr−1, and animal feedstuff inputs between 5 and 19 kg ha−1 yr−1. We identified surpluses especially in areas with a larger proportion of animal husbandry, owing to additional application of manure in excess of crop P demand. However, redistribution of the large amounts of P in manure is not feasible owing to transport limitations. Second, waste management, closely linked to population and industrial density is the driver behind differences in recoverable P flows. Current amounts of potentially recoverable P cannot change the reliance on primary P. The most immediate P re-use potential exists in the areas around the eastern urban agglomerations, from more complete recovery of sewage sludge (with unrecovered P amounts of up to 33% of P in current mineral fertiliser imports) and the biowaste fraction in municipal solid waste currently not collected separately (24% of P in current mineral fertiliser imports), since this region shows both the highest proportion of crop production and fertiliser use and lowest soil P budget.*	To assess anthropogenic P flows for Denmark, both at the scale of the entire country and its economy, and on a smaller, regional level.	Map / table / Sankey flow / stacked bar / grouped bar
27		Graedel, T. E.; Beers, D. v.; Bertram, M.; Fuse, K.; Gordon, R. B.; Gritsinin, A.; Kapur, A.; Klee, R. J.; Lifset, R. J.; Memon, L.; Rechberger, H.; Spatari, S.; Vexler, D. (2004) "Multilevel Cycle of Antropogenic Copper", Environmental Science & Technology, 38 (4), p. 1242-1252	T. E. Graedel, D. van Beers, M. Bertram, K. Fuse, R. B. Gordon, A. Gritsinin, A. Kapur, R. J. Klee, R. J. Lifset, L. Memon, H. Rechberger, S. Spatari, and D. Vexler	1994	*A comprehensive contemporary cycle for stocks and flows of copper is characterized and presented, incorporating information on extraction, processing, fabrication and manufacturing, use, discard, recycling, final disposal, and dissipation. The analysis is performed on an annual basis, ca. 1994, at three discrete governmental unit levels–56 countries or country groups that together comprise essentially all global anthropogenic copper stocks and flows, nine world regions, and the planet as a whole. Cycles for all of these are presented and discussed, and a "best estimate" global copper cycle is constructed to resolve aggregation discrepancies. Among the most interesting results are (1) transformation rates and recycling rates in apparently similar national economies differ by factors of two or more (country level); (2) the discard flows that have the greatest potential for copper recycling are those with low magnitude flows but high copper concentrationselectronics, electrical equipment, and vehicles (regional level); (3) worldwide, about 53% of the copper that was discarded in various forms was recovered and reused or recycled (global level); (4) the highest rate of transfer of discarded copper to repositories is into landfills, but the annual amount of copper deposited in mine tailings is nearly as high (global level); and (5) nearly 30% of copper mining occurred merely to replace copper that was discarded. The results provide a framework for similar studies of other anthropogenic resource cycles as well as a basis for supplementary studies in resource stocks, industrial resource utilization, waste management, industrial economics, and environmental impacts.*	Goal has been to attempt to capture at least 80% of the magnitude of each flow stream by evaluating countries which extract, fabricate, and/or use significant quantities of copper.	flow / Sankey Flow / map bar chart / 3d map bar chart / bar / lollipop
28		Bertram, M., Graedel, T.E., Fuse, K., Gordon, R., Lifset, R., Rechberger, R., and Spatari, S. The copper cycles of European countries. Regional Environmental Change, 2003, Vol. 3, 119-127.	M. Bertram, T. E. Graedel, K. Fuse, R. Gordon, R. Lifset, H. Rechberger, S. Spatari	1994	*A comprehensive technological copper cycle treating a series of life stages (mining and processing, fabrication, utilization, and end of life) has been constructed for sixteen countries on the European continent for the year 1994. In this paper we draw on that information to present country-level copper cycles for a sampling of the countries. We then compare the countries on the basis of their relative and absolute copper production, import/export, usage, recycling, and losses to the environment, and go on to produce per capita assessments of flow and stock changes. Among the results of particular interest are: (1) country-level copper budgets possess features often different from the continental budgets of which they are a part. For example, Europe extracted only slightly more copper from mines than it deposited in landfills, while the mine to landfill flow ratio was about 11:1 in Poland and near zero in the United Kingdom; (2) Germany led all other countries in the group of sixteen in the absolute magnitude of every major copper flow (production, import, export, consumption, and waste generation, and in per capita flows of copper entering use and waste management), while the Benelux countries led all others in per capita flows for all other categories; (3) citizens of essentially all the countries discarded 1–3 kg Cu/year, mostly in obsolete electronics and end-of-life vehicles.*	The goal was to capture at least 80% of relevant copper movement and use within continental Europe.	Flow / table / stacked bar / bar / pictoral flow

Entry No.	Preview Image	Publication	Author(s)	Core Dimensions: Stages	Trade	Linkages	Time	Uncertainty	Stocks	Retinal Variables: Colour	Shape	Orientation	Size	Texture	Value	Comments
24		Rechberger, H. and Graedel, T. E. (2002): The contemporary European copper cycle: statistical entropy analysis. Ecological Economics 42: 1–2 59-72.	H. Rechberger, T.E. Graedel	y		y			y		nominal (Uses shape to differentiate flows from stages)					Arrangement of in/out flows needs to be adjusted and made consistent.
25		Laner, D.; Rechberger, H.; Astrup, T. (2015) „Applying Fuzzy and Probabilistic Uncertainty Concepts to the Material Flow Analysis of Palladium in Austria“, Journal of Industrial Ecology, 19, 0, p. 1-15, ISSN 1088-1980. DOI: 10.1111/jiec.12235	David Laner, Helmut Rechberger, Thomas Astrup					y	y		nominal (uses shape to differentiate process / stage and flow in Sankey flow)		quantitative (uses size(width) in sankey)	nominal (Uses texture in line graph to differentiate categories)	nominal (uses value in sankeyflow to isolate and for focus on grouping)	In / out flows from each stage should be arranged and grouped appropriatey to one side of the process box in the sankey. More consitency required in overall sizes of sankey flows. Issues with alignment and arrangement. Texture in line graphs for nominal differentiation degrades the integrity of the data, in this context the trend line is strong enough to povide accurate detail for the shape of the data. Good use of consistent scales but could be simplified to reduce data ink ratio.
26		Klinglmair, M.; Lemming, C.; Jensen, L.S.; Rechberger, H.; Astrup, T.F., Scheutz, Ch. (2015) "Phosphorus in Denmark: National and regional anthropogenic flows", Resources, Conservation and Recycling, Vol. 96, p. 311-324, dx.doi.org/10.1016/j.resconrec.2015.09.019, ISSN 0921-3449	Manfred Klinglmair, Camilla Lemming, Lars Stoumann Jensen, Helmut Rechberger, Thomas Fruergaard Astrupa, Charlotte Scheutz	y	y			y	y		nominal (uses shape to differentiate process / stage and flow in Sankey flow)		quantitative(Uses size(width) in sankey)	nominal (Uses texture in stacked bar to differentiate categories)		In / out flows from each stage should be arranged and grouped appropriatey to one side of the process box in the sankey. More consitency required in overall sizes of sankey flows. Issues with alignment and arrangement. Value would have been a more effective variable for nominal data in the bar staked bar charts.
27		Graedel, T. E.; Beers, D. v.; Bertram, M.; Fuse, K.; Gordon, R. B.; Gritsinin, A.; Kapur, A.; Klee, R. J.; Lifset, R. J.; Memon, L.; Rechberger, H.; Spatari, S.; Vexler, D. (2004) "Multilevel Cycle of Antropogenic Copper", Environmental Science & Technology, 38 (4), p. 1242-1252	T. E. Graedel, D. van Beers, M. Bertram, K. Fuse, R. B. Gordon, A. Gritsinin, A. Kapur, R. J. Klee, R. J. Lifset, L. Memon, H. Rechberger, S. Spatari, and D. Vexler	y				y	y		nominal (uses shape to differentiate process / stage and flow in Sankey flow.)		quantitative (width in sankey, length in the bar map and bar chart, 3D bar map uses volume.	nominal (Uses texture in bar to differentiate categories)		In / out flows from each stage should be arranged and grouped appropriatey to one side of the process box in the sankey. More consitency required in overall sizes of sankey flows.
28		Bertram, M., Graedel, T.E., Fuse, K., Gordon, R., Lifset, R., Rechberger, R., and Spatari, S. The copper cycles of European countries. Regional Environmental Change, 2003, Vol. 3, 119-127.	M. Bertram, T. E. Graedel, K. Fuse, R. Gordon, R. Lifset, H. Rechberger, S. Spatari	y	y				y		nominal (uses shape to differentiate process / stage and flow in Sankey flow.)		quantitative (length in stacked bar)	nominal (Uses texture in bar to differentiate categories)		In / out flows from each stage should be arranged and grouped appropriatey to one side of the process box in the sankey. Some mnor alignment issues where more space is needed. Consistency in design. Poor use of texture to denote nominal differentiation creates a visually confusing and illegible design.

Entry No.	Source information						Type of diagram(s)
	Preview Image	*Publication*	*Author(s)*	*Date (source data)*	*Publication Summary*	*Purpose*	
29		Dominique Guyonnet, Mariane Planchon, Alain Rollat, Victoire Escalon, Johann Tuduri, et al..Material flow analysis applied to rare earth elements in Europe. Journal of Cleaner Production, Elsevier, 2015, 26 p.	Dominique Guyonnet, Mariane Planchon, Alain Rollat, Victoire Escalon, Johann Tuduri, Nicolas Charles, Stephane Vaxelaire, Didier Dubois, Helene Fargier	2012	*This paper explores flows and stocks, at the scale of the European Union, of certain rare earth elements (REEs; Pr, Nd, Eu, Tb, Dy and Y) which are associated with products that are important for the decarbonisation of the energy sector and that also have strong recycling potential. Material flow analyses were performed considering the various steps along the value chain (separation of rare earth oxides, manufacture of products, etc.) and including the lithosphere as a potential stock (potential geological resources). Results provide estimates of flows of rare earths into use, in-use stocks and waste streams. Flows into use of, e.g., Tb in fluorescent lamp phosphors, Nd and Dy in permanent magnets and Nd in battery applications were estimated, for selected reference year 2010, as 35, 1230, 230 and 120 tons respectively. The proposed Sankey diagrams illustrate the strong imbalance of flows of permanent magnet REEs along the value chain, with Europe relying largely on the import of finished products (magnets and applications). It is estimated that around 2020, the amounts of Tb in fluorescent lamps and Nd in permanent magnets recycled each year in Europe, could be on the order of 10 tons for Tb and between 170 and 230 tons for Nd.*	Mapping the rare earths flows and stock in the EU	Flow / table / grouped bar / Sankey Flow / pie
30		BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW.	Deloitte	2012	*Study on Data for a Raw Material System Analysis*	Mapping flows and stock in the EU of 21 materials (19 criticals from 2014 list + aggregates and lithium)	Flow / pie / Sankey
31		Cullen JM, Allwood JM (2010) The efficient use of energy: tracing the global flow of energy from fuel to service. Energy Policy, 38(1)75–81	Jonathan M. Cullen, Julian M. Allwood	2005	*The efficient use of energy is a key component of current efforts to reduce carbon emissions. There are two factors which are important when assessing the potential gains from energy efficiency technologies: the scale of energy flow and the technical potential for improvement. However, most efficiency analyses consider only the potential gains from known efficiency technologies, while ignoring the complex flow of energy through the chains of conversion devices. In response, this paper traces the global flow of energy, from fuels through to the final services, and focuses on the technical conversion devices and passive systems in each energy chain. By mapping the scale and complexity of global energy flow, the technical areas which are likely to deliver the largest efficiency gains can be identified. The result is a more consistent basis for directing future research and policy decisions in the area of energy efficiency.*	Energy planning an decision making. Tracing energy flows from fuels through to final services.	Sankey
32		Cullen JM, Allwood JM (2010) Theoretical efficiency limits for energy conversion devices. Energy, 35(5)2059–2069	Jonathan M. Cullen, Julian M. Allwood	2005	*Using energy more efficiently is a key strategy for reducing global carbon dioxide emissions. Due to limitations on time and resources, actions must be focused on the efficiency measures which will deliver the largest gains. Current surveys of energy efficiency measures assess only known technology options developed in response to current economic and technical drivers. However, this ignores opportunities to deliver long-term efficiency gains from yet to be discovered options. In response, this paper aims to calculate the absolute potential for reducing energy demand by improving efficiency, by finding the efficiency limits for individual conversion devices and overlaying these onto the global network of energy flow. The potential efficiency gains for each conversion device are found by contrasting current energy demand with theoretical minimum energy requirements. Further insight is gained by categorising conversion losses according to the underlying loss mechanisms. The result estimates the overall efficiency of global energy conversion to be only 11 per cent; global demand for energy could be reduced by almost 90 per cent if all energy conversion devices were operated at their theoretical maximum efficiency.*	Energy planning an decision making. Analysing energy conversion efficiencies at the global level.	Sankey
33		Cullen JM, Allwood JM, Bambach MD (2013) Mapping the global flow of steel: from steelmaking to end-use goods. Environmental Science and Technology, 46(24)13048–55	Jonathan M. Cullen, Julian M. Allwood, Margarita D. Bambach	2008	*Our society is addicted to steel. Global demand for steel has risen to 1.4 billion tonnes a year and is set to at least double by 2050, while the steel industry generates nearly a 10th of the world's energy related CO2 emissions. Meeting our 2050 climate change targets would require a 75% reduction in CO2 emissions for every tonne of steel produced and finding credible solutions is proving a challenge. The starting point for understanding the environmental impacts of steel production is to accurately map the global steel supply chain and identify the biggest steel flows where actions can be directed to deliver the largest impact. In this paper we present a map of global steel, which for the first time traces steel flows from steelmaking, through casting, forming, and rolling, to the fabrication of final goods. The diagram reveals the relative scale of steel flows and shows where efforts to improve energy and material efficiency should be focused.*	Mapping the steel system, including iron/steel flows, recycling, products	Sankey
34		Cullen JM, Allwood JM (2013) Mapping the global flow of aluminum: from liquid aluminum to end-use goods. Environmental Science and Technology, 47(7)3057–64	Jonathan M. Cullen, Julian M. Allwood	2007	*Demand for aluminum in final products has increased 30-fold since 1950 to 45 million tonnes per year, with forecasts predicting this exceptional growth to continue so that demand will reach 2–3 times today's levels by 2050. Aluminum production uses 3.5% of global electricity and causes 1% of global CO2 emissions, while meeting a 50% cut in emissions by 2050 against growing demand would require at least a 75% reduction in CO2 emissions per tonne of aluminum produced—a challenging prospect. In this paper we trace the global flows of aluminum from liquid metal to final products, revealing for the first time a complete map of the aluminum system and providing a basis for future study of the emissions abatement potential of material efficiency. The resulting Sankey diagram also draws attention to two key issues. First, around half of all liquid aluminum (~39 Mt) produced each year never reaches a final product, and a detailed discussion of these high yield losses shows significant opportunities for improvement. Second, aluminum recycling, which avoids the high energy costs and emissions of electrolysis, requires signification "dilution" (~ 8 Mt) and "cascade" (~ 6 Mt) flows of higher aluminum grades to make up for the shortfall in scrap supply and to obtain the desired alloy mix, increasing the energy required for recycling.*	Mapping the aluminium system, including aluminium, scrap and product flows	Sankey
35		Bajzelj B, Allwood JM, Cullen JM (2013) Designing climate change mitigation plans that add up. Environmental Science and Technology, 47(14) 8062–9	Bojana Bajželj, Julian M. Allwood, and Jonathan M. Cullen	2010	*Mitigation plans to combat climate change depend on the combined implementation of many abatement options, but the options interact. Published anthropogenic emissions inventories are disaggregated by gas, sector, country, or final energy form. This allows the assessment of novel energy supply options, but is insufficient for understanding how options for efficiency and demand reduction interact. A consistent framework for understanding the drivers of emissions is therefore developed, with a set of seven complete inventories reflecting all technical options for mitigation connected through lossless allocation matrices. The required data set is compiled and calculated from a wide range of industry, government, and academic reports. The framework is used to create a global Sankey diagram to relate human demand for services to anthropogenic emissions. The application of this framework is demonstrated through a prediction of per-capita emissions based on service demand in different countries, and through an example showing how the "technical potentials" of a set of separate mitigation options should be combined.*	Mapping the global green house gas emissions, and allocation to human activity	Flow / Sankey / stacked bar
36		Talens, L; Villalba G., (2013) Material and energy requirement for extraction and refining of Rare Earth Metals. The Journal of The Minerals, Metals & Materials Society. 65 (10) 1327-1340 DOI: 10.1007/s11837-013-0719-8.	Laura Talens Peiró, Gara Villalba Méndez		*The use of rare earth metals (REMs) for new applications in renewable and communication technologies has increased concern about future supply as well as environmental burdens associated with the extraction, use, and disposal (losses) of these metals. Although there are several reports describing and quantifying the production and use of REM, there is still a lack of quantitative data about the material and energy requirements for their extraction and refining. Such information remains difficult to acquire as China is still supplying over 95% of the world REM supply. This article attempts to estimate the material and energy requirements for the production of REM based on the theoretical chemical reactions and thermodynamics. The results show the material and energy requirement varies greatly depending on the type of mineral ore, production facility, and beneficiation process selected. They also show that the greatest loss occurs during mining (25–50%) and beneficiation (10–30%) of RE minerals. We hope that the material and energy balances presented in this article will be of use in life cycle analysis, resource accounting, and other industrial ecology tools used to quantify the environmental consequences of meeting REM demand for new technology products.*	To estimate the material and energy requirements for the production based on the theoretical chemical reactions and thermodynamics.	Tables / flow

Entry No.	Preview Image	Publication	Author(s)	Core Dimensions: Stages	Trade	Linkages	Time	Uncertainty	Stocks	Retinal Variables: Colour	Shape	Orientation	Size	Texture	Value	Comments
29		Dominique Guyonnet, Mariane Planchon, Alain Rollat, Victoire Escalon, Johann Tuduri, et al..Material flow analysis applied to rare earth elements in Europe. Journal of Cleaner Production, Elsevier, 2015, 26 p.	Dominique Guyonnet, Mariane Planchon, Alain Rollat, Victoire Escalon, Johann Tuduri, Nicolas Charles, Stephane Vaxelaire, Didier Dubois, Helene Fargier	y		y		y	y		nominal (uses shape to differentiate process / stage and flow in Sankey flow.)		quantitative (width in sankeys, length in grouped bar, area in pie chart.		nominal (Uses value to differentiate qualitative groupings)	In / out flows from each stage should be arranged and grouped appropriatey to one side of the process box in the sankey. Some mnor alignment issues where more space is needed. Consistency in design.
30		BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW.	Deloitte	y	y	y			y	nominal (category clasification)			quantitative data (width of flows in sankey, area in pie charts)			Bar charts would be more effective in place of the pie charts. In most cases have good internal alignment with a few exceptions There is a consistency to the presentation Not all sankey diagrams end up as the same size.
31		Cullen JM, Allwood JM (2010) The efficient use of energy: tracing the global flow of energy from fuel to service. Energy Policy, 38(1)75–81	Jonathan M. Cullen, Julian M. Allwood	y						nominal (category clasification)			quantitative data (width of flows in sankey, size of bubbles on sankey)			Colour in sankey diagram has very mixed saliency with some flows given more prominance due to colour choice. Overall the diagram appears very heavy and cluttered making visual clarity difficult.
32		Cullen JM, Allwood JM (2010) Theoretical efficiency limits for energy conversion devices. Energy, 35(5)2059–2069	Jonathan M. Cullen, Julian M. Allwood	y						nominal (category clasification)			quantitative data (width of flows in sankey, size of bubbles on sankey)			Colour in sankey diagram has very mixed saliency with some flows given more prominance due to colour choice. For example high saliency on the coal flow focuses too much attention.
33		Cullen JM, Allwood JM, Bambach MD (2013) Mapping the global flow of steel: from steelmaking to end-use goods. Environmental Science and Technology, 46(24)13048–55	Jonathan M. Cullen, Julian M. Allwood, Margarita D. Bambach	y						nominal (category clasification)			quantitative data (width of flows in sankey)			Use of colour hue to sub categorise data. Good use of colour to provide even saliency across the design. Alignment of values to flow needs to be adjusted.
34		Cullen JM, Allwood JM (2013) Mapping the global flow of aluminum: from liquid aluminum to end-use goods. Environmental Science and Technology, 47(7)3057–64	Jonathan M. Cullen, Julian M. Allwood	y						nominal (category clasification)			quantitative data (width of flows in sankey)			Good use of colour to provide even saliency across the design. Alignment of values to flow needs to be adjusted. Clear use of labelling on line chart to remove the need for a key.
35		Bajzelj B, Allwood JM, Cullen JM (2013) Designing climate change mitigation plans that add up. Environmental Science and Technology, 47(14) 8062–9	Bojana Bajželj, Julian M. Allwood, and Jonathan M. Cullen	y				y		nominal (category clasification)			quantitative data (width of flows in sankey and parallel sets, length in stacked bar charts)			Very salient colour scheme used in the sankey diagram far too many colours used, alignment and text need to be more consistent
36		Talens, L; Villalba G., (2013) Material and energy requirement for extraction and refining of Rare Earth Metals. The Journal of The Minerals, Metals & Materials Society. 65 (10) 1327-1340 DOI: 10.1007/s11837-013-0719-8.	Laura Talens Peiró, Gara Villalba Méndez													Only tables used in diagram for presentation of analysis. Would benefit from consitency in alignment and justification

Entry No.	Source information Preview Image	Publication	Author(s)	Date (source data)	Publication Summary	Purpose	Type of diagram(s)
37		Rademaker, J.; Klejn, R.; Yang, Y. (2013) Recycling as a Strategy against Rare Earth Element Criticality: A Systemic Evaluation of the Potential Yield of NdFeB Magnet Recycling. Environmental Science and Technology, 47, 10129–10136 DOI: 10.1021/es305007w	Jelle H. Rademaker, René Kleijn, and Yongxiang Yang	2011 - 2030	*End-of-life recycling is promoted by OECD countries as a promising strategy in the current global supply crisis surrounding rare earth elements (REEs) so that dependence on China, the dominant supplier, can be decreased. So far the feasibility and potential yield of REE recycling has not been systematically evaluated. This paper estimates the annual waste flows of neodymium and dysprosium from permanent magnets, the main deployment of these critical REEs, during the 2011–2030 period. The estimates focus on three key permanent magnet waste flows: wind turbines, hybrid and electric vehicles, and hard disk drives (HDDs) in personal computers (PCs). This is a good indication of the end-of-life recycling of neodymium and dysprosium maximum potential yield. Results show that for some time to come, waste flows from permanent magnets will remain small relative to the rapidly growing global REE demand. Policymakers therefore need to be aware that during the next decade recycling is unlikely to substantially contribute to global REE supply security. In the long term, waste flows will increase sharply and will meet a substantial part of the total demand for these metals. Future REE recycling efforts should, therefore, focus on the development of recycling technology and infrastructure.*	Future demand and supply (virgin and secondary)	Tables / flow / stacked bar with line / stacked bar
38		Habib, K.; Wenzel, H. (2014) Exploring rare earths supply constraints for the emerging clean energy technologies and the role of recycling. Journal of Cleaner Production, 84 (2014) 348-359 DOI: 10.1016/j.jclepro.2014.04.035	Komal Habib, Henrik Wenzel	2007 - 2050	*The dependency on critical resources like Rare Earth Elements (REEs) has been pronounced as a potential barrier to a wider implementation of emerging renewable energy technologies. This study explores the dependency of such technologies especially wind turbines and electric vehicles along with other background end-uses on two key REEs, i.e. neodymium (Nd) and dysprosium (Dy). Our study reveals that a Business As Usual Development (BAUD) projected primary supply is unable to meet the forecasted demand of Nd and Dy in all the four modelled demand scenarios by 2050. This means that a highly accelerated rate of Nd and Dy mining is unavoidable in order to keep up with the pace of increasing demand from new technologies required in a renewable energy strategy for meeting the climate change challenge. Recycling does not seem to be in a position to close the wide gap between future demand and supply by 2050 mainly due to the long lifetime of key end-use products. However, in the long term, i.e. by 2100, secondary supply from recycling can meet almost 50% of the demand. Moreover, recycling, is found to play major role in reducing the geopolitical aspects of supply risk due to diversification of geographical distribution of supply by 2100. The study suggests that China is very likely to play its dominant role for Dy primary supply in the short-to-medium term future, as 72% of the geological reserves of Dy are in China. Our study indicates that considering the historically proven developments in metal reserve estimates as being analogous for REEs, geological reserves of Nd and Dy will not deplete for many hundred years ahead. Opening of new mines at an accelerated pace remains a supply bottleneck issue in the short-to-medium term future until recycling provides significant secondary supply to reduce the future demand.*	Future demand and supply (virgin and secondary). Reserves depletion with/without recycling until 2100.	Pie / Line / stacked bar with stacked area
39		https://www.carbonbrief.org/mapped-the-global-coal-trade	Rosamund Pearce, Simon Evans	2014	The global coal trade doubled in the decade to 2012 as a coal-fueled boom took hold in Asia. Now, the coal trade seems to have stalled, or even gone into reverse. This change of fortune has devastated the coal mining industry, with Peabody – the world's largest private coal-mining company – the latest of 50 US firms to file for bankruptcy. It could also be a turning point for the climate, with the continued burning of coal the biggest difference between business-as-usual emissions and avoiding dangerous climate change.		Sankey, stacked area, bar, grouped bar, stacked bar, stacked bar with line, parallel sets.
40		https://www.iea.org/Sankey/	International Energy Agency	1973 - 2015	*World energy balance*		Sankey / line / pie
41		http://ec.europa.eu/eurostat/cache/sankey/sankey.html?geo=EU28&year=2014&unit=KTOE&fuels=0000&highlight=&nodeDisagg=0101000000&flowDisagg=true	Eurostat	1990 -2015	*Energy Balance for European Union*		Sankey / line / pie
42		The International Aluminium Institute. (2008). Aluminium for Future Generations. Retrieved from http://www.world-aluminium.org/media/filer_public/2013/01/15/fl0000286.pdf	The International Aluminium Institute	Focus 2007 in context of 1950 - 2030 process	The Aluminium for Future Generations initiative is a programme of continuous improvement on the part of the global aluminium industry, overseen by the International Aluminium Institute (IAI). It comprises voluntary objectives for improvements in the sector's social, economic and environmental performance all across the key phases of aluminium's life cycle. There are currently thirteen voluntary objectives, agreed by the IAI's Board of Directors – chief executives of the Institute's twenty three member companies – and the number is increasing year by year. The industry's performance is measured annually against quantitative performance indicators. This update reports on the survey results for 2007 performance of IAI member companies, which are collectively responsible for up to 80% of global primary aluminium production and around 20% of recycled metal production. For further information on IAI members and activities visit www.world- aluminium.org.		scatter plot / line / Bubble flow
43		Lee, B., Preston, F., Kooroshy, J., Bailey, R., & Lahn, G. (2012). Resources Futures, 249. Retrieved from https://www.chathamhouse.org/sites/files/chathamhouse/public/Research/Energy, Environment and Development/1212r_resourcesfutures.pdf	Lee, Bernice Preston, Felix Kooroshy, Jaakko Bailey, Rob Lahn, Glada		*The spectre of resource insecurity has come back with a vengeance. The world is undergoing a period of intensified resource stress, driven in part by the scale and speed of demand growth from emerging economies and a decade of tight commodity markets. Poorly designed and short-sighted policies are also making things worse, not better. Whether or not resources are actually running out, the outlook is one of supply disruptions, volatile prices, accelerated environmental degradation and rising political tensions over resource access. Fears of resource scarcity are not new. On many occasions, higher rates of investment and improved technology have resolved the problem of the day, though often with additional environmental and social costs. With the maturation of technologies to access non-conventional gas and oil, as well as the global economic downturn, some analysts suggest that the resource boom of the past decade is coming to an end – especially in the extractive industries – and that resource-related tensions will ease.*		Stacked area / Flow Map / Line / Table / Grouped Bar / Stacked Bar / Butterfly / Span / Scatter / Choropleth / BubbleMap with Choropleth / Donut / Candlestick / Area

Entry No.				Core Dimensions						Retinal Variables						
	Preview Image	*Publication*	*Author(s)*	*Stages*	*Trade*	*Linkages*	*Time*	*Uncertainty*	*Stocks*	*Colour*	*Shape*	*Orientation*	*Size*	*Texture*	*Value*	*Comments*
37		Rademaker, J.; Klejn, R.; Yang, Y. (2013) Recycling as a Strategy against Rare Earth Element Criticality: A Systemic Evaluation of the Potential Yield of NdFeB Magnet Recycling. Environmental Science and Technology, 47, 10129−10136 DOI: 10.1021/es305007w	Jelle H. Rademaker, René Kleijn, and Yongxiang Yang	y			y		y	nominal (category clasification)			quantitative data (length in stacked bar)			Inconsistent chart design, uneccessary use of gradients. This means length of bar is changed and infers an uncertaintity to the data. Too many tick marks. Similar colours used on stacked bar with line to make accurate differentiation. Scales are inconsistent.
38		Habib, K.; Wenzel, H. (2014) Exploring rare earths supply constraints for the emerging clean energy technologies and the role of recycling. Journal of Cleaner Production, 84 (2014) 348-359 DOI: 10.1016/j.jclepro.2014.04.035	Komal Habib, Henrik Wenzel				y			nominal and ordinal (category clasification)			quantitative data (area in pie chart and stacked area, length in stacked bar)			Colour schemes are very salient. Charts have too much data ink, pie charts convery little information and would be better suited to a bar chart. Inconsistent labelling.
39		https://www.carbonbrief.org/mapped-the-global-coal-trade	Rosamund Pearce, Simon Evans		y		y			ordinal (grouped bar chart) nominal (all other cases)			quantitative data (width of flows in sankey and parallel sets, length in stacked bar charts, area in stacked area)			Good use of interactivity to provide more detail, i.e. specific figures on parallel sets and bar charts. Done via the use of callout. Design is simple and clean, although could be improved on the parallel sets diargams as they use a heavy background, asthetic choice
40		https://www.iea.org/Sankey/	International Energy Agency	y			y		y	nominal (category clasification)			quantitative data (width of flows in sankey, are in pie chart)			Highly customisable, editable colour palette (rainbow rather than custom schemas), time series graph does not keep consistent intervals. Alignment issues on nodes. Fine tuning and overall alignment is difficult in editor mode.
41		http://ec.europa.eu/eurostat/cache/sankey/sankey.html?geo=EU28&year=2014&unit=KTOE&fuels=0000&highlight=&nodeDisagg=0101000000&flowDisagg=true	Eurostat	y		y	y		y	nominal (category clasification)			quantitative data (width of flows in sankey, are in pie chart)			Unbalanced colour palette which gives high saliency to flows. Interactivity in diagram provides useful exploration of the data to gain further insight. Change over time is shown by generating new sanleys and line charts for node specific changes. Use of highlight provides focus.
42		The International Aluminium Institute. (2008). Aluminium for Future Generations. Retrieved from http://www.world-aluminium.org/media/filer_public/2013/01/15/fl0000286.pdf	The International Aluminium Institute	y	y		y		y	nominal data (target vs actual)	nominal data			nominal data on line graph		Consitecy in colour. However scales are unclear and are too prominent in the charts. Uses size in correctly in line graph to convey unnecescary nominal differentiation.
43		Lee, B., Preston, F., Kooroshy, J., Bailey, R., & Lahn, G. (2012). Resources Futures, 249. Retrieved from https://www.chathamhouse.org/sites/files/chathamhouse/public/Research/Energy, Environment and Development/1212r_resourcesfutures.pdf	Lee, Bernice Preston, Felix Kooroshy, Jaakko Bailey, Rob Lahn, Glada		y		y		y	nominal and ordinal data			quantitative continous (width of flows in sankey, area in stacked area, size of bubble in bubble choropleth map, size of slice in donut,)	Nominal data (used in conjunction with colour on bar with line graph)		Good level of consitency in appearance, type colour and sizes. Poor decisions of charts in places. Specifically the use of a Sankey to demonstrate the chanages in flows as saliency of colours hinders differentiation and sizes are too small to notice. A grouped bar chart would have been far more beneficial.

Entry No.	Source information						Type of diagram(s)
	Preview Image	Publication	Author(s)	Date (source data)	Publication Summary	Purpose	
44		Ciacci, L., Vassura, I., & Passarini, F. (2017). Urban Mines of Copper: Size and Potential for Recycling in the EU. *Resources* , *6* (1), 6. https://doi.org/10.3390/resources6010006	Ciacci, Luca Vassura, Ivano Passarini, Fabrizio	1960-2014	Copper is among the most important metals by production volume and variety of applications, providing essential materials and goods for human wellbeing. Compared to other world regions, Europe has modest natural reserves of copper and is highly dependent on imports to meet the domestic demand. Securing access to raw materials is of strategic relevance for Europe and the recycling of urban mines (also named "in-use stock") is a significant mean to provide forms of secondary copper to the European industry. A dynamic material flow analysis model is applied to characterize the flows of copper in the European Union (EU-28) from 1960 to 2014 and to determine the accumulation of this metal in the in-use stock. A scrap balance approach is applied to reconcile the flow of secondary copper sent to domestic recycling estimated through the model and that reported by historic statistics. The results show that per capita in-use stock amounts at 160–200 kg/person, and that current end-of-life recycling rate is around 60%. The quantification of historic flows provides a measure of how the European copper cycle has changed over time and how it may evolve in the future: major hindrances to recycling are highlighted and perspectives for improving the current practices at end-of-life are discussed.		Sankey / line / stacked area /
45		http://www.world-aluminium.org/statistics/massflow/	The International Aluminium Institute	1962 - 2030	*Map of the global alluminuim cycle with forecasting until 2030 with mutliple scenarios.*		Sankey
46		Lupton, R. C., & Allwood, J. M. (2017). Incremental Material Flow Analysis with Bayesian Inference, *0* (0). https://doi.org/10.1111/jiec.12698	Richard C. Lupton & Julian M. Allwood	2008	Material flow analysis (MFA) is widely used to study the life cycles of materials from production, through use, to reuse, recycling, or disposal, in order to identify environmental impacts and opportunities to address them. However, development of this type of analysis is often constrained by limited data, which may be uncertain, contradictory, missing, or over-aggregated. This article proposes a Bayesian approach, in which uncertain knowledge about material flows is described by probability distributions. If little data is initially available, the model predictions will be rather vague. As new data is acquired, it is systematically incorporated to reduce the level of uncertainty. After reviewing previous approaches to uncertainty in MFA, the Bayesian approach is introduced, and a general recipe for its application to material flow analysis is developed. This is applied to map the global production of steel using Markov Chain Monte Carlo simulations. As well as aiding the analyst, who can get started in the face of incomplete data, this incremental approach to MFA also supports efforts to improve communication of results by transparently accounting for uncertainty throughout.	Modelling Uncertainty within MFA and developing a Bayesian approach and tested	Sankey
47		Haas, W., Krausmann, F., Wiedenhofer, D., & Heinz, M. (2015). How circular is the global economy?: An assessment of material flows, waste production, and recycling in the European union and the world in 2005. *Journal of Industrial Ecology* , *19* (5), 765–777. https://doi.org/10.1111/jiec.12244	Willi Haas, Fridolin Krausmann, DominikWiedenhofer, and Markus Heinz	2005	It is increasingly recognized that the growing metabolism of society is approaching limitations both with respect to sources for resource inputs and sinks for waste and emission outflows. The circular economy {(CE)} is a simple, but convincing, strategy, which aims at reducing both input of virgin materials and output of wastes by closing economic and ecological loops of resource flows. This article applies a sociometabolic approach to assess the circularity of global material flows. All societal material flows globally and in the European Union {(EU-27)} are traced from extraction to disposal and presented for main material groups for 2005. Our estimate shows that while globally roughly 4 gigatonnes per year {(Gt/yr)} of waste materials are recycled, this flow is of moderate size compared to {62~Gt/yr} of processed materials and outputs of {41~Gt/yr.} The low degree of circularity has two main reasons: First, 44% of processed materials are used to provide energy and are thus not available for recycling. Second, socioeconomic stocks are still growing at a high rate with net additions to stocks of {17~Gt/yr.} Despite having considerably higher end-of-life recycling rates in the {EU,} the overall degree of circularity is low for similar reasons. Our results indicate that strategies targeting the output side (end of pipe) are limited given present proportions of flows, whereas a shift to renewable energy, a significant reduction of societal stock growth, and decisive eco-design are required to advance toward a {CE.}	An Assessment of Material Flows,Waste Production, and Recycling in the European Union and theWorld in 2005	table / flow / sankey / pie
48		Levi, P. G., & Cullen, J. M. (2018). Mapping global flows of chemicals : from fossil fuel feedstocks to chemical products. *Enivromental Science & Technology* https://doi.org/10.1021/acs.est.7b04573	Peter G. Levi and Jonathan M. Cullen	2013	Chemical products are ubiquitous in modern society. The chemical sector is the largest industrial energy consumer and the third largest industrial emitter of carbon dioxide. The current portfolio of mitigation options for the chemical sector emphasises upstream 'supply-side' solutions, whilst downstream mitigation options, such as material efficiency, are given comparatively short shrift. Key reasons for this are the scarcity of data on the sector's material flows, and the highly intertwined nature of its complex supply chains. We provide the most up to date, comprehensive and transparent dataset available publicly, on virgin production routes in the chemical sector: from fossil fuel feedstocks to chemical products. We map global mass flows for the year 2013 through a complex network of transformation processes, and by taking account of secondary reactants and by-products, we maintain a full mass balance throughout. The resulting dataset partially addresses the dearth of publicly available information on the chemical sector's supply chain, and can be used to prioritise downstream mitigation options.		sankey / bar

Entry No.	Preview Image	Publication	Author(s)	Core Dimensions: Stages	Trade	Linkages	Time	Uncertainty	Stocks	Retinal Variables: Colour	Shape	Orientation	Size	Texture	Value	Comments
44		Ciacci, L., Vassura, I., & Passarini, F. (2017). Urban Mines of Copper: Size and Potential for Recycling in the EU. *Resources*, *6* (1), 6. https://doi.org/10.3390/resources6010006	Ciacci, Luca Vassura, Ivano Passarini, Fabrizio	y	y		y		y	Nominal data			quantitative data (width of flows in sankey, area in stacked area)			No consitency between tick marks and scales used. Colour schemes in line graph does not provide enough differentiation. Colour Key is within the area of the chart. Could just as have each item labelled and reduce ink usage.
45		http://www.world-aluminium.org/statistics/massflow/	The International Aluminium Institute	y	y		y		y	nominal data (can be altered between nominal lists as to the use of colour and what it represents)			quantitative data (width of flows in sankey)			Interactivity proviedes exploration of the data nodes. On interaction detailed meta data in call out boxes provides further informaition on the flows and the nodes. Interactivity also allows for customisation of the saknkey and aggregation of flows.
46		Lupton, R. C., & Allwood, J. M. (2017). Incremental Material Flow Analysis with Bayesian Inference, *0* (0). https://doi.org/10.1111/jiec.12698	Richard C. Lupton & Julian M. Allwood	y				y		quantitative (used to show uncertainty in flows.)			quantitative data (width of flows in sankey)			Uses colour to group with sub types following hues of the parent colour. In some areas the text is occluded due to the size and density placed behind the text. Colours have more balanced saliency and work well together to provide differentiation but is not immedaiteley obvious without readinf supporting text.
47		Haas, W., Krausmann, F., Wiedenhofer, D., & Heinz, M. (2015). How circular is the global economy?: An assessment of material flows, waste production, and recycling in the European union and the world in 2005. *Journal of Industrial Ecology*, *19* (5), 765–777. https://doi.org/10.1111/jiec.12244	Willi Haas, Fridolin Krausmann, DominikWiedenhofer, and Markus Heinz	y					y	nominal (groupings)			quantitative data (width of flows in sankey, area in pie chart)			Labelling only shows totals at node marks and not individual flows so no accurate coment can be made on the proportions of each flow and comparions drawn. Scales on the two sankeys are different which is not imediatley obvious could lead to misinterpetting the flows.
48		Levi, P. G., & Cullen, J. M. (2018). Mapping global flows of chemicals : from fossil fuel feedstocks to chemical products. *Enivromental Science & Technology* https://doi.org/10.1021/acs.est.7b04573	Peter G. Levi and Jonathan M. Cullen	y						nominal (uses gradients, similarities/groupings)			quantitative data (width of flows in sankey, length in bar chart)		nominal (groupings)	Uses colour to group with sub types following hues of the parent colour. In some areas the text is occluded due to the size and density placed behind the text. Colours have more balanced saliency and work well together to provide differentiation but is not immedaiteley obvious