Deliverable D4.1

Factsheets of Methods for Raw Materials Intelligence

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Notice

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PURPOSE

Deliverable 4.1 contains a description of methods that are important for answering stakeholder questions with regard to raw materials.

EXECUTIVE SUMMARY

Not only data, but also methods are important to provide stakeholders with relevant information on raw materials. Methods help to put data in a certain context. Based on the stakeholder inventory of the MICA project, we can conclude that information is required on a sustainable supply of resources and raw materials, including both the present and future availability of raw materials and the economic, environmental and social consequences of their extraction, production, use and waste management. This asks for methods that operate throughout the life cycle in addition to more confined methods. It also asks for methods in different disciplines, or rather trans-disciplinary fields.

We have identified the need for methodological fact sheets in four categories:

1. Methods to identify and assess geological and anthropogenic (urban) stocks
2. Methods to assess society's metabolism and its environmental impacts
3. Methods to assess the economic aspects of the use of resources
4. Methods to estimate or assess the future use of resources.

These factsheets are input for the Raw Materials Intelligence system as developed in WP6 of the MICA project. In D4.1, we provide fact sheets for the first three categories. The fourth category is the subject of WP5 and is reported there.

DELIVERABLE REPORT

1. Introduction

Raw materials supply the physical basis of our society. They are essential for the wellbeing and prosperity of our society. Resource and raw materials policies aim at continuing to supply society with sufficient resources, and to do so in a sustainable manner. This requires the effort of all stakeholders involved: the producers of raw materials, the manufacturers of products, the providers of services, the consumers and the managers of the waste that is generated at the end of the materials' life cycle.

For the effort of stakeholders to be fruitful, information is needed. The aim of the MICA project is to provide such an information base. MICA builds on a number of projects and initiatives. These projects concentrate mainly on data and databases on raw materials. While these data form the core of an information system, it is not sufficient information. For a continued, sustainable resource supply the data need to be put in context and related to different types of information in order to be relevant. Different methods exist to make this connection in various directions: the (future) availability of raw materials, but also the economic, environmental and social aspects of our extraction, production and use of raw materials. MICA provides extra intelligence compared to other projects among others by including methods for raw materials intelligence in the information system, next to data.

Deliverable 4.1 contains fact sheets of methods that provide essential information in answering stakeholder questions along the supply chain. In Chapter 2, the choice for methods to include is justified and a list is provided of the relevant methods. Chapter 3 contains the fact sheets themselves.

2. Selection of methods to include in D4.1

In an interactive process within the MICA project, we have identified four classes of methods that are important for putting data on raw materials in context:

1. Methods to identify and assess geological and anthropogenic (urban) stocks
2. Methods to assess society's metabolism and its environmental impacts
3. Methods to assess the economic aspects of the use of resources
4. Methods to estimate or assess the future use of resources.

Ad 1. The relevance of methods to identify and assess stocks is obvious, and essential for questions related to the present and future availability of resources. In the MICA project, sources of secondary materials are considered as important as sources of primary materials and are therefore included explicitly. For stocks of primary materials, we rely on the well-established geological estimation methods. To some extent, such methods may also be relevant for secondary stocks. This could be the case for stocks on landfill sites, or underground hibernating stocks in for example pipes and cables. The assessment of urban stocks is a relatively new activity. Mainly the methods can be classified in two categories: the one is an inventory of stocks-in-use, the second is the use of dynamic Material Flow Analysis. Inventories are usually made by assessing amounts of relevant products and materials in use (buildings, infrastructure, electronics) and adding to that information on the content of the relevant materials. Such studies happen mostly at the level of cities and can be linked to municipal statistics. MFA is used in a number of studies to picture the urban metabolism, but these studies focus mostly on flows, ignoring the stocks. Dynamic MFA provides a picture of stock developments over time, if time series have been collected for a sufficiently long period. Such studies also exist at city level, but also at the national or even global level. MFA is a very versatile method, a core method for raw materials intelligence. It is really a method of the second category (society's metabolism) but can also be used in category 4, to estimate future demand and supply.

Ad 2. Methods to describe society's metabolism and the consequent environmental impacts can be taken from the realm of industrial ecology. These methods usually consider larger parts of the life cycle of the raw materials, allowing for insights that may improve resource management. They include Material Flow Accounting, a method that describes the metabolism of national economies in terms of mass and is considered to be the physical counterpart of GDP. Material Flow Analysis, already introduced under item 1., is also a tool of the second category, describing society's metabolism in terms of single materials or substances, having a narrow focus but allowing for much more detail in the description of flows, allowing to model stocks dynamics, and allowing to include environmental flows and stocks as well as those in society. Risk assessment is a well-known method that links local processes to environmental and health risks. It can be used to assess plants or locally defined operations. In contrast, Life Cycle Assessment is a method that assesses environmental impacts throughout the life cycle, at the micro-level of a single product or service. This method, though lacking in location specific risks, is essential for providing information throughout the supply chain. Presently LCA is put in the wider framework of Life Cycle Sustainability Analysis, among others aiming at upscaling the analysis to cover larger parts of society while keeping the life cycle perspective. Footprinting can be seen as a variant of LCA.

Environmentally extended Input Output Analysis is, like Material Flow Accounting, a method operating at the level of national economies. It provides information of exchanges between sectors of the economy in monetary terms, but adds environmental extensions describing emissions to or extractions from the environment. The strong point of this method is the possibility to specify the supply chains at the national or even global level. At the same time, we should not expect any detailed information on resource flows to be correct.

Ad 3. Economic aspects are very important as drivers for raw materials extraction. Market prices and the developments therein provide important information for investing in new mines. While it appears from trend information that for the major metals, the production has grown enormously at relatively constant prices, this is not true for minor metals and especially co- and by-product metals. Here, an increased demand but also an increased supply can cause prices to fluctuate wildly. For secondary production price developments are even more relevant and determine whether or not recycling activities even happen or not. For decisions of companies and investors, market price information is essential as a part of economic assessment methods such as cost benefit analysis, describing the economic sensibility of specific endeavors, and life cycle costing, specifying the costs over the life cycle as a mirror of the LCA environmental assessment.

While these methods have their relevance at the micro-level of individual decisions of companies and investors, there are also methods that have their relevance at the macro-level of sectors, national or even global economies. Econometric and General Equilibrium models can be used to assess relevant economic events at the macro-level. These models to some extent can also be used to explore the future and provide forecasts that include economic mechanisms and feedback loops. While the relevance for resource use in general is apparent, these models usually are not very relevant for resources used in small quantities, such as minor and specialty metals. Also at the larger scale there is Input Output Analysis. The Environmentally Extended variant is included under the methods in section 2, but IOA is basically an economic method that is relevant for describing intersectoral exchanges. Sometimes, CGE methods have an input output model at their core, often one with a low granularity.

A specific method in this section is criticality assessment. This relatively new method is not yet mature – several approaches exist that are converging but have not yet reached a standard. It is however very relevant, especially for minor and specialty metals. Although the approaches usually do not contain monetary information, but rather geological, geopolitical and technical information. Yet the relevance is of an economic nature and aims at protecting supply of essential materials with complications in the availability area. Therefore criticality assessment is included in the methods of section 3.

Ad 4. The last category consists of forward looking methods. Forward looking methods somehow say something about the future. They often do so using scenarios. Scenario analysis can be used to visualize futures. This can be qualitative – developing storylines of potential futures that can be used for imagining what might happen – but it can also be quantitative, involving modeling of some kind. It can be used at all kinds of scale levels: companies, sectors, municipalities, and national and supranational governments. Best known globally are the UN scenarios on climate, energy and food. These start out from major driving forces, usually population and GDP, and include variants of governance that may influence the variables of interest. In the energy and climate scenarios for example, the energy mix is different in different scenarios. In the area of resources and raw materials scenario development no such scenarios exist. Some first attempts are now being made, among others by the UN International Resource Panel. They estimate future demand for raw materials by using projections of population and GDP and correlations of those variables with material demand from the past, basically a top-down approach. Another option to generate demand scenarios for specific materials is to use dynamic MFA in a bottom-up approach. This approach starts from the idea of stock saturation: at a certain level of welfare, the stock of materials per capita does not grow anymore, and therefore the demand can also stabilize, or even be reduced to the level needed to keep up the stock. This approach is necessarily much more detailed and data intensive, as stock saturation must be specified at product (and not material) level. Fact sheet for these methods are developed under WP5 and not reported here.

Table 1 shows the methods that have been selected to include in the MICA raw materials intelligence system.

Table 1 List of methods to be described in fact sheets in MICA WP4.

Methods to identify and assess geological and anthropogenic (urban) stocks

- Geological mapping
- Remote sensing, e.g. regional geophysics
- Geochemical analysis, regional and local scale
- Ground investigation, including drilling (boreholes), trial pits, trenching, etc.
- Resource estimation, including:
    - For primary minerals – 3D models, deposit modelling, deposit assessment (feasibility studies), etc.
    - For secondary raw materials – compositional analysis of various stocks, e.g. municipal waste, mining waste, manufacturing stocks, etc.
- Material Flow Analysis

Methods to assess society's metabolism and its environmental impacts

- Material flow accounting
- Material flow analysis and substance flow analysis: accounting, static modelling and dynamic modelling
- Life cycle assessment, including attributional and consequential LCA, and including Life Cycle Sustainability Analysis
- Environmentally extended Input Output Analysis
- Risk Assessment, including Environmental Risk Assessment
- Footprinting at micro- meso- and macro-level

Methods to assess the economic aspects of the use of resources

- Cost Benefit Analysis
- Life Cycle Costing
- Input Output Analysis
- Criticality assessment, including Herfindahl-Hirschmann-Index or other measures for producer country concentration, and World Governance Indicators, Failed States Index or

other measures for stability
- Econometrics, includes causality tests and instrumental variables as well as time series analysis, structural Vector Autoregression models, dynamic and heterogeneous panel models, Bayesian Networks, Structural Equation Modelling
- Computable Equilibrium Modelling; includes General Equilibrium Modelling and Dynamic stochastic general equilibrium (DSGE) modeling

Methods to forecast or estimate future use of resources

- These methods are reported as part of WP5.

In Chapters 3, 4 and 5 the fact sheets for these methods are provided. Fact sheets provide the following information:

- The scope of the method: a discussion of the main purpose and the main characteristics of the method
- The context of use and the main field of application
- Required data and data sources
- (Mathematical) model used
- System and parameters considered
- Resolution in time and space, accuracy and plausibility
- Indicators and other outputs of the method, including units
- Treatment of uncertainty, verification, validation
- Main publications and important references
- Examples of operational tools
- Key relevant contacts.

Not all categories are equally relevant for all of the tools, but at least this classification provides a homogenous treatment of the different methods.

These factsheets are input for the Raw Materials Intelligence system as developed in WP6 of the MICA project.

3. Fact sheets of Geological methods

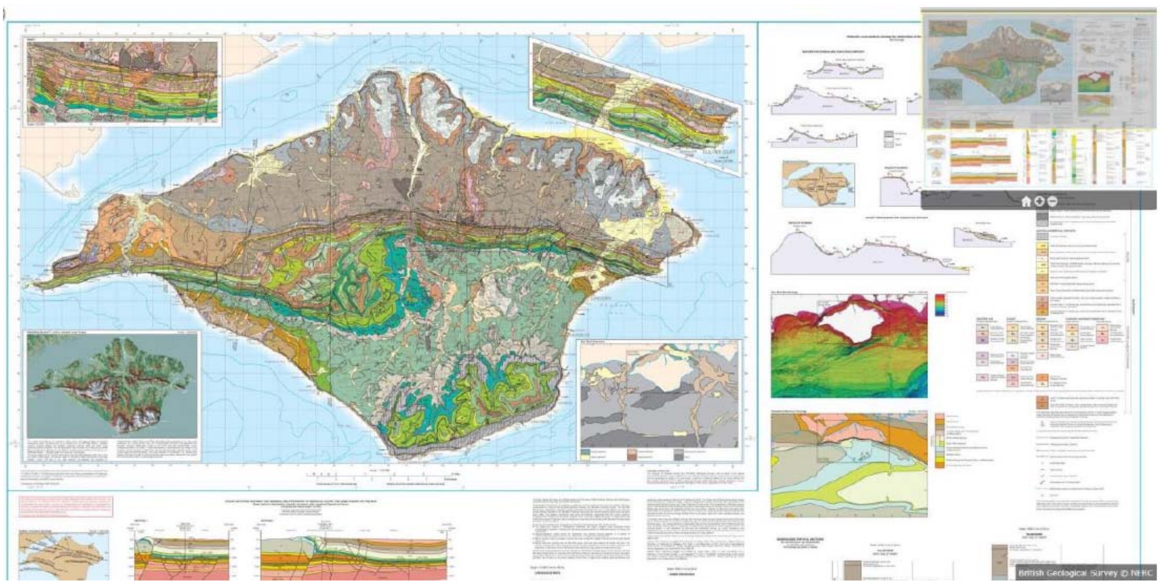
Geological Maps

FACT SHEET

Geological Maps

Scope

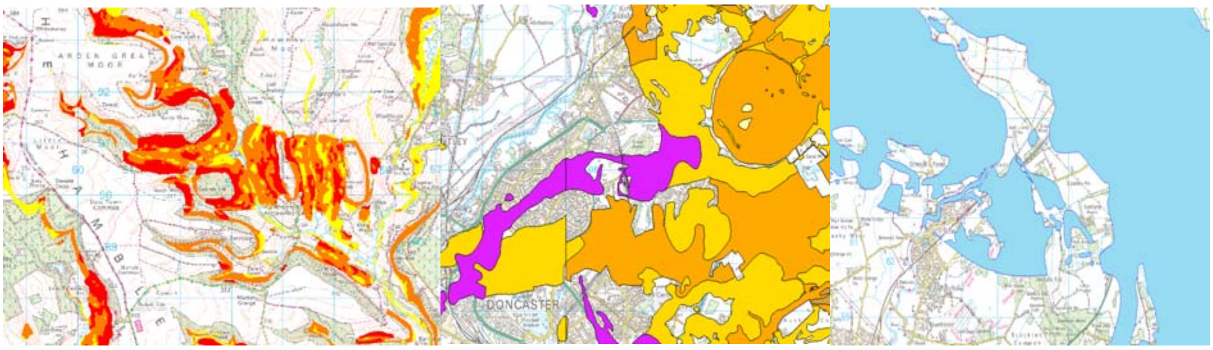
Geological mapping is the process of a creating a graphical representation, normally in two dimensions, as a birds-eye view of the rock types and other geological features. A geological map is a tool for visualising the three dimensional geological relationships on a two dimensional plane, often using a topographical or geographical map as a backdrop with the geology represented by transparent colours on top.



A typical printed paper geological map (Isle of Wight, UK) more detail is shown on inset maps at the top of the sheet and a cross section is shown at the base. Source: BGS

Contexts of use, application fields

Traditional geological mapping will focus on rock and soil types but mapping can also be thematic in nature and record information on hydrogeology, mineral resources, engineering properties, soil type, geological hazards and others, which are based on the underlying geology. The range of rock types/minerals/properties/other information (depending on thematic geological map) will be displayed alongside the map in a key. Maps may also display a cross section which will display a conceptual model of the positions of geological formations at depth and a generalised vertical section which will show the vertical spatial relationship of all the geological units within the map area.



Thematic geological maps showing (left to right) the risk of landslides, the presence of sand and gravel mineral resources, and the susceptibility to groundwater flooding. Source: BGS

Geological mapping is an essential tool for mineral exploration, particularly at the regional reconnaissance scale although maps at greater detail are also available for use in detailed surface or sub-surface exploration. All of these activities may, in turn, generate new data that can be incorporated into improvements to the geological map.

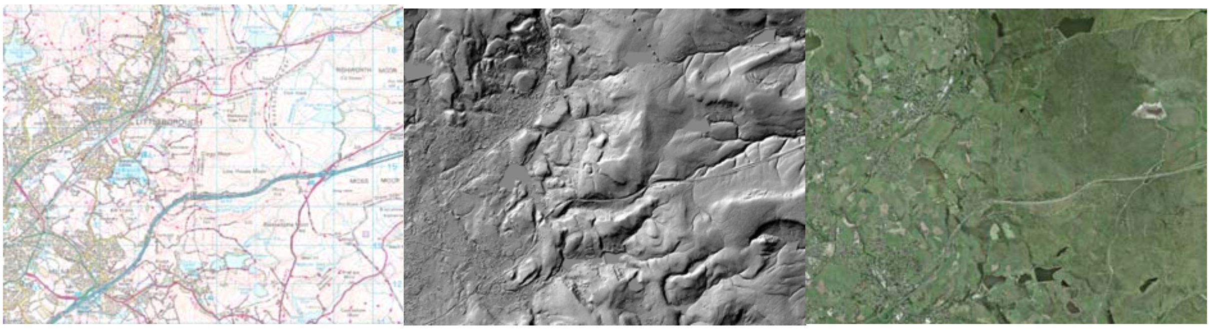
Thematic geological maps displaying the spatial locations of mineral resources can also be used within the process of estimating resources on a broad scale providing additional information such as the thickness of geological formations, maximum likely depth of working and waste: ore ratios are also incorporated. Geological maps can also be useful in determining the best options available for restoration and rehabilitation of closed mine sites; in the formulation of land use, environmental or mineral policies; or in assessing the environmental impact of mining activities.

Input parameters

Not applicable

Type(s) of related input data or knowledge needed and their possible source(s)

Geological mapping requires a topographic base map suitable for use at the scale of mapping required. Modern Geographic Information System (GIS) technology and remote sensing may mean that satellite imagery, aerial photography, digital terrane models and other such representations of the land may be used instead of, or as well as, a topographic base map. Data sets such as these will also often be consulted as well as topographic maps in preparation for, and during, geological mapping to aid in interpretation of surface and sub-surface features.

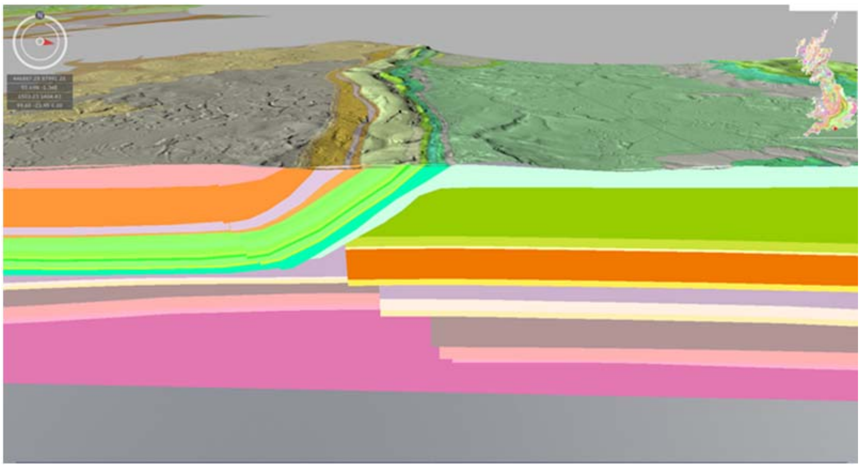


Sources of information for geological mapping (left to right) a base map, a digital terrane model and a satellite image.

In many cases an earlier geological map (whether on paper or digital) may exist, together with the field notes of previous geologists who examined an area and descriptions from boreholes with the area to be mapped. These can provide additional evidence that will assist the geologist in the reinterpretation of an area for the new geological map.

Model used

Geological mapping often relies on the construction of the conceptual model of the area mapped using observations taken from isolated outcrops, supplemented by boreholes and information gained from the topography of an area. This conceptual model will then be applied to areas of little or poor exposure or rocks and adjacent areas which have not been mapped or not mapped in such detail and the geology will be interpolated based on the experience of the geologist.

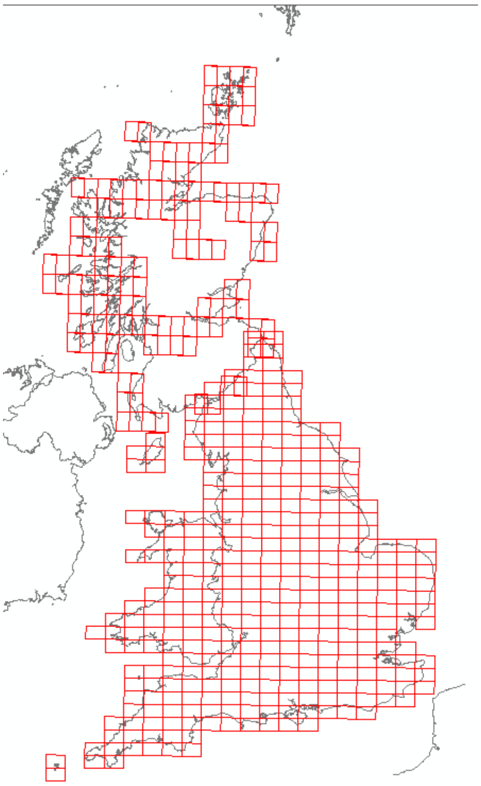


A 3D model showing the expression of rocks mapped at the surface and how the relate to the subsurface. Source: BGS

Usually the purpose of geological mapping is to create a geological model, i.e. an interpretation of the surface and sub-surface geology of an area.

System and/or parameters considered

Geological mapping can be undertaken at almost any scale depending on what the required end use is; mapping for mineral exploration will typically be carried out at between 1:100,000 to 1:25,000 but detailed site investigation work will be conducted at larger scales. Due to its application at almost any scale, geological mapping can be used as an initial tool for mineral reconnaissance, i.e. to initially survey an area for mineral prospectivity to highlight areas for further investigation, or for detailed mapping, i.e. to gain an understating of geological properties at a site-specific level.



1:50,000 scale geological map sheets available for the UK. Source: BGS

The area covered by a geological map, like the scale, will be dependent on the end use of the map. Areas covered can range from continental scale to site specific (such as a mine site or construction site). Like topographic maps geological maps require a spatial reference, this could be a country's national grid, a set of pre-defined grid squares or a global standard such as a latitude-longitude projection.

Time / Space / Resolution /Accuracy / Plausibility

Traditional geological maps are static conceptual models of the geology of a specific area. They cannot show variation throughout a temporal period. Although, the geology of an area rarely changes on the timescale of a human lifespan, a reinterpretation of the evidence can alter the conceptual model of that geology and hence geological maps are updated. In addition, geological mapping carried out at a more detailed scale can result in new geological maps being produced.

Spatial scale is discussed in the section headed "System and/or parameters considered". The scale used for mapping may not be the same one that is used to present the finished map. Often a large scale may be used to map the geology in the field or to interpolate the observations, but a smaller scale will be needed for particular purposes in which case the same data will be used but 'generalised' for that purpose.

Indicators / Outputs / Units

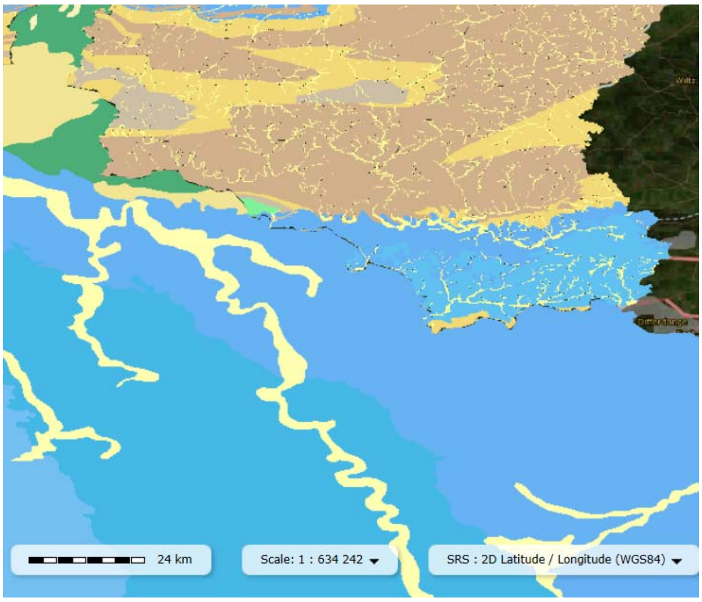
The output is the geological map, at whatever scale is deemed appropriate. This may be a printed paper map or a digital version made available via some form of software either through a web portal or on request using some other digital format. The spatial reference should always be indicated by the key as should the explanation of colours or symbols used. The classification scheme used on geological maps should meet international standards on rock classification. Rocks can be classified by their age (chronstratigraphy) or by their type (lithostratigraphy). National geological surveys will often have a database containing the classification scheme used, for instance the Lexicon of named rock units used by the British Geological Survey. Within the EU these classification schemes should adhere to the INSPIRE directive for standardised geospatial information.

Treatment of uncertainty, verification, validation

As geological mapping is primarily reliant on the observations made by an expert in the field, it is a highly interpretive process and the errors associated with it can be very difficult to quantify as they will be reliant on distribution and number of mapped outcrops, supplementary information (boreholes) and whether the expert's interpretation is accurate. The greatest uncertainty of interpretation will be in areas of low outcrop and/or areas with a high degree of geological variance.

Before publication a geological map should be peer reviewed by another geologist. There can be uncertainties associated with the exact locations of the boundaries between geological formations, particularly in the sub-surface, and where warranted these are often shown as dotted lines on the map. Explanatory notes may also be provided.

It is often the case that between geological maps different classifications for geological units will have been used. This will result in a miss-match of geological boundaries between maps and is common across national boundaries. This miss-match can be due to either different standards being used and/or variation in geological interpretations.



A geological map miss-match along the France-Belgium national boundary. Source: Onegeology

Main publications / references

BENNISON, G. M. (2011). *An introduction to geological structures and maps*. Taylor and Frances Ltd.

LISLE, R.J., BRABHAM, P. AND BARNES, J. (2012). *Basic Geological Mapping 5th edition*, Wiley-Blackwell

MALTMAN, A. (1998). *Geological maps: an introduction*. Chichester, West Sussex, Eng, John Wiley & Sons Publishing.

Related methods

Not applicable

Some examples of operational tools

Modern geological mapping will be conducted using GIS software. This comes in a wide range of both commercially available and freeware products and will often be used on ruggedised handheld computers in the field. This is an update on the more traditional methods using paper base maps and hand drawn notes in the field, but the principles and data recorded remain the same.

Geological mapping using GIS software on a ruggedised handheld tablet. Source: BGS

Key relevant contacts

Geological maps are typically available from the national geological survey of the county concerned. In many EU countries these organisations make small scale geological maps available for free often via online portals. Larger scale maps and associated digital data generally require payment (in particular when for commercial use). Below is listed some of the available geological mapping datasets within the EU.

Country	**Geological map portal**
Croatia	www.hgi-cgs.hr/images/geoloska-karta-republike-hrvatske-1-300.jpg
Czech Republic	www.geology.cz/extranet-eng/maps/online
Denmark	www.geus.dk/UK/data-maps/Pages/default.aspx
Finland	http://en.gtk.fi/informationservices/map_services/index.html
France	http://infoterre.brgm.fr/
Germany	https://geoviewer.bgr.de/
Ireland	www.gsi.ie/Mapping.htm
Norway	www.ngu.no/en/topic/applications
Poland	http://bazagis.pgi.gov.pl/website/cbdg_en/viewer.htm
Romania	http://81.196.111.132/testgeo2/
Slovakia	http://infoportal.geology.sk/web/guest/mapovy-portal
Spain	http://info.igme.es/visorweb/
Sweden	http://apps.sgu.se/kartvisare/kartvisare-index-en.html
Switzerland	https://map.geo.admin.ch
United Kingdom	www.bgs.ac.uk/geoindex/

There are also data catalogues (such as OneGeology) that provide geological maps for a wider geographical extent. Typically these are small scale, but made available for free via an online portal.

Geological maps will also be held by commercial companies who undertake mapping as part of their work (i.e. mineral exploration) these maps will generally not be publically available and will be commercial-in confidence for the duration the company maintains an active exploration license and normally for a period of time thereafter.

Geological Mapping for Mineral Exploration

MICA Mineral Intelligence Capacity Analysis

FACT SHEET

Geochemical Mapping for Mineral Exploration

Scope

Geochemical mapping provides a means of visualising spatial variations in the chemical composition of the Earth's surface. The chemical signature of any specific mineral deposit will reflect the commodities that it contains, and is likely to contrast significantly with that of surrounding rocks. Geochemical maps display and quantify these geochemical contrasts, and are therefore an important line of evidence from which to guide mineral exploration. Geochemical maps are typically produced using data collected by chemical analysis of soil or stream sediment samples, but other media may be used, such as stream water, ground water or rock chips. Soils and stream sediments are generally favored as they strike a good balance between ease of collection (low cost) and the quality and relevance of information obtained. Stream sediment data may be more useful than soils at a first-pass reconnaissance scale as the samples represent material from their entire upstream catchment area, and therefore with careful planning are capable of providing complete representation of a study area, albeit in a topographically-aggregated format. Soil data on the other hand is simpler to work with as in most cases it can be assumed that the sampled material did not originate a great distance from the collection site, and thus contains information reflecting the bedrock at that point. Soil samples can be collected quickly, easily, and consistently using a hand auger. Stream sediment samples are subject to greater compositional inconsistencies as a result of local variations in stream flow, though this can be minimised by using sieving to target finer grain sizes at the expense of collection time. Johnson *et al.* (2005) describe the collection of both media in more detail.

Regardless of the chosen media, interpolation is central to the process of geochemical map production because the high cost of chemical analysis prevents exhaustive sampling. Interpolation is therefore required to produce a continuous surface from data collected at a relatively coarse sampling density. Interpolation is generally conducted using one of three main approaches:

1) Naïve interpolation, e.g. Inverse Distance Weighting (IDW; Shepard, 1968), to predict values between geochemical observations using a standard simplistic model for spatial autocorrelation.
2) Geostatistical interpolation, e.g. Ordinary Kriging (OK; Cressie, 1988), to predict values between geochemical observations by modelling the spatial autocorrelation of the data.
3) Regression / machine learning, e.g. Random Forest (RF; Breiman, 2001), to predict values between geochemical observations based on the values of spatially continuous auxiliary variables that have been measured across the region, such as from geophysical survey and other remotely sensed data sets.

Naïve interpolation is often favored for its simplicity, but it can be expected to be less accurate than geostatistical interpolation provided that the necessary assumptions of the geostatistical model are met, namely that the input variable is normally distributed and exhibits second-order stationarity, i.e. that the mean and autocorrelation of the data do not exhibit regional trend. The regression / machine learning approaches are becoming increasingly viable as the world becomes more data-focused: more auxiliary variables are being collected and machine learning techniques are improving. Regression approaches can in fact be combined with geostatistical approaches; for example the residuals of a regression model may be geostatistically interpolated in a procedure known as Regression-Kriging (Hengl *et al.*, 2007).

Contexts of use, application fields

Geochemical mapping is generally implemented at the earliest stages of mineral exploration as it provides a cost-effective line of evidence from which to hone in on targets for subsequent drilling. The high cost of drilling means that it generally pays to be thorough at the geochemical mapping stage in order to increase the chances of success at the exploratory drilling stage. Geochemical mapping may therefore be conducted iteratively: An initial regional scale survey is generally used to identify target areas which may then be resampled at a higher density in order to produce more accurate and precise geochemical maps of the individual targets.

At every stage, geochemical mapping provides data on the chemical composition of the Earth's surface, within which is contained information on the composition of the subsurface. For mineral exploration, geochemical maps provide evidence of the locations of subsurface ore deposits by highlighting concentrations of commodity elements. Additionally, geochemical maps provide information on the concentrations of environmentally harmful elements which may co-occur with commodities; an important consideration when assessing the viability of ore extraction. Examples of geochemical maps include the UK Geochemical Baseline Survey of the Environment (G-Base) project (BGS, 2016) and the Geochemical Atlas of Europe (FOREGS, 2005). Several similar databases and projects exist in Europe and beyond.

Type(s) of related input data or knowledge needed and their possible source(s)

Both naïve and geostatistical interpolation methods (e.g. Inverse Distance Weighting and Ordinary Kriging) require only geochemical observations and their coordinates as input data in order to produce continuous-surface geochemical maps (though geostatistical methods do also require data-derived model parameters to be chosen by the operator). In addition, the regression / machine learning approaches to geochemical mapping require continuous observations of auxiliary variables throughout the desired mapping extent.

Geochemical observations are obtained from soil and stream sediment samples (e.g. Johnson and Breward, 2004) using a variety of analytical methods, but most commonly either x-ray fluorescence spectrometry (XRF) or inductively coupled plasma mass spectrometry (ICP-MS) is used, with additional fire-assay for precious metals such as gold. Depending on the specifics of the equipment used, concentrations may be reported for more than 50 elements, effectively quantifying the entire chemical composition. Coordinates are generally measured using handheld GPS at the site of sample collection, though they may still be map-read in areas of forest cover.

While it is simplest to produce geochemical maps using the concentration data for individual elements this practice has come under criticism because it does not respect the compositional nature of the data (McKinley *et al.*, 2016). In compositional data the variables are not independent of one another because they are confined together within the total sum of the closed composition, whether or not all components have been measured. The concentration of a single element therefore does not necessarily reflect the amplitude of the underlying process through which it was concentrated, but may simply reflect the absence of (or dilution by) other elements. In these compositional data sets each variable is said to carry only relative information, and it is the ratios between elements, rather than their individual concentrations, that are meaningful (Pawlowsky-Glahn and Egozcue, 2006). For effective mineral exploration it is therefore recommended that suitable log-ratios and compositional components are identified and mapped, rather than single element concentrations.

Model used

The most common naïve interpolation method, Inverse Distance Weighting (Fig. 1, top), predicts new values as an inverse distance weighted average of surrounding observations, i.e. a predicted value will be more similar to nearby observations than to distant observations, and will not extrapolate beyond the range of observed values. This simple method adheres to Tobler's first law of geography: that "everything is related to everything else, but near things are more related than distant things" (Tobler, 1970).

The core geostatistical method, Ordinary Kriging (Fig. 1, middle), builds on the logic of Tobler; nearby observations are given greater weights than those far away, but the function which assigns these weights is statistically fitted according to the spatial autocorrelation of the data. This fitting increases the accuracy of the interpolation over IDW provided the model fit is good. In Kriging the weights are adjusted to account for spatial dependence of the observations; observations within clusters are down weighted to provide overall uniformity of observation weight across the study area.

There are many possible models that can be used for regression / machine learning approaches, but in general the predictions will purely be made according to the values of auxiliary variables present at the prediction location, rather than according to nearby observations of the variable to be predicted. The success of these methods therefore depends on the quality and relevance of available auxiliary datasets, but can produce very good results with sufficient data. For example, Kirkwood *et al.* (2016) demonstrated the effectiveness of the Random Forest algorithm for geochemical map production supported by high resolution geophysics and remotely sensed auxiliary data (Figure 1, bottom).

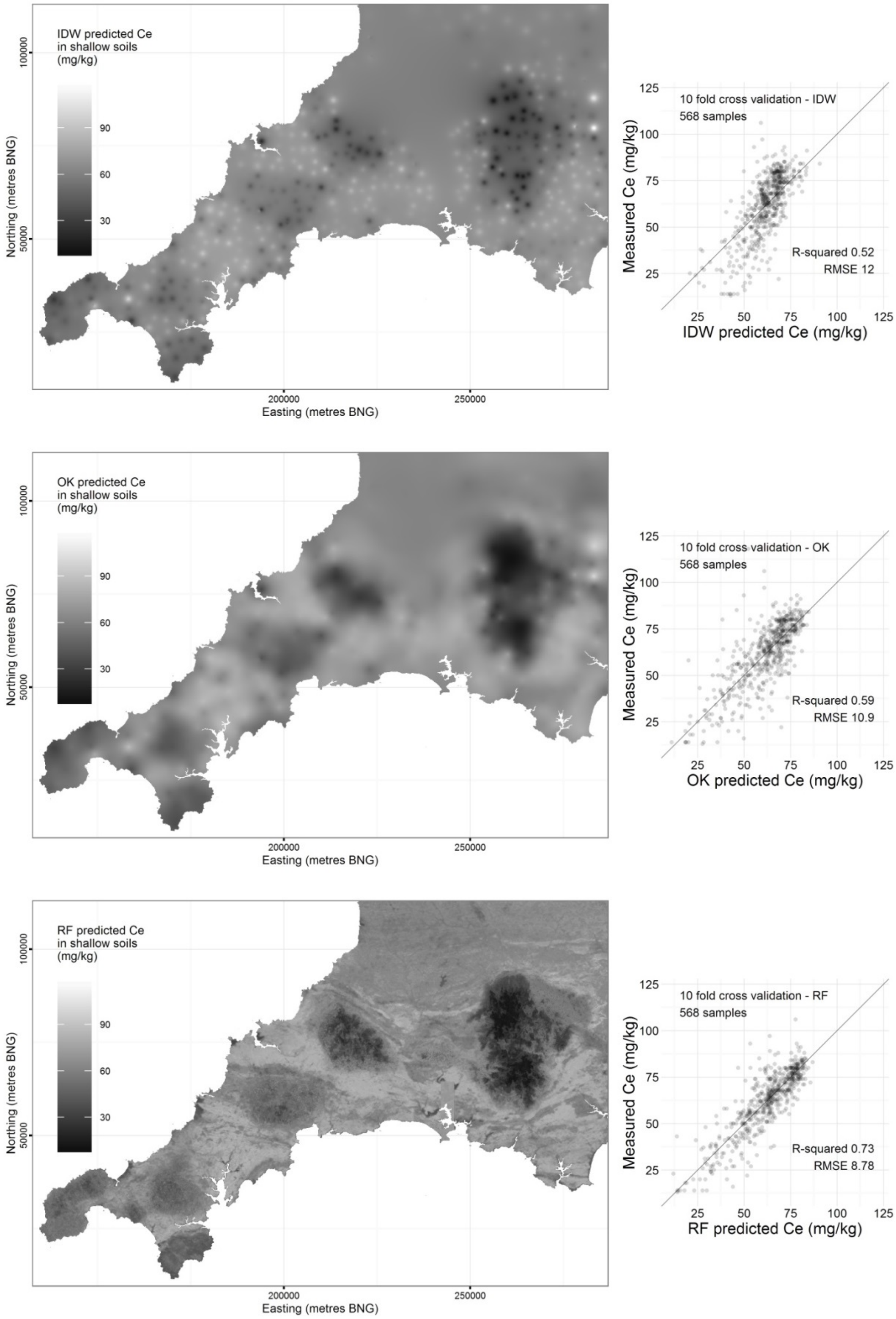


Figure 1 Comparison of cerium maps for south west England produced by IDW, OK and RF, with cross-validation plots.

Input parameters

Input parameters vary according to the method used. Inverse Distance Weighting has only one adjustable parameter: power. The weightings are derived from the inverse of distance raised to this power. Increasing the power decreases the influence of distant observations relative to nearby observations. IDW tends to be run with a default power value of 2. For all interpolation types it is generally possible to set a maximum distance and a maximum number of samples to be used at each prediction, which may be desirable to reduce computation time.

Ordinary Kriging requires the user to select an appropriate model type and parameters to represent the relationship between the distance between observations and the difference between their values. This relationship is visualised using the variogram (Figure 2). In principal there are three parameters to decide; nugget, sill, and range. Nugget is the semivariance value at which the model intercepts the y axis. The nugget represents variation in the data that is not spatially auto correlated on the scale of the survey, and may be due to measurement error or fine scale processes. The sill is the semivariance value at which the model levels off, and the range is the distance at which the sill is reached, representing the distance beyond which observations are no longer related.

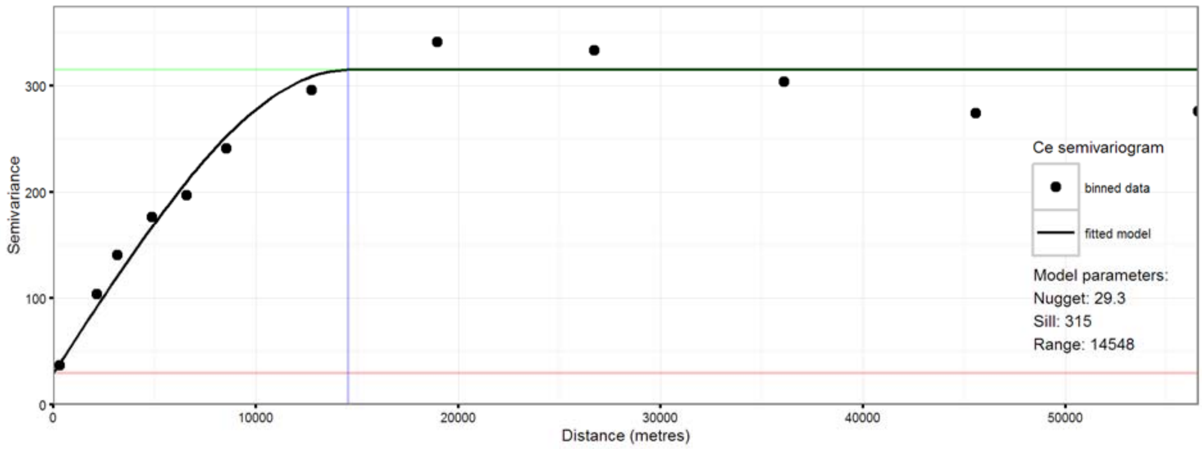


Figure 2 Example variogram using cerium data from south west England. The horizontal red and green lines mark the nugget and sill, while the vertical blue line marks the range.

Classical regression requires parameterisation in terms of an intercept and coefficients for each predictor variable; however in all modern software packages this process is automated and so little user input is required. However, selection of predictor variables and specification of any supposed interactions still requires user discretion. Machine learning approaches are highly automated, but may have tuning parameters that allow generalisation (resilience to over-fit) to be optimised for the data in hand. Again, provision of suitable predictor variables is down to the user.

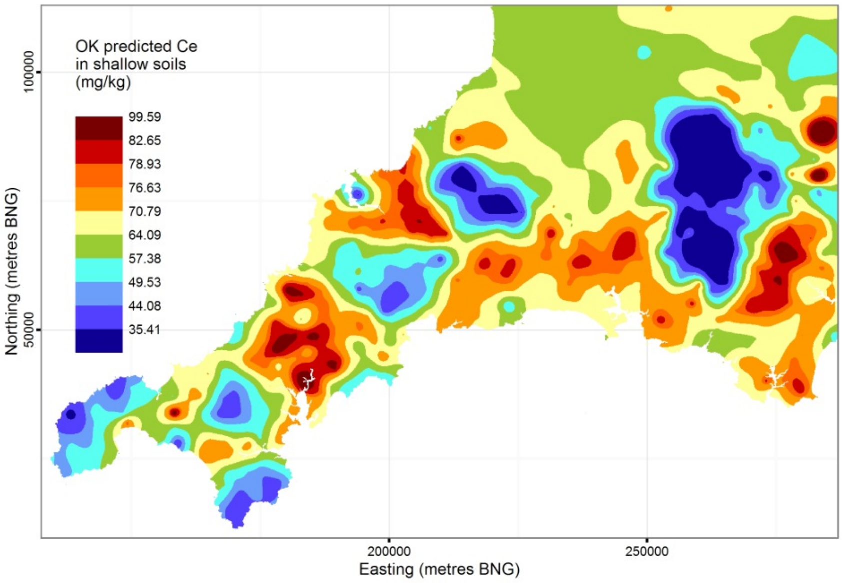
Time / Space / Resolution /Accuracy / Plausibility

Geochemical maps for mineral exploration are produced as static models. Repeating observations through time may reveal some seasonal changes in surface processes but the mineral deposits of interest are likely to be static on human timescales and so geochemical mapping for mineral exploration does not typically deal with the dimension of time.

Spatially, geochemical maps may be produced at a range of extents and scales. The extent is dictated by the extent of the area of interest, but sampling should extend beyond the boundaries of this extent to ensure that predictions are always interpolations rather than extrapolations. The maps are usually presented in a raster format; i.e. a grid is constructed and values are predicted for each grid cell. There are no hard specifications for the size of the grid cells, but they should be sufficiently fine to retain all useful information within the map without being so fine as to cause computational difficulties. For example national scale surveys may use 1km grid cells, while regional scale surveys may use 100m grid cells and targeted surveys may use 1m grid cells.

Indicators / Outputs / Units

The output is a geochemical map, a raster in which each grid cell contains predicted values of the geochemical variable in question. For individual element maps, the units will either be percentages (%), parts per million (ppm, or mg/kg) or parts per billion (ppb), depending on whether they show a major element, minor element, or trace element respectively. Log-ratio maps are without units, but provide a more informative representation of geochemical composition than individual element concentrations (see ‘types of input data’).



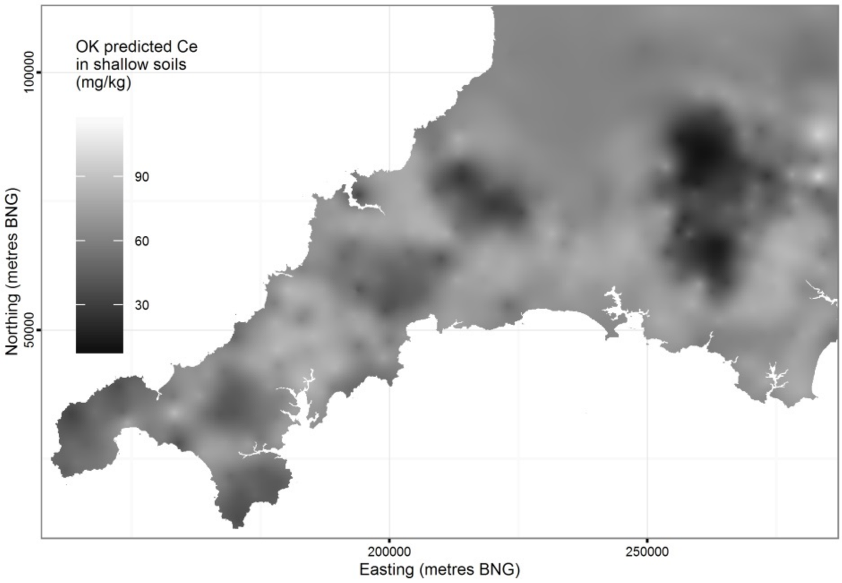


Figure 3 The same map of cerium in south west England, symbolised using both quantile-classified rainbow and continuous greyscale colour schemes. The continuous map is instinctively more intelligible. Arbitrary classification and rainbow colours only serve to impede the clear conveyance of information, even to the fully colour-sighted.

The grid cell values of a geochemical map are symbolised with a colour scheme of the producer's choosing. Geochemical maps are often displayed using a classified renderer, wherein different colours are used to represent a range of quantile classes in the data. Such visualisations sacrifice a lot of detail and introduce misleading hard boundaries in what is fundamentally continuous data, and so should be avoided unless there is a genuine reason for classification. Even in continuous colour scales, 'rainbow' colour schemes should be avoided as they obscure the information in the data (Borland and Taylor II, 2007, Moreland, 2016).

Single hue continuous colour scales, or at least perceptually uniform colour scales, are recommended for geochemical maps as they provide the most natural representation of the detail in the data, and offer the best chance to understand the features in the data (Figure 3). If the data is highly skewed, histogram equalisation can be used to improve detail across the map.

Treatment of uncertainty, verification, validation

Treatment of uncertainty depends on the modelling method used. Naïve interpolators such as IDW have no statistical basis and are unable to provide prediction intervals. Geostatistical methods such as Ordinary Kriging provide variance as an output of the interpolation; allowing the production of an accompanying uncertainty map, which displays how uncertainty increases with increasing distance from observations. Regression / machine learning approaches will also offer prediction intervals according to the particular methodology used. Prediction intervals are a useful tool for iterative mapping, as they identify locations with the greatest uncertainty, which should therefore be targeted in later rounds of sampling.

All geochemical maps should be validated to provide users with information on their accuracy. K-fold cross-validation is the most commonly accepted method for doing this (Kohavi, 1995). The value of k can be chosen by the user, but it is generally accepted that 10 provides a good balance between the high bias of using too few folds and the high variance of using too many. In 10-fold cross-validation the data is split into 10 separate folds of approximately equal distribution using stratified sampling. The chosen model is then trained using the data in 9 of these folds, and used to predict values for the locations of the observations in the remaining 'test' fold. By repeating this process 10 times, so that each fold is used as test data, the accuracy of the model can be assessed by comparing the predicted and observed values. Accuracy will often be reported using cross-validated root mean square error (RMSE) in map units, or coefficient of determination (R^2) for unitless comparison between the accuracy of maps for different variables.

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Related methods

Geophysical survey
Remote sensing
Geological mapping
Prospectivity analysis
Resource estimation

Some examples of operational tools

QGIS - QGIS Development Team, 2016. QGIS Geographic Information System. Open Source Geospatial Foundation Project. www.qgis.org/

SAGA - Conrad, O., Bechtel, B., Bock, M., Dietrich, H., Fischer, E., Gerlitz, L., Wehberg, J., Wichmann, V., and Böhner, J. (2015): System for Automated Geoscientific Analyses (SAGA) v. 2.1.4, Geosci. Model Dev., 8, 1991-2007, doi:10.5194/gmd-8-1991-2015.

GRASS - GRASS Development Team, 2015. Geographic Resources Analysis Support System (GRASS) Software, Version 7.0. Open Source Geospatial Foundation. http://grass.osgeo.org
R - R Core Team (2015). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. www.R-project.org/

Key relevant contacts

The geological survey of the country concerned should be contacted in the first instance; they may well have conducted their own national-scale geochemical mapping programs, which are an ideal starting point from which to plan more detailed mapping.

Remote sensing for mineral exploration

MICA Mineral Intelligence Capacity Analysis

FACT SHEET

Remote Sensing for Mineral Exploration

Scope

Remote sensing is the science of acquiring, processing and interpreting images and related matter and electromagnetic energy (Sabins, 1997). Remote sensing can be used to detect, identify and ultimately map hydrothermally altered rocks that are present on the earth's surface. Multi and hyperspectral satellite and airborne data can be used for mineral exploration and mine waste mapping.
Data of satellites and sensors used for mineral exploration include: Landsat, ASTER, Hyperion, WorldView-3 (satellite based sensors) and HyMap, Eagle Hawke (sensors mounted on an airborne platform). Sensors are also now being made small enough to be mounted onto unmanned aerial vehicle (UAV) platforms. Using satellite data large areas can be mapped in a short space of time, although it is important to undertake ground truthing[1] to establish the confidence of the remote sensing mapping. More detail can be achiveved using airborne data, but a smaller area is covered by each scene.

The sensors on the platforms mentioned above all measure the interaction of solar energy with the ground surface. When solar energy hits an object, five different types of interaction are possible. The energy from the sun is either:

- Transmitted – The energy passes through with a change in velocity.
- Absorbed – The energy is taken in by the object.
- Reflected – The energy is returned unchanged. The wavelength reflected and not absorbed determines the colour of an object.
- Scattered – The direction of energy propagation is randomly changed.
- Emitted – The energy is first absorbed by the object and the re-emitted at longer wavelengths i.e. the object heats up.

Certain wavelengths of light are absorbed by rocks due to vibrations caused by solar energy. It is the presence of these absorption features, in satellite and airborne data, which indicate the type of bonds present allowing for mineral identifications to be made. These absorptions are seen as minima in the spectra. The molecular bonds activated in the Short Wave Infrared (SWIR) are major constituents of clays, sulphates, carbonates and many other minerals. The wavelength position of the absorption features within the spectra will ultimately determine what minerals are present. For example most clay minerals have absorption features around 1400nm and 1900nm, carbonates have diagnostic features closer to 2300nm (Figure 4). These absorption features are due to the different chemical bonds present within the structures of the different minerals.

[1] In remote sensing, the term ground truthing is used to describe the process of verifying a satellite image with what is already known about the location on the ground.

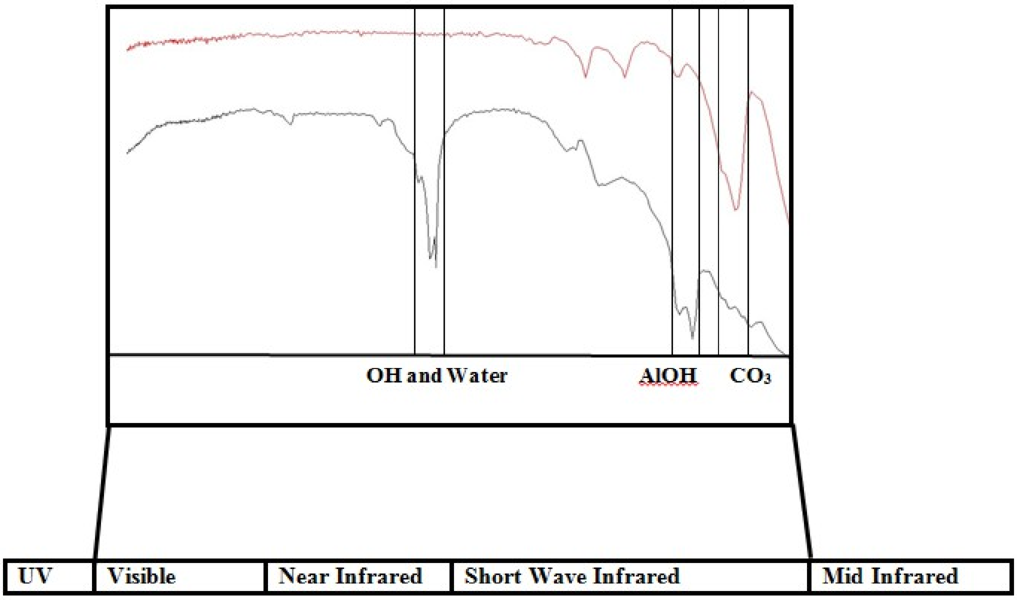

Figure 4 Visible to SWIR region of the electromagnetic spectrum with position of absorption bands for kaolinite and calcite (Adapted from Spectral Interpretation Field Manual, AusSpec International).

Multi spectral sensors, such as Landsat and ASTER, collect this information as discrete bands at certain wavelengths. Figure 5 shows the position of these bands for Landsat and ASTER. These bands have been pre-defined at wavelengths known to be useful for certain minerals and for vegetation analysis amongst other things. Table1 shows each Landsat TM band with corresponding application. Hyperspectral data is acquired as a continuous spectrum and so more subtle differences in mineral type, and vegetation health can be determined using hyperspectral data.

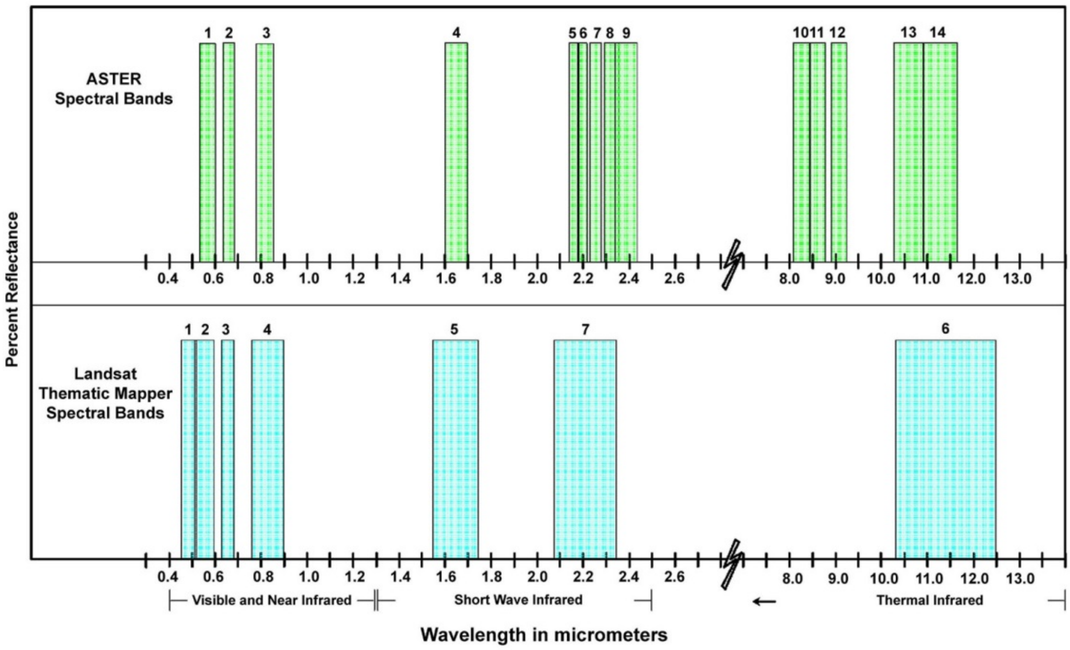

Figure 5 Position of bands for Landsat and ASTER.

Table 2 Landsat TM sensor characteristics.

Spectral band	Wavelength (µm)	Spectral location	Spatial res. (m)	Temporal res. (days)	Principal application
1	0.45 - 0.52	Blue	30	16	Water body penetration, soil/vegetation discrimination, forest type mapping & cultural feature identification
2	0.52 - 0.60	Green	30	16	Designed to measure peak green reflectance of vegetation, for vegetation discrimination and stress assessment
3	0.63 - 0.69	Red	30	16	Designed to sense chlorophyll absorption, aiding in vegetation monitoring
4	0.76 - 0.90	Near infrared	30	16	Soil moisture discrimination, determination of vegetation types and stress, and delineation of water bodies
5	1.55 - 1.75	Mid-infrared	30	16	Designed for sensing soil moisture content, and vegetation moisture content. Differentiates between snow and clouds
7	2.08 - 2.35	Mid-infrared	30	16	Designed to discriminate between mineral and rock types and to sense vegetation moisture content
6	10.4 - 12.5	Thermal infrared	120	16	Vegetation stress analysis, soil moisture discrimination and thermal mapping applications

Minerals associated with ore deposits have distinctive spectral signatures and absorption features within the visible and short wave infrared region of the electromagnetic spectrum. Minerals such as kaolinite, dickite and alunite are indicator minerals that can help to focus mineral exploration in zones of hydrothermal alteration. Their presence can indicate the degree of alteration and therefore show where the mineral deposit is located. Other minerals such as iron oxide minerals display a characteristic red or orange discolouration on exposure to the air and so can readily be detected using remote sensing techniques.

Vegetation and cloud cover will hinder the process of geological and mineral mapping as it is the Earth's surface that is of interest. If the surface is covered by vegetation then certain techniques can be used to lessen the effect of the vegetation or the vegetation itself can be used to determine the location of the mineral deposit. Underlying mineral deposits may 'stress' the vegetation and result in a diagnostic absorption feature indicating the less healthy vegetation. That can be used to show the presence of a mineral deposit underneath the vegetation cover.

Contexts of use, application fields

The more bands available the closer you can get to a mineral map, especially where ground measurements can be collected. Hyperspectral airborne data especially can be used to produce a mineral map and this type of data has been used in the mapping of mine waste and acid mine drainage at abandoned mine sites. Mine waste contains complex mixtures of minerals and so ground spectral data of these mixtures is important in classifying the minerals of a site's mine waste. Pure minerals can be identified using spectral libraries such as the USGS and JPL spectral libraries, where pure minerals have been measured spectrally in the laboratory to provide reference spectra for mineral identification either on the ground or using remote sensing data.

An example of this type of hyperspectral mine waste mapping can be taken from the MINEO project, carried out by several European geological surveys (BGS, BGR, BRGM, GEUS, GTK, LNEG) from 2000 to 2003. HyMap hyperspectral airborne data was acquired over seven mine sites around Europe. The aim of the project was to look at mine waste rather than mineral exploration and to do this in a populous temperate environment rather than the more typical arid environment. The outputs of the project were various mine waste maps over the mines in the region, using the techniques described above. Extensive field work was also undertaken in order to calibrate the airborne data and also for validation of the results. Figure 6 shows an example of one of the mine waste maps over the tailings dam of the Wheal Jane mine. The various minerals are presented with different colours on the map.

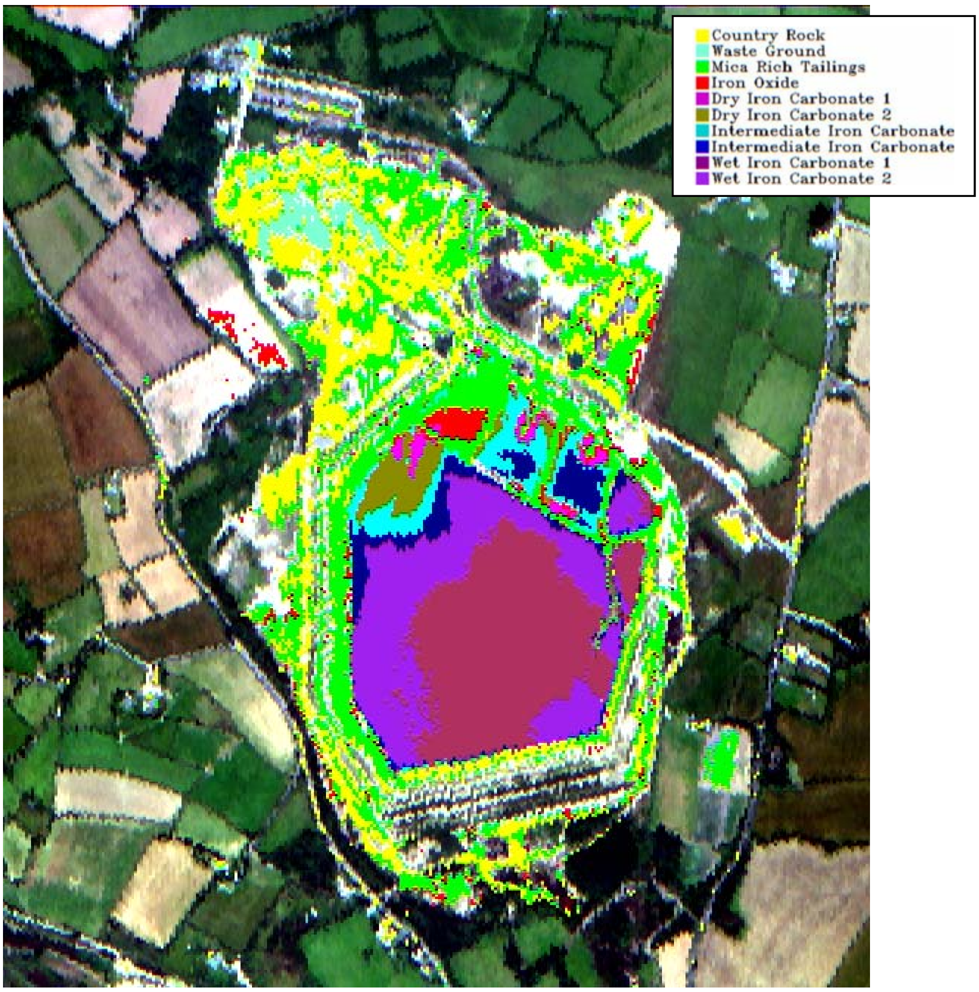

Figure 6 Mine waste map of the Wheal Jane mine in Cornwall.

Input parameters

As already discussed in the Scope and Context sections, the following input parameters are required for remote sensing for mineral exploration:

- Suitable satellite images or airborne data
- Suitable storage and RAM capacity on computers used for image processing
- Image processing software
- Spectral Libraries, either pure spectral libraries from USGS or JPL or self-derived spectral libraries following ground spectral measurements

Type(s) of related input data or knowledge needed and their possible source(s)

As already discussed in the Scope and Treatment of uncertainty sections, the following input parameters are required for remote sensing for mineral exploration:

- Ground truthing is very important.
- Knowledge of the wavelength position of absorption features important in the mapping of mineral deposits or mine waste
- Geological knowledge of the possible mineralogy present.

Model used

Certain bands can be used to produce ratios for mineral identification. Dividing one band by another and using the result to produce a false colour ratio map can aid geologists get closer to a potential ore deposit. The output from the above will be a single band greyscale image; it is often desirable to combine 3 ratios to be displayed in red, green and blue.

Common band ratios for ASTER for example are:

- Iron Oxide band 2/band 1, 4/1, 4/3
- Ferrous Iron 7/4
- Clays (Al-OH abundance) (5+7)/6
- Carbonate (Mg-OH abundance) (6+9)/(7+8)
- Silica abundance 11/(10+12), 11/10, 13/12, 13/10

Principal components analysis, a statistical technique used to reduce the redundancy in multispectral data, is also widely used to detect and map alteration minerals associated with metallogenic deposits. The Crosta technique is a more refined principal components methodology where the principal components containing spectral information about specific minerals can be identified and used to produce mineral exploration maps.

There are various techniques to process hyperspectral data in order to create a classification map of mineral deposits or mine waste maps. The spectral analyst, an ENVI module that uses spectral libraries to automatically determine the mineralogy of image spectra, can be used to select regions of interest within the image data. For these regions of interest a supervised classification is performed by applying the Spectral Angle Mapping (SAM) method, for which the selected reference spectra is used. The reference spectra can be of distinct types, for example field spectral measurements of waste materials and contaminated soils and sediments. Smaller angles in the SAM represent closer matches to the reference spectrum, while pixels outside the specified maximum angle threshold are not classified.

System and/or parameters considered

Satellites, such as Landsat, pass over the earth's surface every 16 days and so the whole earth can be mapped, depending on cloud cover and other factors.

The wavelength range of the sensor used is also a parameter to be considered. The data is either available as discrete bands, as in multi spectral sensors, or as a continuous spectrum, as in hyperspectral sensors. The wavelengths covered also vary depending on the sensor used.

Time / Space / Resolution /Accuracy / Plausibility

The resolution depends largely on the type of remote sensing data used. If using satellite data there are many different scales and resolutions. With Landsat ETM+ for example you can achieve 15m pixels and each scene covers an area of 185/180km, so a large area can be mapped at a usable resolution. More detail can be achieved by using an airborne platform, i.e. the pixel size is much reduced (anywhere from 2 to 5m pixels depending on the flying height of the aircraft) but a much smaller area is covered by each swath or scan line. Much of the satellite data available i.e. Landsat and ASTER are free to download for research purposes, whereas areal campaigns and more detailed satellite data comes at a cost.

Satellite data is acquired regularly as the platform passes over the earth's surface in a set orbit so many scenes, covering several years, will be available over a single geographic coordinate. Airborne data is generally acquired as a one off campaign, although time series data can be acquired as required.

Indicators / Outputs / Units

Outputs from the methodology described would be classification maps indicating either the occurrence of hydrothermally derived minerals or the associated mine waste during and/or following extraction.

Mineral exploration maps will show where the indicator minerals are. Similar to a geological map but showing the zonation of minerals associated with hydrothermal alteration. Different colours on the map show the presence of different minerals. An example can be seen in Figure 7.

Mine waste maps indicate the location of the mine waste and can be used to monitor the presence of acid mine drainage if present (Figure 6). This may also be in the form of a vegetation stress map, indicating where less healthy vegetation is present in association with the mine waste.

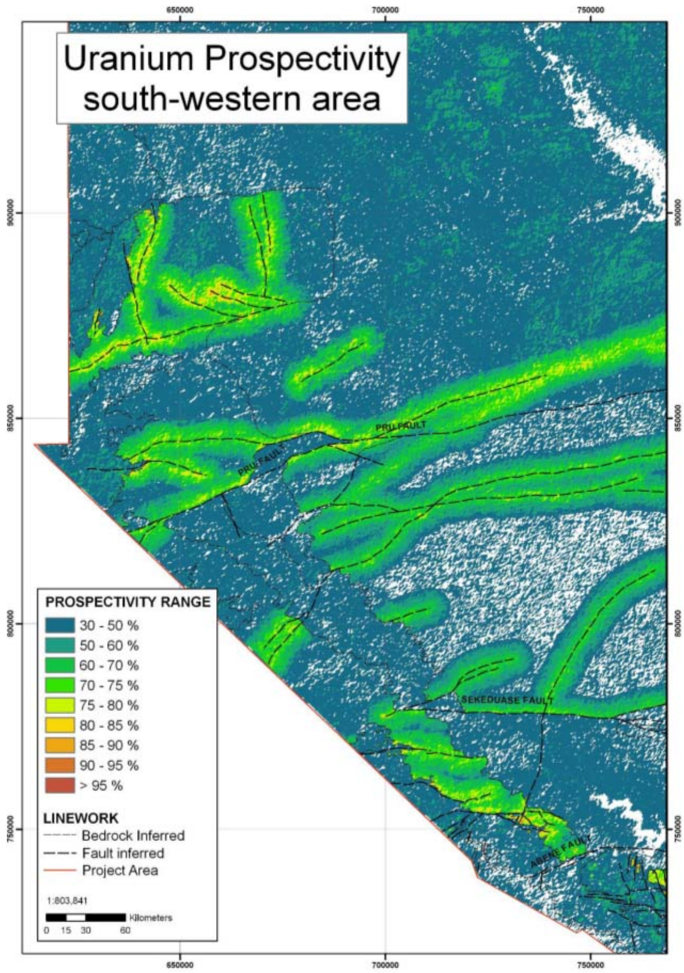

Figure 7 Example of mineral exploration map derived from satellite data: Uranium prospectivity map of the south-western Volta Basin, Ghana.

Treatment of uncertainty, verification, validation

Remote sensing should always have an element of ground truthing to establish the actual condition of the ground surface. Field spectrometers can be used to directly measure the spectral response of the ground surface and then these spectra can either be used to calibrate the satellite or airborne data or can be used as ground truth data to determine the accuracy of the mineral mapping and verify the results.

Main publications / references

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Related methods

Geophysical survey: the systematic collection of geophysical data to undertake spatial studies
Geological mapping: the process of a creating a graphical representation, normally in two dimensions, as a birds-eye view of the rock types and other geological features.
Geochemical exploration: the visualisation of spatial variations in the chemical composition of the Earth's surface.
Prospectivity analysis: is a predictive tool typically used for targeting exploration at the regional to site scale.
Mineral resource estimation: methods used to define a mineral resource in three dimensions, with the ultimate aim of determining both the size (typically reported in tonnes) and grade (generally expressed as the metal content in wt. % or g/t) of the resource.

Some examples of operational tools

ENVI – www.harrisgeospatial.com/ProductsandSolutions/GeospatialProducts/ENVI.aspx

ERDAS Imagine – www.hexagongeospatial.com/products/producer-suite/erdas-imagine

Key relevant contacts

CSIRO
USGS
BRGM

These are all Institutions that have a strong background in mineral exploration and mine waste mapping using remote sensing techniques. The national geological survey of the country being studied should also be contacted to determine if any remote sensing has already been undertaken in any particular area of interest.

Exploration phases

FACT SHEET

Exploration Phases

Scope

Mineral exploration is the process of identifying mineral deposits of economic interest within the earth's crust which if successful may lead to the extraction or mining of the deposit.

Who

Mineral exploration is carried out primarily by the private sector but in some cases the public sector may also carry out this work. Private sector mineral exploration may be carried out by pure mineral exploration companies – often referred to as the *'junior sector';* or by integrated mining companies which have both mining and exploration activities and are often referred to as *'majors'* or '*mid-caps*', depending on their market capitalisation. Junior companies commonly do not have an income stream and rely on funding from the Stock Market or private investors. Majors or midcaps would normally have an income stream from their mining operations and would fund exploration from the profits of these operations.

What

What commodity is explored for depends on the company (essentially their expertise) and the market (primarily price). Some companies explore for a single or limited range of commodities while others may explore for any or all minerals.

Phases

Four main exploration phases within an exploration programme may be identified:

1. Ground selection;
2. Target generation or reconnaissance;
3. Target testing or investigation; and

4. Deposit delineation.

Most exploration programmes do not complete all four phases and the programme may cease at the end of or within one of the phases. It has been estimated that the success ratio or rate of exploration is less than one percent (Table 3). While different writers describe the different phases of exploration differently they do come up with broadly comparable figures. Success rate in this case refers to the percentage of anomalies which become mines.

Table 3 Exploration success rates according to various authors.

EXPLORATION SUCCESS RATES								
Source	**Region**	**Description and number**						**Success ratio (%)**
IAEA (1973)	USA	Anomalies	Prospects	Deposits				**0.70%**
		100,000	4,000	700				
Perry (1968)	SW USA	Prospects	Surveys conducted	Drilled	Possible development			**0.57%**
		352	47	23	2			
Bear Creek Mining data (1967)	? USA	Possible targets	Drilled	New mineralization	Tonnage potential	Deposit	Orebody	**0.30%**
		1,649	60	15	8	5	1	
Cominco data (1971)	? Worldwide	Properties	Major exploration effort	Mines	Profitable mines			**0.70%**
		1,000	78	18	7			
Subramaniam (1972)	India	Anomalies	Targets	Promising prospects				**0.55%**
		1,100	25	6				
Kreuzer et al (2007)	Australia	Projects	Mines					**1.03%**
		970	10					
Rio Tinto data (2007)	? Worldwide	Greenfields						**0.03%**

Ground selection

Ground selection is the process of selecting a region (this might be a geological domain or mineral province) or an area within the region to evaluate for mineral resources. Usually this is an office based phase but may include visits to the region under consideration. Normally publicly available information is compiled, integrated and evaluated in order to identify regions worthy of moving to the next phase.

Desired outcome: Regions or areas identified or a prioritised list developed for exploration.

Target generation or reconnaissance

Target generation or reconnaissance selects prospective locations and reduces a broad search to areas which are deemed to be most likely to host economic mineralization. Target generation may use any one of many techniques including prospecting, mapping, remote sensing surveys, geochemical surveys, geophysical surveys, or even drilling for geological information.

Desired outcome: Targets identified within the exploration area which will be tested by sampling.

Target testing or investigation

Target testing or investigation is the phase of an exploration programme the target is sampled and measured for its size, quality and the identification of features associated with the potential deposit, often considered essential according to the deposit model under consideration. The latter may include the presence of the sought after mineral, appropriate structures, or other associated features, such as alteration. Sampling may take the form of taking samples from the surface or underground, trenching, or drilling.

Desired outcome: Mineralization identified in sufficient quality and quantity that warrants further evaluation.

Deposit delineation

Deposit delineation aims to quantify the amount (tonnage or volume) of mineral present within and the quality (usually grade) of a mineral deposit. This phase involves extensive and intensive sampling of the deposit, and assay or analysis of those samples so that a mineral reserve can be calculated. Such sampling may be carried out on the surface or underground but commonly involves much drilling. The actual calculation of the resource is highly regulated by codes or standards such as those developed by PERC (Pan-European Reserves and Resources Reporting Committee) for Europe, JORC (Joint Ore Reserves Committee) for Australasia or NI 43-101 (National Instrument) for Canada. These standards or codes, and others, are aligned to the CRIRSCO (Committee for Mineral Reserves International Reporting Standards) template for the reporting of reserves and resources.

Desired outcome: A mineral deposit with a well-founded calculation of the quantity and quality of the minerals in the deposit compliant with a recognised Code or Standard.

Following the successful outcome of the last phase other studies are carried out, such as geotechnical, metallurgical, marketing, planning, environmental, and social studies which support the development of evaluations of the mineral deposit. These evaluations include Preliminary Economic Assessments, Pre-feasibility Studies, Feasibility Studies, and Bankable documents. Once a Pre-feasibility or Feasibility Study has been carried out a mineral reserve may be reported.

Desired outcome: A mine which makes a profit.

Contexts of use, application fields

Mineral Exploration is an economic activity carried out by private industry and in some instances government agencies to identify the location of economically viable mineral deposits. Private industry normally means the minerals sector but may also include the manufacturing sector that may need a particular raw material to manufacture the products it fabricates. Mineral exploration consists of many activities and continually seeks to test an idea or hypothesis. If the outcome is sufficiently positive then the programme normally continues to the next activity or question. However, external factors, e.g. the price of a commodity, may change with time and alter the direction of the organization carrying out the exploration or its priorities.

The principal stakeholders and their question(s) for Mineral Exploration are:

Stakeholder	Stakeholder Question(s)
Minerals industry	Where (country, region, metallogenic province etc.) should I explore? Which projects should I invest in?
Manufacturing industry	Where will I source the raw materials I need to manufacture my products?
Construction sector	Where will I get the raw materials I need to build?
Government	Why you should invest in our country? Where will we get the raw materials to construct our infrastructure?

Input parameters

Mineral exploration commences with an idea or hypothesis. The idea often comes from experience, for example, a company may have experience in working with a particular type of deposit in one country and wishes to apply this experience and knowledge to another country. Or perhaps a company has developed a new exploration method and wishes to apply it to look for a particular type of deposit where it has been successful or wishes to apply it to another known type of deposit. Alternatively, perhaps a company has an excellent track record in looking for a particular deposit type using a specialised conceptual model (the conceptual model may in this instance be considered to be a sophisticated idea). Mineral exploration can thrive where there is excellent government, or other, geoscience information available to the exploration sector. However, excellent geoscience of itself is not sufficient. A thriving exploration sector also needs an excellent and transparent regulatory regime; government encouragement (not necessarily financial incentives); public understanding and approval; good infrastructure (access, telecommunications, water, and power); good services (technical and financial); a capable workforce; certainty (timeliness, legal, environmental, permitting, implementation, consistency, lack of duplication, corruption free, etc.); security; and political stability.

Type(s) of related input data or knowledge needed and their possible source(s)

Under this heading we consider topics that are relevant to Mineral Exploration but do not necessarily fit into the generic heading. This includes:

- Permission to explore
- Basic geographical and topographical data (maps)
- Geoscience data
- Software

Permission to explore

The most basic requirement is permission to carry out exploration. This varies from jurisdiction to jurisdiction. It may mean obtaining a permit or licence to explore from a government, provincial or local authority. In some countries it may mean obtaining permission from a land or mineral rights owner. In addition, it may be necessary to obtain permission to carry out certain activities or to carry out activities in or near protected sites or certain material assets. There are too many jurisdictions across Europe for a comprehensive review of the permissions required to carry out exploration and suffice it to say that permission is required. The onus is therefore on the explorer to determine what permissions are required in the jurisdiction they are operating and to obtain them an d ensure that they keep them in good standing.

Basic geographical and topographical data (maps)
The most basic requirement is a geographical and/ or topographical map – *sensu lato*. In modern times topographical maps may be either hard copy (paper) or soft copy (digital). If the latter then software will be required to view, store and manage the maps. The scale of the maps required will depend on the stage at which the project is at and may be small scale (for example 1:250,000 for regional work) or large scale (for example 1:1,000, or larger, for deposit evaluation).

A topographical map may be a traditional map; satellite imagery; aerial photography; digital terrane (or elevation) models; or other representations of the land surface. Such maps are often used as base maps upon which information of interest is displayed.

Geoscience data
Mineral Exploration does not require information or data to carry it out. However, it is greatly facilitated by prior reliable geological information and data. This prior information may come from government (commonly from Geological Surveys), exploration companies, universities, or the internet.

Government
Available datasets such as geochemistry, geophysics and boreholes (primarily from national or regional geological surveys) will also often be consulted to aid in interpretation of surface and sub-surface features and to generate exploration targets. Such information may also be available on an exclusive or non-exclusive basis from third part vendors. In addition, companies may enter into data exchange arrangements where seek to gain understanding and benefit.

Exploration companies
In some jurisdictions it is mandatory for exploration companies to report their work to a government agency. Subsequently these reports may be made available either after a specified period or upon the relinquishment (or withdrawal) of the exploration permit.

Universities and Research Institutes
The geoscience or mining departments of universities and research institutes often contain much information of interest to the exploration community. This primarily relates to detailed geological knowledge of an area or deposit type, and also geochemical and geophysical surveys.

It is common practice for exploration companies to sponsor student projects (up to and including post-doctoral projects). Such projects are carried out on a mutual interest basis with the university providing expertise and the exploration company financial support.

Internet
Modern exploration makes use of the wealth of information available over the internet. There are many sites dedicated to providing basic information such as www.minerals4eu.eu/ and individual geological surveys normally have an abundance of data available much of it free

to download. There are also information services available from commercial vendors with some available for free with more available for purchase.

Software
Modern day topographical and exploration data is often stored, manipulated, processed, visualised and displayed in [Geographical Information Systems (GIS)](). In addition, specialist software for geoscience data sets (geological, geochemical, geophysical and remotely sensed data) is often used to process, interpret and visualise, and display information and data as well as to generate new insight and knowledge.

Model used

Different types of model are used in mineral exploration. As referred to above often times an exploration programme is guided by reference to a particular model of the type of mineralization or commodity being sought, e.g. a porphyry copper deposit model. This is often referred to as a **genetic model**. A second type of model would be a model that guides the exploration – the **exploration model**. This sort of model takes features from the genetic model which can be observed or measured. In our porphyry copper model example the geologist may look for the signature alteration that accompanies all such deposits. These would be the features that would be looked for in the first instance. Another type of model relates specifically to the geological situation in the area under consideration and may be termed the **conceptual exploration model** or simply the **conceptual model**. It would combine the known geological features of the area and the exploration guides being sought. These may be portrayed in a simple three dimensional cartoon highlighting the salient features. This model would be constructed from the known (or presumed) geology, existing maps, field observations and/ or remote sensing. It is often this model which is tested throughout the exploration process.

System and/or parameters considered

Boundaries
In terms of boundaries, exploration may have **national**, **geological** or **permit** boundaries.

National boundaries
Exploration may be restricted to a single jurisdiction as regulations generally vary from one country to another. However, geology does not recognise the political borders of countries and favourable geological features and lithologies cross from one jurisdiction to another. In such cases exploration companies may take out exploration permits on either side of the political border.

Geological boundaries

Geological boundaries on the other hand may define the area of interest of the exploration company. If a company is interested in exploring for carbonate hosted zinc-lead deposits then the area being explored should be underlain by such rocks and not volcanic rocks, for example. The change from one rock type to another may form the boundary of the system. However, rock type is not the only geological boundary. Other geological boundaries include: metallogenic provinces; structural style; age of rocks and age of mineralizing system.

Permit boundaries

Often times the area being explored is constrained by the permit. The permit would normally have a map illustrating the area where exploration may be carried out by the permit holder or licensee. It may be that the ground adjoining the area under permit is another permit held by another explorer. Permit boundaries may be defined by rectangular coordinates or geographical features visible on the ground – depending on the jurisdiction. The size of individual permits may also vary from jurisdiction to jurisdiction.

Scale

Scale in this case refers to the size of the area over which exploration is being carried out. Scale depends on numerous factors including the financial resources available, target commodity or deposit type, time, and permit conditions. It may begin at a national level and then proceed to regional level targets which in turn may be reduced to targets at a local level.

Financial resources

The magnitude of the exploration programme and its intensity ultimately depends on the financial resources available to the company. Often times the availability of funds is dependent on the success of a previous phase of exploration. If the previous phase was successful then it will be easier to justify additional expenditure than if there little or no success. But the availability of funds also depends on the current market conditions. For example, if the price for the commodity being sought decreases then it will be more difficult to justify further expenditure regardless of the success of previous phases.

Target commodity or deposit type

Different commodities occur in deposits of different sizes. For example, iron deposits typically occur on a much larger scale than precious metal deposits. Therefore typically the area over which exploration for iron is carried out will normally be much larger than for, say gold deposits. On the other hand the deposit type or commodity being sought may become fall out of favour – perhaps for an environmental reason and the exploration company may find it difficult to justify exploring for the deposit type to the investing community, the regulators, or its own management. An example might be uranium deposits.

Time

Exploration may take place over timescales as short as individual field seasons to as long as several decades, particularly when attempting to expand known deposits. Exploration around working mines is particularly important for long term and very long term planning – ranging up to tens of years.

Regulations

Some jurisdictions require that the area under permit be reduced on a phased or planned basis. For example a permit holder may have to reduce the area of the permit after stated periods, by 50% after 5 years; by 90% after 10 years.

Time / Space / Resolution /Accuracy / Plausibility

Conceptual models of the geology of a specific area need to be dynamic. Although the geology of an area rarely changes on the timescale of a human lifespan the uncovering of new evidence or a new or reinterpretation of the evidence may alter the conceptual model and hence the model may be updated and the exploration programme may be revised.
Spatial scale is discussed in the section headed “System and/or parameters considered”. The initial scale for target generation is unlikely to be the same one that is used to delineate an economic ore-body. Often a large scale target generation programme on a regional scale will create numerous smaller local scale target areas that can be investigated individually.
While high resolution and accuracy are important at all phases of exploration it is crucial for the deposit delineation stage. At this stage an estimate of the tonnage and grade of the deposit is made and a value may be put on the deposit. It is at this stage that major decision on whether to proceed with the development of the deposit may be made which may result in expenditure of hundreds of millions or billions of euros are made. Therefore the accuracy of the estimate is crucial. Accuracy is guided by reference to codes and standards often determined by the world’s Stock Exchanges. Most Stock Exchanges require the standard or code to be aligned to the CRIRSCO template. CRIRSCO is the Committee for Mineral Reserves International Reporting Standards and comprises representatives of organisations that are responsible for developing mineral reporting codes and guidelines in Australasia (JORC), Brazil (CBRR), Canada (CIM), Chile (National Committee), Europe (PERC), Mongolia (MPIGM), Russia (NAEN), South Africa (SAMREC) and the USA (SME).

Indicators / Outputs / Units

The desired output from mineral exploration is ultimately the identification and delineation of an economically viable mineral resource which can then be mined. Each phase of exploration corresponds to a more advanced step along the path to an operating mine.

Mineral resources are measured in terms of their mass or volume and a measure of quality which may be the grade or amount of a substance in the deposit, although standard units vary for different commodities.

Treatment of uncertainty, verification, validation

Ore body validation is covered by the various international reporting codes for mineral resources, e.g NI 43-101, JORC and PERC.

Main publications / references

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Kreuzer, O.P., Etheridge, M.A., and Guj, P., 2007b. Australian junior exploration floats, 2001-06, and their implications for IPOs. Resources Policy, v. 32, p. 159-182.

Related methods

Not applicable

Some examples of operational tools (CAUTION, this list is not exhaustive)

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Key relevant contacts

National and Regional Geological Surveys, Mineralogical and Geological Associations.

Ground investigations for mineral exploration

FACT SHEET

Ground investigations for mineral exploration

Scope

Once a prospective area of mineralisation has been identified by regional mapping, geochemistry or remote sensing further detailed ground investigations will be required to assess if a mineral resource is present and, if so, what is the size and properties of the resource. These ground investigations can consist of a range of different methods, depending on the scope of the project, the nature of the mineral deposit and the level of detail/information required. For example much more information will be required for delineating a mineral reserve compared to a resource and delineation of a gold resource will require considerably more information than an aggregate resource.

The most common methods used include:

- Drilling (this can include diamond drilling, rotary percussion drilling and auger drilling)
- The digging of trenches and trial pits
- Shallow geophysical techniques (including resistivity, electromagnetic, magnetic, radiometric and shallow seismic)
- Geochemical surveying on a local scale
- Geological mapping on a local scale

The latter two methods are described in more detail in separate factsheets; the first three will be covered in more detail here.

Contexts of use, application fields

Drilling
Drilling is one of the primary tools used when exploring for minerals as it is the most economical and quickest method which can return physical samples of rocks at depth for analysis. Drilling is an essential part of any mineral resource assessment and the quantity of drilling undertaken will, in most cases, directly correspond to the confidence levels associated with delineating mineral resources. There are multiple types of drilling with different advantages and disadvantages, the method selected will depend on the budget available for the survey, the minerals which are being studied and the level of geological detail required.

Auger drilling

Auger drilling. Source NERC © BGS

This is the simplest type of drilling and also the least expensive, it is however only suitable for unconsolidated or loosely consolidated material and the maximum depths reached by this method can be limited. Auger drilling can vary from a screw auger where a motor will drive a threaded bar into the ground to percussion auguring where a weight is dropped onto a core barrel to drive it down. The former method will produce a disturbed record of the subsurface via chippings in the thread of the auger whereas the latter will produce an in-situ core which will lessen the possible of contamination from different horizons and allow primary structures and features in the geological record to be observed. Auger drilling can be conducted via small lightweight vehicles with the minimum of surface infrastructure requirements.

Rotary percussion drilling

A rotary percussion drill rig. Source: NERC © BGS

This is the most common type of drilling used for mineral exploration due to its suitability for depths of several hundred metres and its low cost compared to the alternative of diamond drilling. Rotary percussion drilling consists of a drill bit attached to a rotating string which is rotated by a motor at the surface. The rotation is combined with a percussion or hammer action to break rock up. High pressure air is pumped down the drill-hole and used to both lubricate the drilling surface and transport loose material back to the surface. This material or 'cuttings' is collected and used to characterise the underlying geology and mineralisation. Issues from contamination can arise when the cuttings are brought back to the surface if material from the walls of the drill hole is incorporated with material from the drilling surface. This can make it difficult to characterise the geology at specific depth horizons. As a result a technique known as reverse circulation drilling is often used where the cuttings are transported back via a separate tube inside the drill stem. This will produce a sample where the down hole depth is exactly known which, if prospecting for minerals which are susceptible to low levels of contamination like gold, is essential. The downside of this method is that no core is produced and therefore no observations on structure or geological features can be made. Also the drill rigs required are substantially larger than for auger drilling which may require site preparation to allow access. Controlling the orientation of the hole is also difficult with this method of drilling.

Diamond drilling

Core produced from diamond drilling. Source: NERC © BGS

Diamond drilling is the most expensive drilling method and is considered the highest quality for both determination of geology and for characterisation of core subsamples. Diamond drilling differs from the others methods discussed in that a solid rock cylinder is produced by a spinning cylindrical diamond tipped cutting bit. The rock sample that is retrieved can be tied precisely to downhole depth and the core allows detailed geological and structural observations of the rock occurrence in-situ. These types of core can also yield large uncontaminated samples which can be used for subsequent geochemical assay. The diameter of the core taken will depend on the diameter of the drill bit used, generally the larger the diameter the better the core recovery, however drilling costs rises significantly with larger diameters. Disadvantages with this technique include its high cost as well as the large amounts of water that are required to lubricate the cutting bit. This method is also slow compared rotary percussion drilling.

Digging of trenches and trial pits

Geological investigations in a trial pit. Source NERC © BGS

Trenching and trial pitting is the simple exercise of digging shallow holes, usually between one and four metres deep to obtain lithological information under shallow cover. Bulk samples can also be obtained via these techniques as large volumes of undisturbed material can be easily accessed. These types of techniques are best employed for shallow flat lying mineral bodies and to aid in the interpretation of cuttings from rotary percussion drillings as structural and lithological relationships can be seen in-situ. These techniques are also employed where large sample sizes need to be taken. For example if there are issues with grade distribution for deposits were mineralisation is localised (e.g. gold) or where large volumes of material are required to test processing techniques. Trenches and trial pits will be dug using heavy plant such as bulldozers, excavators and back-hoes, however in areas where a high availability of affordable labour and restricted access to vehicles they can be hand dug.

Shallow Geophysical Techniques

Shallow geophysical techniques are used where cover from soil, non-prospective deposits, or a deep weathering profile cover the deposits of interest or to join observations made from disparate surface observations or samples from drilling. Geophysical techniques use a physical or chemical property of a rock which can be detected remotely, either passively or by applying an external input, which can be used to build an interpretation of the 3D geology at depth. However is must be noted that the geophysical properties of rocks could be related to one of many geological parameters for example mineralisation, lithology, structure, etc. and careful interpretation combined with ground truthing (i.e. comparing with observations from other methods) is required to best utilise these techniques.

Resistivity surveys

A resistivity survey array, mounted on the back of a vehicle. Source: NERC © BGS

This type of survey involves installing electrodes into the ground surface, passing a current through them and measuring the resistance of rocks and soil through which the current passes. A variation on this type of survey is commonly used in mineral exploration is known as Induced Polarity or IP. In IP surveys the primary electrical charge induces an electro chemical charge within sulphide minerals. When the initial current is switched off this secondary charge can be detected.

This type of survey works best within the top hundred metres of the rock profile and does not work well if there is a deep weathering profile or high salinity groundwater is present. These surveys also require arrays of electrodes to be installed which is labour intensive; as such it can be expensive and is often used for detailed target delineation on a site specific level.

Electromagnetic surveys

Electromagnetic surveys measure how conductive a rock is. This can be done either by using the Earth's naturally occurring radioactive field or by applying an external electromagnetic field by laying a charged cable over the surface. The latter technique is more commonly used for ground based surveys. For rapid surveys both the transmitter and receiver will be carried by the operator when conducting traverses over the area of interest.
This technique will highlight boundaries between conductive and non-conductive rocks and so works especially well for metallic minerals. Conductivity of rock or soil will depend on a number of factors such as any pore spaces present, fluids present in fractures and pore spaces and the chemical and mineralogical makeup of the area being surveyed. The effects of these factors need to be clearly understood when results are interpreted. This type of survey can also be utilised down drill holes to log the conductivity in detail of rocks at depth. Electromagnetic surveys are best for looking at near surface features, up to several hundred metres in depth as interpreting the results and filtering out noise becomes increasingly difficult as depth is increased. This technique is also relatively expensive compared to other geophysical techniques and is commonly used for detailed target characterisation once drilling has taken place. Electromagnetic surveys are also difficult to interpret if deep weathering profiles, saline groundwater or large bodies of magnetic minerals such as graphite or magnetite are present.

Magnetic surveys

All rocks have some degree of magnetic susceptibility. In a magnetic survey an instrument known as a magnometer measures disturbances in the earth's magnetic field and as such the different magnetic signature of different rock types will be recorded. Magnetic surveys are often used in regional reconnaissance and are mounted in aircraft, however, they can also be used for local site specific ground-based surveys. Here the instrument is mounted on a pole to prevent any interference from near-surface anomalies and the area of interest is traversed, often on foot. The data recorded then requires interpretation to link magnetic properties to areas of mineralisation or to particular lithologies. Ground based magnetic surveys are predominantly employed to identify strongly magnetic targets (i.e. containing magnetite or pyrrhotite) that occur under cover for subsequent further investigation by drilling.

Radiometric surveys

A radiometric survey is a passive method of recoding the natural radiation emitted by rocks at the surface. The instrument used is known as a spectrometer and will be carried by hand when conducting site specific surveys or used to lower down drill holes to find horizons of rocks with high levels of radioactivity. Many rock types contain radioactive elements such as potassium, thorium and uranium. If a particular style of mineralisation or rock type of interest contains minerals with high levels of these elements then radiometric surveys is a rapid way of identifying such deposits. A spectrometer can only detect one type of radioactive elements at a time so before conducting a survey the element of most interest needs to be defined. One limitation with radiometric surveys is that they have no depth penetration and can only record readings from the surface so are of no use in areas of cover sediments.

Shallow seismic surveys

A vibroseis truck survey in progress. Source: NERC © BGS

Seismic reflection surveys are most commonly used in oil and gas exploration in marine environments, but the technique is also commonly used in terrestrial settings. This traditionally involves a high frequency, short duration pulse of acoustic energy being generated at the surface, which propagates through the soil and rock profile. This then reflects the pulse back up to the surface and an array of receivers. Reflections will be generated from interfaces which represent changes in acoustic impedance. These changes could be due to a range of factors such as a change in rock type, nature of fluid-fill, mineralisation, structural features etc... and like all geophysical techniques requires careful interpretation to ensure the correct model is derived. As such, control from boreholes or surface observations are often required to interpret the results.

The acoustic signal can be generated in a number of ways, the simplest being naturally generated signals (passive seismic) such as from ambient noise (natural or man-made such as traffic); however it can be difficult to distinguish noise from true returns via such methods. The strength of the return and depth of penetration will be determined by the strength of the initial acoustic pulse, therefore for shallow surveys an operator striking a block at the surface with a sledgehammer can acquire near-surface data, whereas for larger areas and greater depths, airgun or dynamite sources may be used. Specially designed seismic, or vibroseis, trucks are now commonly used. These trucks use a piston mounted in the centre of the vehicle to generate the signal using a vibrating moveable element. Vibroseis methods require relatively level ground and surfaced tracks to operate, and as such are only suitable in certain settings.

Input parameters

Not applicable

Type(s) of related input data or knowledge needed and their possible source(s)

The techniques described in this factsheet involve collecting primary data. However, the processing and interpretation of the results and data these techniques collect does require some form of geological knowledge or model to be known. These techniques will never be conducted in isolation but will be utilised once regional reconnaissance has already been conducted and broad areas of mineral resources or potential areas of interest have been identified. Such regional reconnaissance may include geological mapping, regional geophysics and regional geochemistry. The techniques described in this factsheet are designed for site specific studies on known and/or partially understood targets.

Model used

The geophysical techniques described in this factsheet will all require some degree of modelling to convert the various properties measured into geological parameters (physical or chemical) this process is known as inversion. Geophysical inversion will require a range of computational and statistical processes to convert primary data and will require expert input. The details of the inversion process will depend on the exact technique used.

System and/or parameters considered

The techniques described in this factsheet are designed to be used on a site specific scale when prospecting for minerals. The size of specific site covered will depend on the budget available and the type of mineral that is being sought. Normally the larger the area studied the cheaper and more rapid techniques will be used, so for larger areas rotary percussion drilling will be used to identify specific targets which can subsequently be studied in more detail using diamond drilling and ground based geophysical techniques. Generally areas for these more expensive techniques will be several square kilometres or less.

Time / Space / Resolution /Accuracy / Plausibility

The resolution will vary depending on the precise method used and the purpose required.

Indicators / Outputs / Units

These will vary depending on the precise technique used.

Treatment of uncertainty, verification, validation

Interpretation of drill core relies on the observations made by an expert, it is a highly interpretive process and the errors associated with it can be very difficult to quantify as they will be reliant on existing geological knowledge, the complexity of the geological setting and whether the expert's interpretation is accurate. The greatest uncertainty of interpretation will be in areas with a high degree of geological variance.

Treatment of uncertainly using geophysical techniques also is subject to the difficulty of quantifying uncertainty when using expert judgement. However, due to the statistical techniques used to process these data from their raw form into models of the physical properties of the subsurface some quantitative degree of measuring uncertainty can be applied.

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Related methods

Not applicable

Some examples of operational tools

Not applicable

Key relevant contacts

Geological survey organisations
Exploration companies
Geological or exploration consultancies

Resource Estimation

FACT SHEET

Resources and reserves estimation

Scope

There frequently is confusion in the understanding of the terms '**resources'** and '**reserves'**, and they are sometimes, incorrectly, used interchangeably. It is important to clearly define these terms and ensure their correct usage, particularly if comparisons are to be drawn between deposits or investment decisions are to be made based on them.

Mineral resources are defined as natural concentrations of minerals or bodies of rock that are, or may become, of economic interest due to their inherent properties (for example the contained quantity of a metal [known as its 'grade'] or high crushing strength of a rock that makes it suitable for use as an aggregate [an assessment of the deposit's 'quality']). The mineral will also be present in sufficient quantity that there are reasonable prospects for eventual economic extraction.

The part of a mineral resource which has been fully evaluated and is deemed commercially viable to work is called a mineral reserve. This process includes the assessment of several 'Modifying Factors' including (but not restricted to) mining, processing, metallurgical, infrastructure, economic, marketing, legal, environmental, social and governmental factors. In the context of land-use planning, the term mineral reserve should be further restricted to those minerals with legal access and for which a valid permission for extraction also exists (i.e. permitted reserves). Without a valid planning consent no mineral working can legally take place.

The relationship between resources and reserves is shown in Figure 8. A mineral resource may be classified as inferred, indicated, or measured, whilst a mineral reserve may be classified as either probable, or proved. These categories will depend on the associated degree of geological certainty, feasibility of economic extraction, accessibility and legal status (i.e. planning permission).

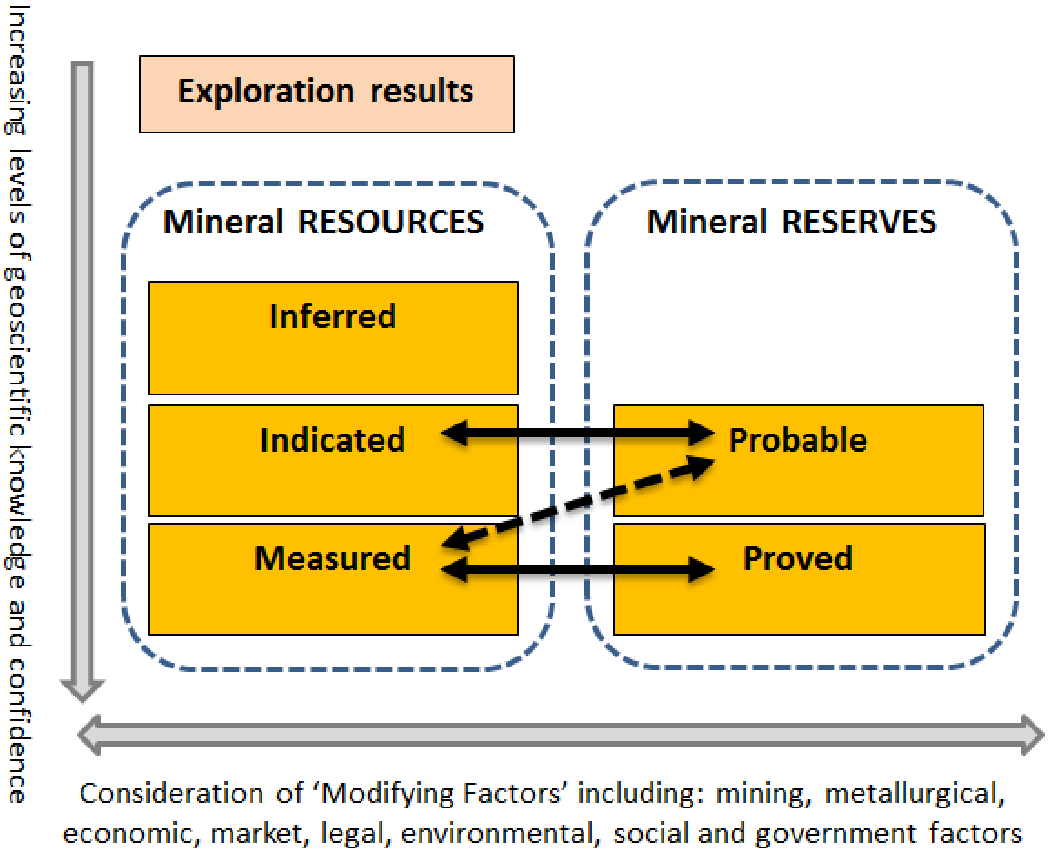

Figure 8 The relationship between mineral resources and mineral reserves.

The process of resource estimation is used to define a mineral resource in three dimensions, with the ultimate aim of determining both the size (typically reported in tonnes) and grade (generally expressed as the metal or mineral content in wt. % or g/t) of the resource. A 3D ore deposit model (or block model as they are known) is used to show the extent of the deposit below the surface but also the distribution of metal or mineral within the deposit (i.e. zones of high- and low-grade) (Figure 9). With increasing amounts of information and consideration of other factors, such as economic, social and environmental aspects, a mineral resource may be upgraded to a mineral reserve. However, it is important to note that a reserve typically only forms a very small part of a resource.

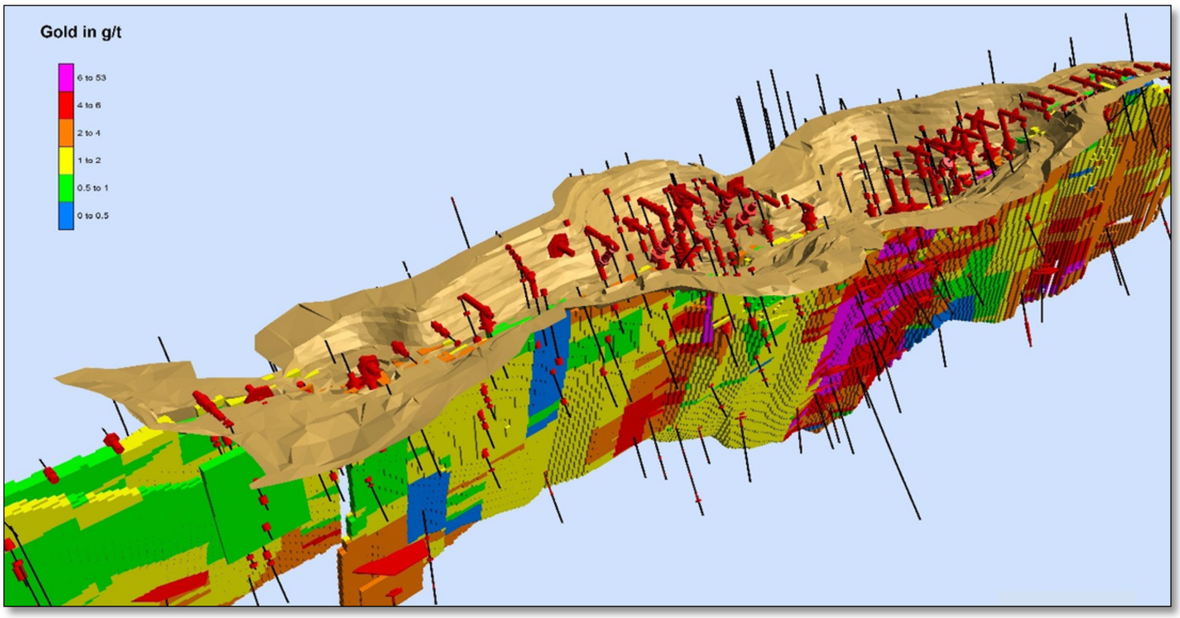

Figure 9 Example of a 3D ore deposit block model showing the distribution of low grade (blue and green) and high grade (red and pink) zones (used with permission of Goldstone Resources).

Contexts of use, application fields

Many of the individual steps involved in the process of estimating a mineral resource (e.g. geochemical assay and geostatistical analysis) are transferable to many other application fields, including environmental monitoring, groundwater and mineral exploration. However, resource estimation is a specifically concerned with determining the size and quality of a mineral resource with a view to commercial exploitation, hence the process is largely utilised by mining companies.

Input parameters

Input parameters will vary depending on the estimation method selected. For example, traditional resource estimation methods (e.g. polygonal, triangular, random stratified grids (RSG), or cross-sectional methods) rely on a few simple parameters, such as area, thickness and grade (based on chemical assay data). Geostatistical estimation techniques, such as Kriging, block modelling, and inverse distance weighting (IDW) are typically more sophisticated than traditional methods and therefore rely on a greater number of input parameters. For instance, Kriging requires the selection of an appropriate model type (e.g. global variograms, relative variograms, or directional variograms) and parameters that best describe the relationship between the distance from one observation to the next and the difference in the observed values at those points.

There are three key parameters to consider (Figure 10):

1. Nugget – this represents sample variability over small distances caused by either small-scale geological or mineralogical controls, or by sampling and assaying errors.
2. Range – the distance (in field units) at which samples become independent of each other (i.e. a long range might indicate geological continuity, whereas a short range might suggest variability over a short distance).
3. Sill – a measure of the variance between sample values (i.e. a high sill value indicates a high degree of variance, whilst a low sill value indicates a small amount of variance).

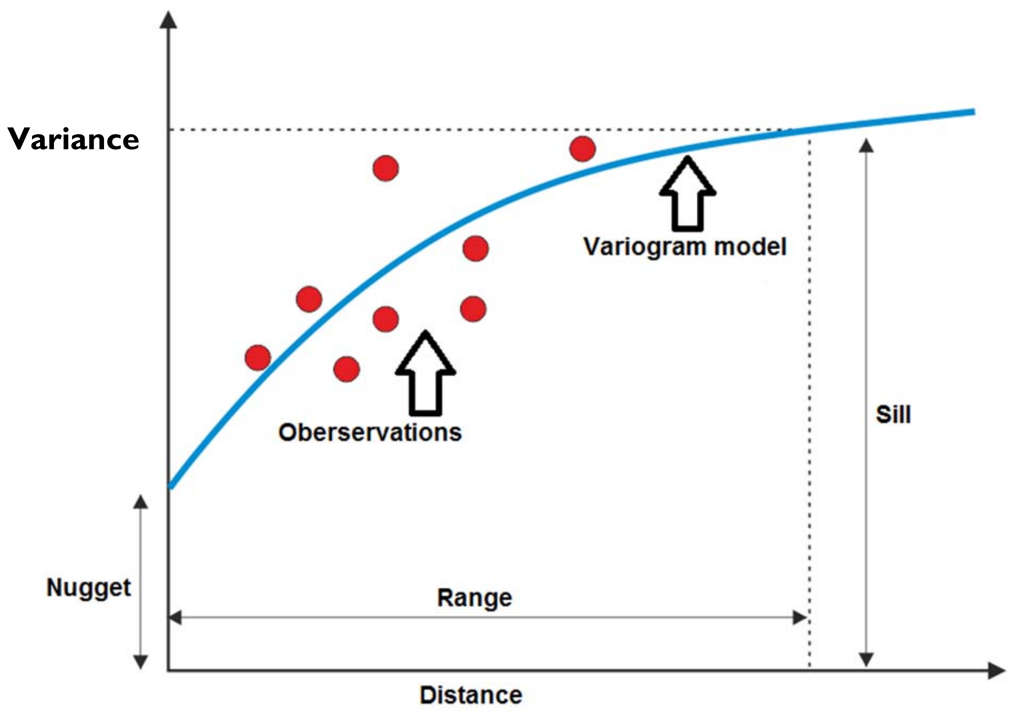

Figure 10 Example variogram showing the nugget, range and sill.

Type(s) of related input data or knowledge needed and their possible source(s)

During exploration for a mineral resource a number of data sources may be used, these might include: topographic base maps; geological maps; geophysical survey data (e.g. radiometrics); geochemical (e.g. rock, soil or stream sediment) data and; historic exploration data (if they are available). These data are typically recorded in a geographic information system (GIS) and are interrogated (e.g. using prospectivity analysis – Figure 10) to define a target, or series of targets. Once a target has been identified core drilling is used to gain information about the geology, structure and mineralisation in three dimensions. The number of drill holes and their spacing will depend on the size and type of mineral deposit. Drill core is carefully logged by a geologist to record important information about host-lithology, structures, distribution of mineralisation, etc. Some of the core material will also be sub-sampled and sent to a laboratory for assay. All of the data and information gained from the exploration programme and drill campaign will be statistically interpolated (e.g. using methods such as Ordinary Kriging or Regression Kriging), with the intention of producing a resource estimate.

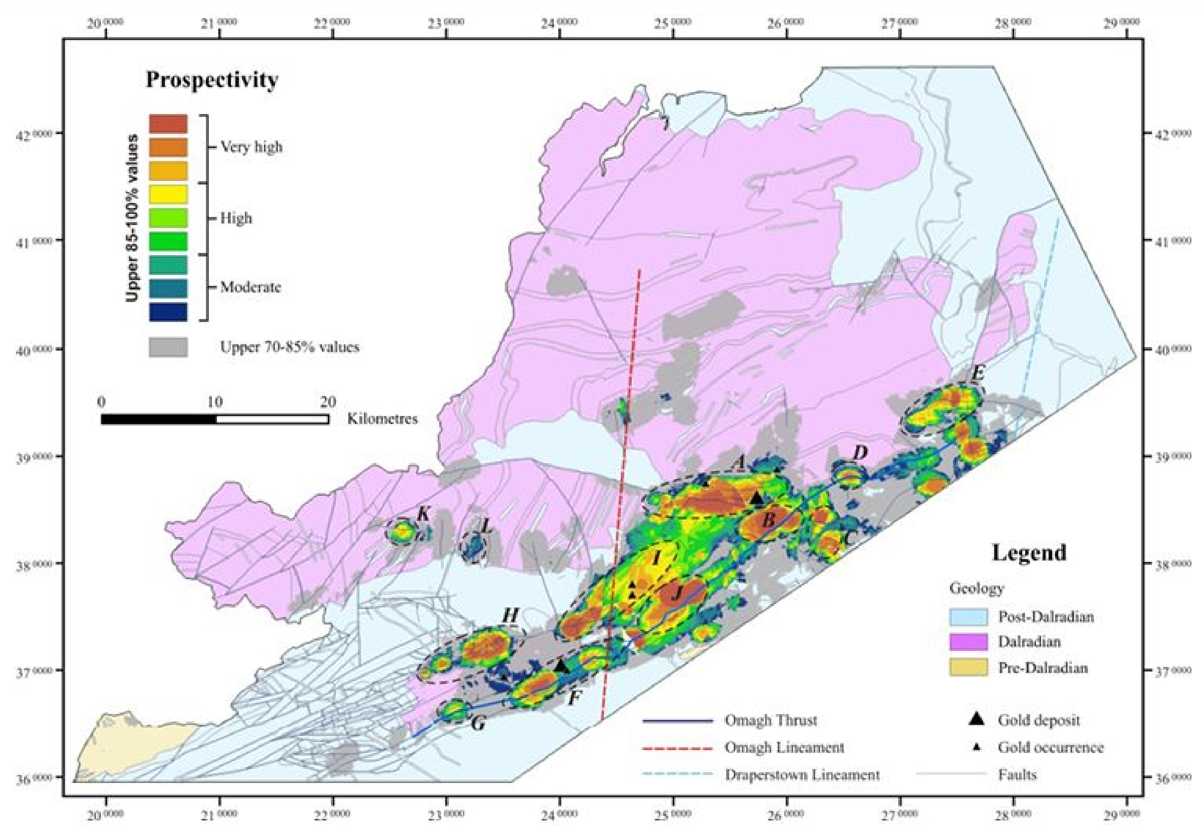

Figure 11 An example of the type of output generated in a GIS using prospectivity analysis techniques. Areas in red would be considered as targets for further work or drilling.

Model used

Resource estimation can use a number of different models depending on which are most appropriate for the particular circumstances. Geological modelling maybe used to understand the structure of a mineral deposit, for example is the deposit folded or faulted. Genetic mineral deposit models are used to understand the broad-scale features of a deposit and what might be expected in terms of size, grade, ore mineralogy, and host-lithologies. Genetic models may also be used in the validation of 3D block models. Geostatistical modelling, for example inverse distance weighting (IDW) and Kriging are widely utilised in modelling mineral resources.

System and/or parameters considered

Mineral resources are constrained by geology (i.e. certain deposit types only occur in specific geological settings) and by their very nature have a geographical location. Resource estimation occurs at the individual mineral deposit scale, although this can be hugely variable between hundreds of thousands of tonnes and many billions of tonnes. The boundaries of a metallic mineral deposit may be diffuse, i.e. the metal grade may gradually decrease towards the deposit boundaries, or at depth. However, the distribution of grades in a deposit is likely to be highly complex and certainly not uniform (Figure 9). These boundaries will be defined as part of the resource estimation process by a series of cut off grades (COG). Cut off grades are used to delineate ore from waste, low-grade ore from high-grade ore, mineralised rock from non-mineralised rock, etc.

Time / Space / Resolution /Accuracy / Plausibility

The scale of a resource estimate will largely be defined by the size and type of deposit, and the range of COG used to delineate economic and sub-economic mineralisation. Mineral resource estimates do have a temporal component in that a resource will eventually become depleted; this period is often termed the life of mine (LOM). Again, this is subject to the type and size of deposit, but also a host of economic and technological factors.
Mineral resources may also change (increase or decrease) over time depending on market conditions, prices, economics and technology. The latter can include both technological developments that increase or decrease the demand for a mineral and improvements in the methods used to extract a mineral which results in greater quantities becoming economic to extract.

The resolution and accuracy of a resource estimate will, to some extent, be determined by the amount of data gathered to produce the resource estimate. For instance, a small, complex deposit (e.g. vein-hosted gold) might require a higher sampling density (i.e. a greater number of drill holes between 50–100 m apart) than a large, relatively simple deposit (e.g. coal) that would require fewer drill holes with a spacing of about 400–500 m. This would mean that the resource estimate for the vein-hosted gold deposit is based on a greater number of actual measurements/observations and thus reduced interpolation. It also reduces the distance, and therefore the variance, between observed points.

Indicators / Outputs / Units

Mineral resource estimates are typically reported in tonnes, with the grade being expressed as g/t or wt. % of metal or mineral. In some cases the metal may be reported as the oxide (e.g. tungsten as WO_3 or rare earth elements as RE_2O_3) rather than as the pure metal.
The tonnage and average grade figures are derived from the 3D resource block model (Figure 9), which is comprised of a number equally sized of blocks, with each block representing a volume of ore at a given grade. Each block will have a unique set of attributes

(e.g. density, rock type, grade, confidence level, etc.). Block models can be viewed in specialised software packages (often the software package used to create the model), in which the model may be rotated, tilted or sliced to produce different views of the deposit. The models can also be viewed as a static image. Grade envelopes (areas of similar average grade) are often coloured to allow easy identification of high- and low-grade areas of the deposit (e.g. in Figure 9 areas of low-grade are coloured blue and green, whereas higher grades are represented by orange and red colours).

Treatment of uncertainty, verification, validation

Ultimately, a resource estimate is a model that relies on large amounts of data, but also human judgement and interpretation. Data and information used to produce a resource estimate are subject to different levels of quality control and validation. For example, assay laboratories will typically have strict quality control and quality assurance protocols that allow errors to be quantified. However, core logging is an interpretive exercise that relies on the skill and experience of the person undertaking the logging, therefore errors associated with logging are much harder to quantify. In terms of errors directly associated with the production of a 3D block model it is not always possible to quantify the model uncertainty. This is particularly true for models produced using traditional estimation methods (e.g. triangular methods); however, geostatistical methods, such as Kriging, do allow uncertainties to be calculated.

In many countries, companies that are seeking investors are required to report their resource and reserve estimates in accordance with an internationally recognised system of reporting. These systems (or reporting codes) will include a requirement for resource and reserve estimation to be conducted by a 'competent person' or appropriately 'qualified person'. Importantly these systems of reporting will also recommend that resource estimates are subject to auditing by an independent, competent person. Many of these reporting codes, such as JORC, PERC, NI 43-101 and SAMREC, adhere to a common 'template' known as CRIRSCO (see publications /references and key relevant contact sections of this fact sheet for more information).

Main publications / references

CRIRSCO. 2013. *Committee for mineral reserves international reporting standards, International Reporting Template*

JORC. 2012. *Australasian code for reporting exploration results, mineral resources and ore reserves.*

NI 43-101. 2011. *Standards of disclosure for mineral projects.*

PERC. 2013. *Pan-European standard for reporting of exploration results, mineral results and reserves.*

SAMREC. 2016. *The South African code for the reporting of exploration results, mineral resources and mineral reserves.*

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Related methods

- MICA Factsheet '*Geochemical mapping for mineral exploration*'
- MICA Factsheet *'Remote sensing and geophysics'*

Some examples of operational tools

A number of 3D resource modelling software programs are commercially available, including:

- Leapfrog GEO – 3D geological modelling software (www.leapfrog3d.com)
- Datamine Studio RM – resource modelling software (www.dataminesoftware.com)
- ThreeDify GeoModeler – http://threedify.com/geological-software/

Software programs are listed for information only, no endorsement or recommendation is provided or implied.

Key relevant contacts

There are a number of resource reporting committees worldwide that publish internationally recognised reporting codes, against which mineral resources and reserves may be reported. These reporting codes, and their updates, are often made freely available via an online portal. Below are listed some of the available reporting codes.

Region	**Code**	**Reporting code portal (website)**
Europe	PERC	www.vmine.net/PERC/index.asp
Australasia	JORC	www.jorc.org/
South Africa	SAMREC	www.samcode.co.za/samcode--ssc-mainmenu-66/samrec-mainmenu-67
Canada	NI 43-101	http://web.cim.org/standards/MenuPage.cfm?sections=177&menu=178

Those listed above comply with the CRIRSCO International Reporting Template; more information on this is available here: www.crirsco.com/welcome.asp

4. Fact sheets of methods for analyzing society's metabolism and related environmental impacts

Material and Substance Flow Analysis

FACT SHEET

Material and Substance Flow Analysis (M/SFA)

Scope

Material Flow Analysis (MFA) is a group of methods analysing material flows in society with the aim to match the use of material resources and the release of wastes and pollutants with the capacity of the environment to provide these resources and to absorb the wastes and emissions. Within the MFA field, two variants can be distinguished that have a more specific scope and methodology: Economy-Wide Material Flow Accounting (EW-MFA), accounting for all material flows in national economies, and Material/Substance Flow Analysis (M/SFA), accounting or modelling the flows (and sometimes stocks) of individual materials, substances or groups of substances at different geographic scale levels. This factsheet will focus on Material/Substance Flow Analysis (M/SFA).

M/SFA analyses the flows and (sometimes) stocks of a material, substance (element or compound) or group of substances in, out and through a geographically bounded system. It systematically monitors or models the physical flows (in terms of mass units) of a material through the life cycle: extraction, production, fabrication, use, recycling, and final disposal. Flows (and sometimes stocks) through society or the economy are always included in the analysis. Flows (and sometimes stocks) in the environment are included in some cases, but often the analysis is limited to the economic system.

Older M/SFA studies have been conducted often with an environmental purpose. For a number of elements (individual heavy metals, nitrogen, phosphorus, carbon, chlorine compounds) and at different scale levels (national economies, groups of countries like the EU, continents, the world, but also regions and cities) (Bergbäck et al., 1997; van der Voet et al. (eds.), 2000). Such studies are still done, but recently the angle has shifted to materials supply, with a focus on metals and critical elements. The STAF project (Stocks and Flows project) of the Yale University (STAF, 2016) is an important research project in this area, which has generated many important publications (Graedel et al., 2004; Graedel et al., 2005; Yang et al., 2014; Johnson et al., 2005; Johnson et al., 2006; Wang et al., 2007; Reck et al., 2008; Reck et al., 2010; Eckelman et al., 2012; Mao et al., 2008; Nassar, 2013; Kavlak et al., 2013; Harper et al, 2012). Even more recent are the investigations of stocks in society, from the point of view of urban metabolism and urban mining (UNEP, 2010; Baccini & Brunner, 2012; Tanikawa et al., 2015; Krook & Baas, 2013).

The method is not standardized but some conventions are observed in the field. Brunner & Rechberger (2004) have developed a practical handbook of MFA, linked to the MFA software tool 'STAN' (see section 'operational tools').

Contexts of use, application fields

Types of applications:
M/SFA enables to spot the major flows and stocks, to signal future problems in an early stage, to trace the fate of inflows, to link specific pollution problems to their origins in society, and to assess the consequences of management changes. The main users of the M/SFA outcomes so far have been regional and national governments. It has been used for environmental statistics and to support resource and environmental policies. Since the 1980s M/SFA is used in a policy context in Austria, Denmark, Belgium, Sweden, the Netherlands, for example to monitor, analyze and forecast environmental problems related to those substances. Recently, the focus has been more on resource availability, specifically of critical materials. M/SFA is used to analyse global trade flows and to assess stocks of materials, mostly metals. These stocks are regarded as sources of (secondary) materials. The concept of urban mining is especially interesting from the point of view of moving towards a circular economy. M/SFA can also be used at the company level, for example by industries or waste and sewage treatment plants, to identify the origin and fate of the throughput (bulk materials and/or substances). In the Netherlands and Germany M/SFA is used by farms to keep track of minerals (mineral bookkeeping).

M/SFA-studies exist in three types:

1. accounting
2. static/steady state modelling
3. dynamic modelling.

All three types have their own specific applications.
Material Flow Accounts are used to quantify and monitor flows and stocks of materials and substances (e.g. van der Voet, 1996; Van der Voet et al., 2000; Pacyna, 2009; Müller et al., 2014; Graedel et al., 2004; Graedel et al., 2005; Yang et al., 2014; Johnson et al., 2005;

Johnson et al., 2006; Wang et al., 2007; Reck et al., 2008; Reck et al., 2010; Eckelman et al., 2012; Mao et al., 2008; Nassar, 2103; Kavlak et al., 2013; Harper et al, 2012)

- to get a complete overview of flows of substances in a specific region
- to find out how different flows are dependent on each other
- to find problem flows, identifying leaks,
- to monitor problem flows, spotting trends
- early warning

Static Material Flow Models are used to evaluate the effects of policy measures (e.g. van der Voet, 1996; Van der Voet et al., 2000)

- tracing of origins in society of critical flows in the environment
- comparing management options, including problem shifting within the system between sectors or environmental emission compartments

Dynamic Material Flow Models are used to model substance flows and stocks over time. The stocks have an essential place in this, as in many cases stock dynamics determine flows, rather than the other way around. Such dynamic M/SFA models can also be used for forecasting. By combining demand projections with stock saturation per metal application, it is possible to estimate future flows (e.g. Elshkaki, 2007; Elshkaki & Graedel, 2013; Müller et al, 2006; Müller et al, 2014; Elshkaki et al., 2016). Combining those demand scenarios with supply scenarios allows to include environmental aspects and comment on potential future supply problems.

Type(s) of data or knowledge needed and their possible source(s)

An M/SFA-study requires data on flows and/or stocks included in the region under study. Mostly such data are collected on a case-by-case basis, preferably from statistical sources but sometimes also from grey literature and with the help of the companies involved. Flows and stocks refer to all kinds of commodities that the material is used in. In addition, M/SFA needs information on the content of the substances in those commodities. This information is more difficult to obtain, as the information on product composition is not standardly available. Especially for substances applied in tiny amounts, studies have to rely on the sparse literature or own estimates.
M/SFAs are compiled using many different sets of data, like:

- Data on extraction of resources
- Production data of (intermediate) materials and final products
- Trade data: imports and exports of ores, intermediate materials and final products
- Emission data on substances to air, water and soil
- Materials and product specifications, especially material content

- Data about stocks of materials and products in society (amount, composition, age, lifetime, etc.)
- Expert knowledge about behavior of substances in the environment, like deposition, volatilization, leakage, run off etc., often part of distribution models

Several relevant databases that can be used for the compilation of M/SFAs:

- Production and trade statistics, e.g. Europroms (Eurostat, 2016)
- Air emission accounts, like National emission accounts of UNFCCC (UNFCCC, 2016), National emission accounts of EMEP (EMEP, 2016), National Air emission accounts, by activity from EUROSTAT (Eurostat, 2016)

Data on product composition may be found in LCA databases (see factsheet on LCA) and dedicated studies on material end product composition (e.g. Buchert et al., 2012)
Detailed data on extraction of resources may be found at USGS commodity statistics. (USGS, 2016)

Model used

For the accounting variant, flows and stocks are quantified based on data of commodities and the content of the material involved. Mass-balance is applied to each economic or environmental (sub)system. The choice for balancing item then is an issue.
Static models are derived by translating the account into a set of transfer coefficients which are used to redistribute the inflows over outflows (or, in some cases, the outflow over the inflows). Matrix inversion can be used to solve the set of equations, as a MFA system can be regarded as a specific type of input output model.

Dynamic Substance flow modeling makes use of additional information on stocks in society. There are various ways to combine stock and flow information. Most dynamic models use the life span of the commodities as a delay function:

outflow(t) = inflow (t – L), L being the life span of the commodity.

In most cases this is combined with some life span distribution function to cover uncertainties.

System and/or parameters considered

M/SFA analyses a geographically bounded system. Scale levels vary from the global level to the local level. Usually the system corresponds to administrative units such as countries, counties or municipalities. Sometimes other geographical systems are selected, such as river basins.

M/SFA follows a cradle-to-grave approach: all production and consumption processes within the region, connected with the substance (group), from the extraction of resources until the final disposal of waste are considered. The M/SFA sometimes includes the environment of the chosen region.

Within the economic system several subsystems might be defined, e.g. all sectors or industries within the geographical boundary of a country. M/SFA also includes flows between the economy and the environment, both extractions from the environment and emissions to the environment. Within the environmental system several subsystems might be defined, e.g. environmental compartments (air, surface water, groundwater, sea, sediment, agricultural soil, industrial soil etc.) within the geographical boundary of the system.

Time / Space / Resolution / Accuracy / Plausibility

M/SFA is specific in space and time. Usually flows are specified as kg / year, while stocks have the dimension kg at a specific moment in time. M/SFA accounting is used to observe trends and developments in the past by drafting accounts for a series of years. Static models represent the situation in one year, or an equilibrium situation in an undefined year in the future. Dynamic models can be used to forecast future flows and stocks in time series. A relatively new development concerns the monitoring or modelling of the development of specific stocks – both societal and environmental - over a more extended period of time, i.e., over decades or even centuries.

At the global level, M/SFA is used to specify international trade flows and to estimate global stocks (UNEP, 2010). Presently, scenarios are developed for several metals at the global level using dynamic M/SFA. The STAF project (STAF, 2016) focuses at the national and continental level, while attempting a global coverage. Within the EU the SOCOPSE project (Pacyna, 2009) can be mentioned, using M/SFA for river basin management plans throughout the EU. At a lower scale level, M/SFAs are performed for specific applications in a country to support material or resource policies, or it is used to specify stocks at city level to support urban mining and circular economy initiatives.

The level of detail and representativeness in terms of region and time will depend on the scope of the M/SFA case. There are no EU member states that perform M/SFAs for the total economy or parts of the economy on a regular basis, although many commission such studies occasionally.

Indicators / outputs / units

All inflows and outflows of the (sub)systems in and between the economic system and environmental system can be used as indicators. Indicators for societal flows and stocks are relevant for early warning: inflows, accumulations, stocks. Other indicators refer to the management of the substances: resource efficiency, losses from the cycle, recycling rates. Indicators at the pressure level are the environmental interventions, i.e., the extractions and emissions. In M/SFA the flows can be followed further along the environmental cause-effect chain, thus linking the environmental interventions to some form of ERA (see ERA factsheet). Impact indicators can then refer to environmental concentrations and human intake. When a group of substances is considered, a translation is sometimes made to LCA impact categories (See factsheet on LCA). It is also possible to compare extraction flows with geological stocks, to comment on potential scarcity or criticality problems.

Additional indicators can be derived using and combining a selection of the flows, e.g. total of emissions per total input as an indicator for the closedness of the economic system etc.
The indicators are expressed in mass units per year. To make comparisons between countries possible indicators also can be expressed per capita (material intensity).
When combined with monetary flows related to the same system boundaries, the M/SFA indicators can be expressed as eco-intensity indicators expressing for example the emission or extraction (in kg) per value added (in euro).

Treatment of uncertainty, verification, validation

The scope of the M/SFA is quite narrow: only flows and stocks of a specific substance. While this can be used to support a resource policy, it must be clear at all times that the consequences of that policy will be much broader and won't show up in the M/SFA.
Because of the diverse nature of sources and the varying quality and availability of data, MFA results are inherently uncertain (e.g. uncertainties of concentrations of elements in ores, materials and products; interpretation of production and trade statistics; illegal trade, losses in industrial processes etc.). Uncertainty analyses have received increasing attention in recent MFA studies, but systematic approaches for selection of appropriate uncertainty tools are missing. Laner et al. (2014) reviews existing literature related to handling of uncertainty in MFA studies and evaluates current practice of uncertainty analysis in MFA. Based on this, recommendations for consideration of uncertainty in MFA are provided. In Patrício et al. (2015) a quantification of the uncertainty in nationwide, regional, and urban MFA methodologies is provided. Also the ASTER project (Systemic Analysis of Rare Earth Elements – flows and stocks) started in 2012 aims to take into account uncertainty analysis in MFA. (ASTER, 2016)

Additional uncertainties will appear in the modelling applications, since process characteristics become very important. Whereas the steady state analysis has a robustness of its own - in the steady state situation, the outflows can be described solely as a function of the inflows – the dynamic type of analysis is rather sensitive to flow and process data errors. The instrument mostly used to assess the robustness of the outcomes is a sensitivity analysis.

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Related methods

M/SFA can be combined with risk assessment tools.

In dynamic M/SFA regression methods are used to forecasting demand projections and stock saturation of substances. The simplest way to estimate the future magnitude of any variable is to extrapolate from the situation in the recent past. For example the analysis of the historic demand for metals can be carried out using regression analysis, with per capita GDP, the level of urbanization, population, and time as explanatory variables.

M/SFA can also be combined with LCA to link the material flows to their (potential) environmental impacts (see separate factsheet on Life Cycle Assessment).

Substance flow accounts and economy wide material flow accounts (EW-MFA) are different methodologies that belong to the same family of Material Flow Accounts. They both monitor material flows in physical units, mass (kg) of substances, raw materials, products, wastes and emissions related to economic activities in a geographical region, comprising extraction, production, consumption, waste disposal.

Some examples of operational tools

Software availability:
M/SFA accounts are often conducted with the help of general database and spreadsheet tools such as Excel and Access. For steady state and dynamic modelling, various research groups involved in M/SFA use their own models, often also based on spreadsheets. The only generally available MFA software tool is the STAN tool, developed by the Technical University in Vienna. STAN is software tool that can be used for both accounting and static modeling M/SFA. If used for accounting, users can enter known data in the model and missing data will be estimated on the basis of the mass-balance principle. In static modeling so-called transfer coefficients (TCs) are used to redistribute the inflows over outflows. See www.stan2web.net/ for more details

Key relevant contacts

There is no institution for M/SFA studies. Such studies are conducted by a large number of research groups in all parts of the world.

Economy-wide Material Flow Accounting

FACT SHEET

Economy Wide Material Flow Accounting (EW-MFA)

Scope

Goal and scope:
Material Flow Analysis (MFA) is a group of methods analysing material flows in society with the aim to match the use of material resources and the release of wastes and pollutants with the capacity of the environment to provide these resources and to absorb the wastes and emissions. Within the MFA field, two variants can be distinguished that have a more specific scope and methodology: Economy-Wide Material Flow Accounting (EW-MFA), accounting for all material flows in national economies, and Substance Flow Analysis (SFA) accounting or modelling the flows (and sometimes stocks) of individual substances or groups of substances at different geographic scale levels. This factsheet will focus on Economy Wide Material Flow Accounting (EW-MFA).

EW-MFA is supposed to form a physical complement to the monetary national economic accounts (System of National Accounts) in the System of Environmental-Economic Accounting (SEEA) (UN, 2016). EW-MFAs are part of official statistics of the European Union. Its main indicator, the Domestic Material Consumption (DMC), is presented as a counterpart of the Gross Domestic Product (GDP) and forms the bridge to an assessment of the state of a nation's natural resources.

Object of analysis:
EW-MFA takes into account all material inputs and outputs of a national economy. It accounts for a large number of resources within four main categories: fossil fuels, metals, minerals and biomass. It generates an overview of annual material inputs and outputs of an economy (see also Figure 12). These include inputs (extractions) and outputs (emissions,

waste) from and to the domestic environment, as well as the imported and exported goods via trade flows (Eurostat, 2013 & 2001). The difference between inputs and outputs is classified into two categories: either domestic waste and emissions, or net addition to stock. The accounts are expressed in physical units: kg per year.

Contexts of use, application fields

In general the EW-MFAs are used to support government policy on resources, resource use and resource efficiency.

EW-MFA may serve as a database for data on the input, output and (net) use of materials in national economies. This information can be used in different types of policy supporting studies. The domestic extraction data are highly detailed and can be useful information for a national resource conservation policy. Import and export data can be used to assess the physical trade balance of a nation. Together with the information on extraction, the self-sufficiency of a nation can be assessed. Countries can be characterized with regard to the nature of their economy: resource producing or resource consuming nations. Also the state of development of a country can be characterized by its metabolic profile. On an aggregated level the materials flows accounts determine the resource productivity (€/kg) or resource intensity (kg/€) of an economy. These aggregated mass indicators are used by EEA and Eurostat. Presently, the leading indicator for the EU Resource Efficiency policy is GDP/DMC: the national income over the domestic material consumption, an indicator for resource productivity. The methodology can be used to monitor de-coupling, that is the de-linking of the physical system from the monetary system. The use of MFA indicators as proxys for environmental pressure is disputed. Presently the main view is that material flows form the interface between economic development and environmental pressure, as also mirrored in the EU resource efficiency policy.

Conceptually Economy-wide Material Flow Accounts (EW-MFA) belong to the international system of environmental economic accounting (SEEA-Central Framework) (UN, 2016). Furthermore, EW-MFA is one of several physical modules of Eurostat's programme on European environmental economic accounts. It is covered by Regulation (EU) No. 691/2011 (EC, 2016) on European environmental economic accounts.

Type(s) of data or knowledge needed and their possible source(s)

EW-MFAs are part of official statistics of the European Union (Eurostat, 2016). The data set 'material flow accounts' (env_ac_mfa) are annual and start with the year 1990 (EU since 2000). The data set 'resource productivity' (env_ac_rp) are annual and start with the year 2000 (EU since 2000).

Within the next year, a global database will become available with time series information for all countries in the world from 1970 until 2013 (UNEP and CSIRO, 2016). It has been used to develop the reports of UNEPs International Resource Panel on decoupling, and it can be used by nations to assess their progress on the decoupling road.

According to the Eurostat methodological guide (Eurostat, 2013 & 2001), the following components are distinguished on the material input side of an economy-wide MFA (see also Figure 12). On these components, data must be collected, for the most part statistical data:

- Used domestic extraction i.e.: raw material extractions from the domestic environment which are directly used in subsequent economic processing
- Unused domestic extraction (domestic hidden flows): i.e. those primary material inputs associated with the above mentioned used domestic extractions which are not directly used in economic processing and hence are not valued economically. Examples are mining overburden, harvest losses and soil erosion.
- Imports: i.e. the materials in goods imported to the national economy
- Indirect flows associated with imports (foreign hidden flows): i.e. the 'hidden' cradle−to−border primary resource extractions (used and unused) that have been required to produce the imported good (often referred to as 'ecological rucksacks')

On the material output side, the following components are distinguished:

- Processed outputs to nature: i.e. the emissions and waste flows of production or consumption processes
- Exports: i.e. the materials of exported goods
- Unprocessed outputs: this equals the unused domestic extraction (domestic hidden flows)
- Indirect flows associated with exports i.e. the 'hidden' lifecycle−wide primary resource extraction that had been required to produce the exported good (often referred to as 'ecological rucksacks')

The difference between inputs and outputs is labelled "Net Addition to Stock" (NAS). Data on imports, exports and extractions are generally present in production and trade statistics. Data on waste and emissions are more difficult to obtain and the quality varies per country. Data on hidden flows are not collected regularly and standardly. In EW-MFA, these are based on very rough estimates.

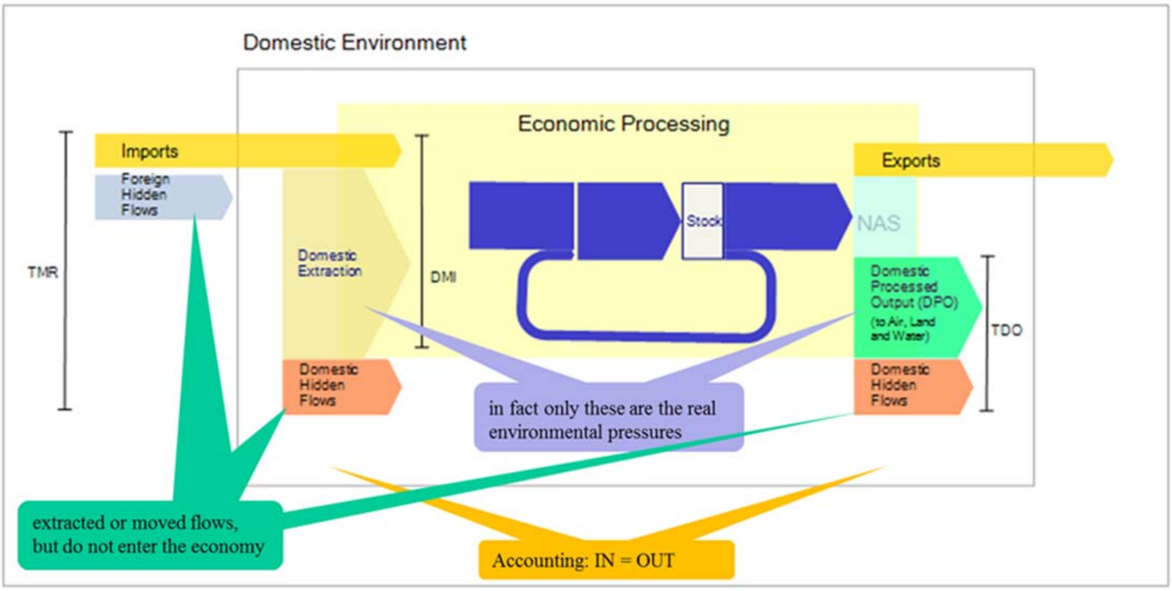

Figure 12 The system of Economy Wide Material Flow Accounts

Model used

EW-MFA is an accounting scheme. The only mathematical model used is the mass balance of a national economy in a given year. Information on natural resources extracted and traded products is provided by different statistical units. That implies either some data reconciliation must be done, or the discrepancies between the different data sources will end up in the balancing item: net additions to stock.

System and/or parameters considered

Economy-wide material flow accounts (EW-MFA) uses administrative system boundaries: the object is a national economy in a given year. Different accounts can be combined into larger administrative or geographical units. Different years can be combined in time series. Like the system of national accounts, EW-MFA constitutes a multi-purpose information system. The detailed material flows provide a rich empirical database for numerous analytical purposes. Further, EW-MFA is used to derive various material flow indicators (see below).
Material flow accounts include all solid, liquid and gaseous materials used in the economic system (excluding water and air) crossing the system boundary on the input side or on the output side. The economy is demarcated by the conventions of the national accounting system (resident units).

Time / Space / Resolution / Accuracy / Plausibility

EW-MFA is specific in space and time. EW-MFA applications consider flows in a national economy during a year. EW-MFA monitoring is used to observe trends and developments over time. Global time series data are available for all countries in the world, for 1970–2013.

EW-MFA uses a specific hierarchical classification (up to 4-digits) with some 50 material categories such as biomass, metal ores, non-metallic minerals, and fossil energy materials/carriers. Material inputs from the natural environment to the economy are called domestic extraction.

Indicators / Outputs / Units

EW-MFA specifies in- and outflows of society in an overview of society's metabolism. The metabolism of society in general is linked to environmental pressures, however, EW-MFA normally do not specify environmental interventions. When they do, all environmental interventions are lumped together and expressed in one indicator (Total Domestic Output, TDO). Specific attention is sometimes given to the "ecological rucksacks" or hidden flows of primary production.

Material flows from the EW-MFA are combined into indicators such as:

- Domestic extraction (DE): total amount of material extracted for further processing in the economy, by resident units from the natural environment;
- Imports (IMP): imports of products in their simple mass weight;
- Direct material input (DMI): a sum of DE and IMP, all materials that enter the national economy
- Exports (EXP): exports of products in their simple mass weight;
- Domestic material consumption (DMC): measures the total amount of material actually consumed domestically (DE+IMP-EXP).

The indicators are expressed in mass units per year. They can be compared over time for one nation, or can be compared across countries for one year. To make comparisons between countries possible, these indicators also can be expressed per capita, or per monetary unit.

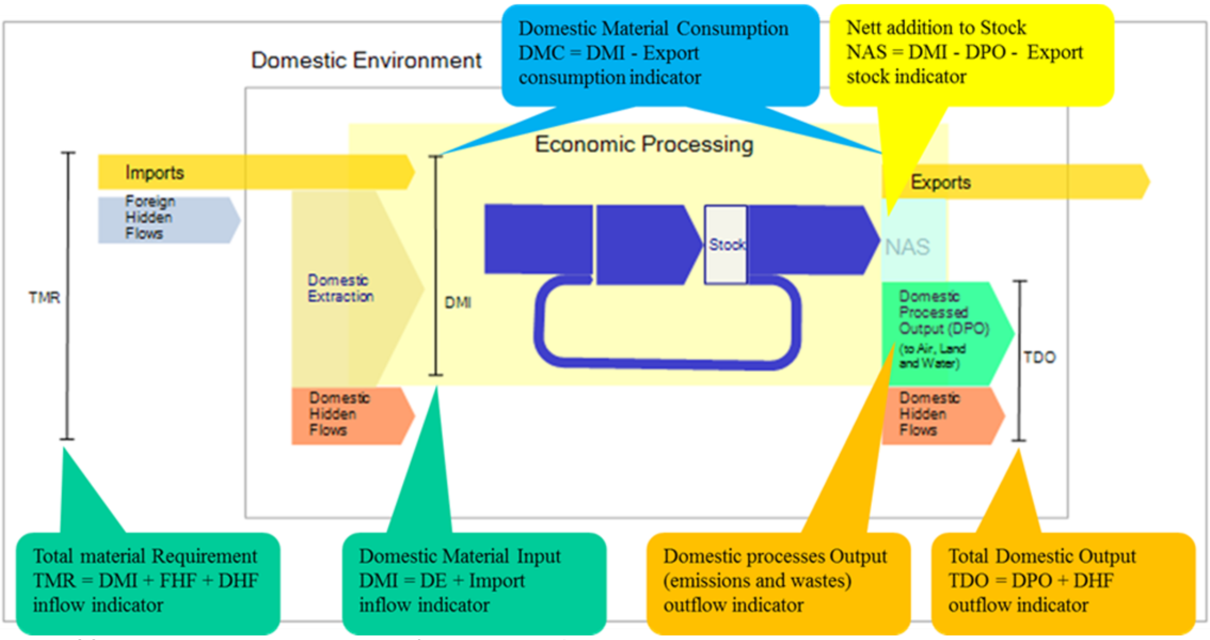

Figure 13 Material indicators derived from EW-MFA

Resource productivity (GDP/DMC) is defined as the ratio of gross domestic product (GDP) over domestic material consumption (DMC) and commonly expressed in Euro per kilogram of material. The term designates an indicator that reflects the GDP generated per unit of resources used by the economy. This is typically a macro-economic concept that can be presented alongside labour or capital productivity.

Treatment of uncertainty, verification, validation

Limitations:
EW-MFA only describes transboundary flows: the national economy itself is a black box. No relation can be established between inputs and outputs, nor between the different consumption and production activities. In what way the resources are used and enter the consumption phase is therefore invisible, with consequences for the possibility to perform checks and sensitivity analyses. Recycling and reuse activities are only indirectly visible, as a reduction of flows of primary materials. This means that disaggregation is not really possible, and that the accounts are not suitable for any analysis at a more detailed level.

The DMC, and other indicators derived from EW-MFA, are a measure for the metabolism or material basis of a society. DMC is also coined as a measure, be it indirect, for the total environmental pressure of a national economy: with each kilogram being taken out of the environment some impact is being created. However, the impact potential of the different materials is not taken into account, which may differ largely between materials. This reduces the usefulness of the DMC as an environmental indicator.

Handling of uncertainties:
To ensure quality of the data Eurostat implements the following procedures/guidelines:

1) Methodological guidelines to assist countries in compiling EW-MFA;
2) Extensive validation procedure of the data received. The validation tools check:
   - consistency (several cells check, validation level 1);
   - plausibility with an extra check for fluctuations between two consecutive years;
   - illegal symbols (cell by cell check, validation level 1)
   - illegal footnote.

   The validation procedure offers a gap overview, the response rate and an annual plausibility that enables the comparison of data for common reporting years between the previous and the current questionnaire which constitutes a validation check at level 2.
3) Gap-filling of missing statistical information.

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Related methods

The accounts of material and substance flows in physical units allow for a link to regional economic performance indicators (integrated environmental and economic accounting). The EW-MFA is designed to form a physical complement to the monetary national economic accounts (System of National Accounts) in the System of Environmental-Economic Accounting (SEEA) (UN, 2016).

Substance flow accounts (SFA) and economy wide – material flow accounts (EW-MFA) are different methodologies that belong to the same family of Material Flow Analysis (see separate factsheet Material / Substance Flow Analysis). They both monitor material flows in physical units, mass (kg) of substances, raw materials, products, wastes and emissions related to economic activities in a geographical region, comprising extraction, production, consumption, waste disposal.

To add an environmental dimension to the EW-MFA accounts, the Environmentally weighed Domestic Consumption (EMC) indicator has been developed (van der Voet et al., 2005). This indicator combines mass balances for the individual materials in the account with an environmental multiplyer based on LCA data (see separate factsheet Life Cycle Assessment).

Some examples of operational tools

Software availability:
EW-MFA studies are mostly conducted with the help spreadsheet or database tools such as Excel and Access.

Key relevant contacts

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Life Cycle Assessment

FACT SHEET

Life Cycle Assessment (LCA)

Scope

Life Cycle Assessment (LCA) is a comprehensive evaluation of the cradle-to-grave life cycle of a product or a service with regard to its environmental impacts. The environmental assessment of the product or service is based on a complete overview of environmental interventions: emissions of substances and extractions of resources. These emissions and extractions are translated into a limited number of environmental impact categories.

The object of the analysis is the so-called product system: the total of processes which are involved in the production, use and waste disposal of a product or service. In these systems all (technical) processes are included from cradle-to-grave. LCAs can be made of a specific product system to identify hotspots in the cradle-to-grave chain. Comparative LCAs specify alternative systems to fulfill the same function, to assess the environmental consequences of different options.

The methodology of LCA is standardised by the International Organization for Standardization in ISO 14040/14044 (ISO, 1996 and ISO, 2006). There are also European initiatives to harmonize the performance of LCA in compliance with ISO, such as the International Reference Life Cycle Data System (ILCD) (EC, 2016a) and Product Environmental Footprint (PEF)/Organisation Environmental Footprint (OEF) (EC, 2016b).

Methodological steps have been defined in ISO 14040:

1. Goal and Scope Definition
2. Life Cycle Inventory Analysis (LCI)
3. Life Cycle Impact Assessment (LCIA)
4. Life Cycle Interpretation

In the Goal and Scope Definition, the functional unit is defined and the mode for analysis is selected.

In the Life Cycle Inventory, process information is collected for all processes in the cradle-to-grave chain. For each process, inputs and outputs are specified: extracted resources, inputs of goods and services from other processes, emissions and final waste emitted into the environment, and outputs of goods and services to other processes. These processes are linked to form the product system. Allocation choices have to be made to attribute process inputs to outputs, in case a multi-output process is part of the product system. Emissions and extractions are then aggregated to form the Life Cycle Inventory table.

The aggregate emissions and extractions are the input for the Life Cycle Impact Assessment. The translation of emissions and extractions into state or impact indicators is based on characterization models. These models take into account the dispersion, deposition, exposure and (potential) damage characterisation models thus translate the emission of a certain substance into a contribution to certain environmental impact categories, such as global warming, toxicity or eutrophication. These impact categories are sometimes further modelled into impacts further down chain the cause-effect chain into damages of different safeguard areas, i.e. damage to resources, human health and ecosystem health.

In the Interpretation step, the results are scrutinized and may give rise to a re-visiting of the earlier steps. The interpretation step is also the step to specify uncertainties, do sensitivity analysis, and assess the consequences of certain methodological choices.

Contexts of use, application fields

LCA is generally used to answer one of the following three questions

1. Where in the product system are the main sustainability impacts?
2. How do the sustainability impacts of alternative product system compare to each other?
3. Do the sustainability impacts of a specific product system comply with external standards?

To answer the first type of questions, a contribution or hotspot analysis is performed. The aim is to guide improvement of the production. For the second type of question, a comparative analysis is used for alternative products. There are stricter guidelines when the results of a comparative analysis are published. Statements that show one product superiority over another can be misleading as the outcomes of an LCA depend on the data availability and assumptions made by the researchers (Guinée 2002). The third question leads to a compliance evaluation to evaluate whether a product complies with externally set standards.

The core application of LCA is product related decision support. It can be used by companies, for hotspot identification in product systems, product development, product comparison, green procurement and market claims. However, LCA is also, next to other tools, important for technology choices, setting technologies into a product related chain perspective. LCA is increasingly used at a strategic level for business development, policy development and also for education. In policies, LCA is the main tool to support ecolabelling. At EU-level, it is used to support product policies by standardizing it into Product Environmental Footprints (PEFs). Another development is the Organisational Environmental Footprint (OEF) that follows the life cycle approach but takes the "product portfolio" of the organization as the functional unit (EC, 2016b). LCA based tools are also used to support policies on bio-energy, both in Europe and in the US. The CO_2 calculators used there to determine the potential benefits of various bio-energy supply chains are LCAs with a standardized set of data and methodological choices.

A relevant distinction in applications is that between attributional LCA (a-LCA) and consequential LCA (c-LCA). While the starting point of a-LCA is the present situation, c-LCA is concerned with change. In a-LCA, therefore, the analysis specifies the contribution of the functional unit to the presently existing environmental pressure. In c-LCA, the changes in environmental pressure of the addition of one functional unit are specified (EC, 2010a; EC, 2010b). The difference at the micro-level is subtle, but when larger changes are involved it becomes critical.

The life cycle approach is gaining territory in many different policy applications. A new development in the LCA field is the movement towards Life Cycle Sustainability Analysis (LCSA) (Guinée, 2016). This includes upscaling from the micro-level to the macro-level, it includes expanding the analysis to include economic and social impacts, and it includes developing forward-looking analyses, especially the assessment of emerging technologies. Such new applications also call for new additions to the methodology, new databases and new ways to deal with uncertainties and unknowns.

Type(s) of data or knowledge needed and their possible source(s)

A quantitative LCA-study requires Life Cycle Inventory (LCI) data on technical processes included in the system under study. Mostly such data are collected on a case-by-case basis with the help of the companies involved.

In addition, Life Cycle Impact Assessment (LCIA) data are required. These include characterization factors and normalization factors, to aggregate extractions and emissions into a limited set of environmental impact categories.

The collection of data for an LCA is a very elaborate job. However, several (commercial) databases are available that contain descriptions for some general processes. Also for impact assessment several databases exist that contain data for characterization sets and normalization sets. Sometimes the databases come in packages, together with the LCA software tool (see section 'operational tools').

LCI data
In LCI databases process data are often organized around a unit process. A unit process describes the produced goods (economic output), consumed goods (economic input) , emitted substances (environmental output) and consumed resources (environmental input). In existing LCI databases, process data are almost always quantified in relation to some physical economic output (e.g. 1 kg of produced material or 1 MJ of produced electricity). Process data provided by companies are often also organized around unit processes, but given in terms of inputs and outputs per unit of time, e.g. emission of 5 tonnes of CO_2 per year, input of 1000 tonnes of wood per year, etc..

There are many LCI databases available. An overview of available databases and their descriptions is provided by open LCA Nexus. https://nexus.openlca.org/
The overview of databases contains commercial databases, like Ecoinvent and GaBi, as also initiatives to build open source databases, like the UNEP/SETAC Database Registry (the registry) and the European ELCD database with the Commission's "European Reference Life Cycle Database" (ELCD) of Life Cycle Inventory (LCI) data sets.

Sometimes the databases are a combination of LCI data and Impact Assessment data. For details is referred to the description given in OpenLCA Nexus.

LCIA data
Life Cycle Impact assessment (LCIA) is the phase in which the set of results of the Inventory Analysis, mainly the inventory table with emissions and extractions, is further processed and

interpreted in terms of environmental impacts and societal preferences. To this end, a list of impact categories (environmental problems) is defined, and models for relating environmental interventions to suitable category indicators for these impact categories are selected. The actual modeling results are calculated in the characterization step, and an optional normalization serves to indicate the share of the modeled results in a worldwide or regional total. Finally, the category indicators results can be grouped and weighted to include societal preferences of the various impact categories.

There are many different sets of characterization factors. Some of these characterization factors model effects on the state level, so called midpoint level, resulting in impact scores for global warming, ozone layer depletion, human toxicity etc. (e.g.CML2002). Other sets take into account further modeling of these state indicators into damage indicators for areas like human health, ecosystem health and resources, so called endpoint indicators (e.g. Ecoindicator99, ReCiPe). Finally , there are impact assessment factors that also take into account the valuation of these damages into monetary terms and thus also include a weighting step across the impact categories (e.g. NEEDS, EDP).
On a European level there is an initiative from ILCD to develop a recommended set of Impact Assessment data (EC, 2011). The actual ILCD compliant characterization and normalization factors for the recommended set of data are made available in a downloadable spreadsheet (EC, 2016a).

The Life Cycle Impact Assessment (LCIA) guide of the ILCD handbook (EC, 2016b) provides two documents:

- A framework and requirements for Life Cycle Impact Assessment (LCIA) models and indicators (EC, 2010a);
- Analysis of existing Environmental Impact Assessment methodologies for use in Life Cycle Assessment (LCA)(EC, 2010b).

Recent developments in the LCIA field include the development of resource depletion, resource scarcity and criticality indicators. This increases the applicability of LCA for resource management issues.

Model used

Quantifying the product system is based on matrix inversion. The matrix is a product by product matrix with appending environmental extensions: extractions, land use and emissions. It is comparable to the mathematical model of Input Output Analysis (IOA, see separate factsheet) but operates at the micro-level, using a much more detailed matrix of a limited number of products.

For the Life Cycle Impact Assessment, characterization factors are used as multipliers for the environmental interventions. These characterization factors are based on environmental fate models.

System and/or parameters considered

The LCA method uses a functional system boundary, determined by the product and including all that is involved in producing, using and managing the waste. Unit processes are linked together in a product system. Unit processes are described in physical units by the consumption and production of materials by technological processes (see Figure 14). The relevant processes are combined in a process tree (see Figure 15). The processes in a process tree most likely are situated in different countries of the world, and emissions and extractions are occurring in different places and over multiple years. Hence the LCA system is neither time nor location specific. The resolution of processes in the process tree is very high, detailed technological processes, but the scope is limited to one specific function.

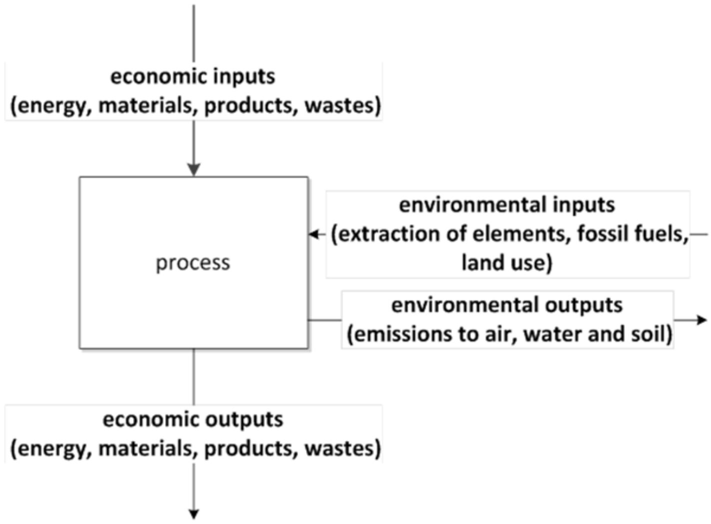

Figure 14 Unit process in LCA.

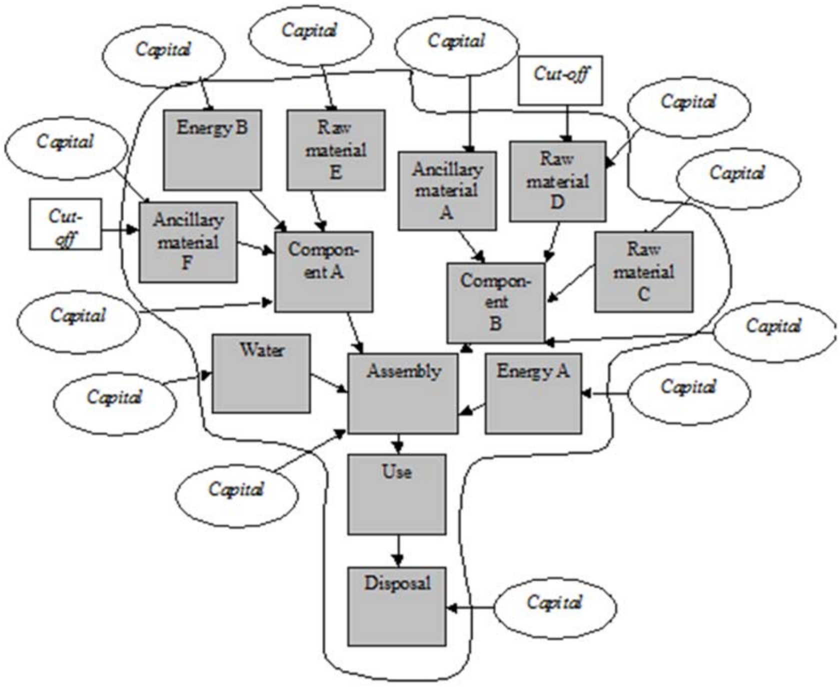

Figure 15 A generalized LCA process tree, with the product system boundary.

The object of analysis in LCA thus is the product system, i.e., the total of processes which are related to the provision of a given function. LCA follows a cradle-to-grave approach: all processes connected with the function of a product (or other types of function), from the extraction of resources until the final disposal of waste, are considered.

Time / Space / Resolution /Accuracy / Plausibility

LCAs are highly detailed and product-specific and have a very high resolution in terms of processes, applied technologies and their environmental pressures (Guinée et al., 2002; EC, 2010a&b; EC, 2016).

LCA usually does not specify space, i.e., no distinction is made for where exactly emissions or extractions take place. LCA therefore only concerns "potential" effects and is not suitable to assess "actual" environmental damage, transgression of environmental quality standards, or risks. Attempts are made nowadays to define the LCI data more location or at least country specific, leading to a variety of unit processes to produce the same product. Attempts are also made to define more location specific impact factors. This is especially relevant in the applications around c-LCA and bio-energy, related to land use.
Likewise LCA does not specify when extractions and emissions take place. Most LCA methods and software model processes and reaction mechanisms in a steady state mode of analysis. However, developments take place to model future scenarios depending on specific future conditions (SETAC-Europe working group on scenario development).

The region and time representativeness of processes and their interventions will depend on the scope of the LCA case. Databases exist that describe background processes, like Ecoinvent and ELCD (see section data needs/databases). In these databases the representativeness of the technology in terms of region and year is defined. The databases give a static description of technologies. They seldom contain data describing the change of technologies over time. The databases are irregularly updated.

Indicators / Outputs / Units

The main aim of LCA is to provide environmental information, and its main indicators therefore are related to environmental pressures and impacts. LCA is comprehensive with respect to the environmental interventions and environmental issues considered.
In the LCA, results can be specified on various different positions in the cause-effect chain. Many LCA-studies (or more correctly LCI-studies) stop after the inventory phase and do not aggregate the interventions in terms of impact categories. The resolution of interventions in LCA is very high. An inventory table might include thousands of substance-compartment-emissions and extractions. In the environmental impact assessment these interventions are aggregated into a limited number of environmental problems, so called impact categories. In order to facilitate the interpretation these emissions and extractions (pressure indicators) are transformed into state (e.g. concentrations in air) or impact indicators (e.g. % of species affected) and aggregated. For this purpose characterization factors are used based on characterization models that model the cause-effect chain from pressure (emission, extraction) to state or impact. Impact assessment indicators are often defined at "midpoint" level, the contribution to well-known environmental impact categories such as global warming, ozone layer depletion, or toxicity. Equivalency factors are used for that, for example global warming emissions are translated into CO_2-equivalents. Some methods, for instance the Eco-indicator 99, model up to the level of "endpoints" describing damage to human and ecosystem health.

An LCA-study may include normalisation and weighting of the different impact category results, which makes it possible to aggregate the LCA result into one figure. A number of different weighting methods are used in LCA-studies based on Distance-to-(political)Target, on monetization of environmental impacts or on panel methods.
There are many different impact assessment methods available, see for example Analysis of existing Environmental Impact Assessment methodologies for use in Life Cycle Assessment (LCA) (EC, 2010b) and OpenLCA (GreenDelta, 2014). The table below gives an overview of ILCD recommended impact categories on midpoint and endpoint level and their units.

Table 1 ILCD recommended midpoint and endpoint impact categories and their units (EC, 2011) (references to the original methods are given in the ILCD report)

LCIA method	Flow property (= quantity measured by the indicator of the LCIA method, i.e. of the characterisation factor per reference unit of elementary flow)	Unit group data set (with reference unit)
ILCD2011; Climate change; midpoint; GWP100; IPPC2007	Mass CO_2-equivalents	Units of mass (kg)
ILCD2011; Climate change; endpoint - human health; DALY; ReCiPe2008	Disability Adjusted Life Years (DALY)	Units of time (a)
ILCD2011; Climate change; endpoint - ecosystems; PDF; ReCiPe2008	Potentially Disappeared Fraction of species (PDF)	Unit of items * time
ILCD2011; Ozone depletion; midpoint; ODP; WMO1999	Mass CFC-11-equivalents	Units of mass (kg)
ILCD2011; Ozone depletion; endpoint - human health; DALY; ReCiPe2008	Disability Adjusted Life Years (DALY)	Units of time (a)
LCD2011; Cancer human health effects; midpoint; CTUh; USEtox	Comparative Toxic Unit for human (CTUh)	Units of items (cases)
ILCD2011; Non-cancer human health effects; midpoint; CTUh; USEtox	Comparative Toxic Unit for human (CTUh)	Units of items (cases)
ILCD2011; Cancer human health effects; endpoint; DALY; USEtox	Disability Adjusted Life Years (DALY)	Units of time (a)
ILCD2011; Non-cancer human health effects; endpoint; DALY; USEtox	Disability Adjusted Life Years (DALY)	Units of time (a)
ILCD2011; Respiratory inorganics; midpoint; PM2.5eq; Rabl and Spadaro 2004	Mass PM2.5-equivalents	Units of mass (kg)
ILCD2011; Respiratory inorganics; endpoint; DALY; Humbert et al 2009	Disability Adjusted Life Years (DALY)	Units of time (a)
ILCD2011; Ionizing radiation; midpoint - human health; ionising radiation potential; Frishknecht et al 2000	Radioactivity Uranium235-equivalents	Units of radioactivity (kBq)
ILCD2011; Ionizing radiation; midpoint - ecosystem; CTUe; Garnier-Laplace et al 2008	Comparative Toxic Unit for ecosystems (CTUe)	Units of volume*time (m3*a)
ILCD2011; Ionizing radiation; endpoint- human health; DALY; Frishknecht et al 2000	Disability Adjusted Life Years (DALY)	Units of time (a)
ILCD2011; Photochemical ozone formation; midpoint - human health; POCP; Van Zelm et al (2008)	Mass C2H4-equivalents	Units of mass (kg)
ILCD2011; Photochemical ozone formation; endpoint - human health; DALY; Van Zelm et al (2008)	Disability Adjusted Life Years (DALY)	Units of time (a)

ILCD2011; Acidification; midpoint; Accumulated Exceedance; Seppala et al 2006, Posch et al 2008;	Mole H+-equivalents	Units of moles
ILCD2011; Acidification; endpoint; PNOF; Van Zelm et al 2007;	Potentially not occurring number of species in terrestrial ecosystems * time	Unit of items * time
ILCD2011; Eutrophication terrestrial; midpoint; Accumulated Exceedance; Seppala et al 2006, Posch et al 2008	Mole N-equivalents	Units of moles
ILCD2011; Eutrophication freshwater; midpoint;P equivalents; ReCiPe;	Mass P-equivalents	Units of mass (kg)
ILCD2011; Eutrophication marine; midpoint;N equivalents; ReCiPe;	Mass N-equivalents	Units of mass (kg)
ILCD2011; Eutrophication freshwater; endpoint;PDF; ReCiPe	Potentially Disappeared Fraction of species (PDF)	Unit of items * time
ILCD2011; Ecotoxicity freshwater; midpoint; CTUe; USEtox	Comparative Toxic Unit for ecosystems (CTUe)	Units of volume*time (m3*a)
ILCD2011; Land use; midpoint; SOM;Mila i Canals et al 2007)	Mass C deficit	Units of mass (kg)
ILCD2011; Land use; endpoint; PDF; ReCiPe	Potentially Disappeared Fraction of species (PDF)	Unit of items * time
ILCD2011; Resource depletion - water; midpoint; freshwater scarcity; Swiss Ecoscacity2006	Scarcity adjusted amount of water used	Units of volume
ILCD2011; Resource depletion-mineral, fossils and renewables; midpoint;abiotic resource depletion; Van Oers et al 2002	Mass Sb-equivalents	Units of mass (kg)
ILCD2011; Resource depletion-mineral, fossils and renewables; endpoint;surplus cost; ReCiPe	Marginal increase of costs	Units of currency 2000 ($)

Treatment of uncertainty, verification, validation

The credibility of LCA can be limited by unclear or unspecified methodological choices. Also when well documented, methodological choices related to system boundaries, the functional unit and especially allocation have a large influence on the outcomes. This is unavoidable and required a careful interpretation of results. Because all economic processes and all environmental consequences must be specified, the LCA system is often complex and it has extensive data requirements, which in practical applications often cannot be fully met.

The uncertainty is highly dependent on the question at stake and the used data and models. The uncertainty of an LCA may be expressed in terms of data quality indicators, sensitivity analysis and peer reviews. Uncertainty treatment is presently an important topic in the LCA field, and approaches are being developed to add to any LCA case study.

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Related methods

Hybrid LCA is a combination of LCA and EEIOA (see separate factsheet) and might be used to overcome the drawbacks of both methods. The LCA system has a high resolution but has a limited scope while the EEIOA system has a low resolution but represents the total economy (which makes it possible to take into account background systems and other systems then the functional system of the LCA)(Suh & Nakamura, 2007; Heijungs et al., 2006). To relate micro level changes to effects on the macro level it is necessary to embed the micro system into a macro system. In this sense both methods, LCA and EEIOA, seem to be complementary. In Van Oers et al. (2013b) the possibilities of the use of hybrid LCA EEIO models is further elaborated.

When the LCSA field is further developed, other models will increasingly be used, or a life cycle dimension will be added to other methods and tools.

Some examples of operational tools

Computer programmes are indispensable for the complicated LCA operations. Dozens of such programmes exist in various research groups involved in LCA. Mostly such software tools are designed for specific purposes, such as for use in product design, the comparison of different products, or products in specific economic sectors (energy production, plastics, waste management, building materials). Only a very few are designed as general LCA software to be used by other than their developers.

LCA software tools are an interface to manage LCI and LCIA data. There are many tools available; some of them may also include LCI and/or LCIA databases. Some overviews of LCA-tools:
www.buildingecology.com/sustainability/life-cycle-assessment/life-cycle-assessment-software
www.linkcycle.com/comparison-of-best-life-cycle-assessment-software/
www.openlca.org/

Key relevant contacts

The Society for Environmental Toxicology and Chemistry (SETAC) has, since the beginning of the nineties, acted as a platform for scientific discussions, both in North America and in Europe, and recently also in South-east Asia. LCANET, an EU concerted action, acted in 1996-1997 as a platform for discussing research needs. The LCA methodology is currently standardised within the ISO framework (ISO 14040 series). Methodology guides have been published on national levels (e.g., Guinée et al., 2002).

The methodology of LCA is standardized by the International Organization for Standardization in ISO 14040/14044 since 2006.

The Institute for Environment and Sustainability in the European Commission Joint Research Centre (JRC), in co-operation with the Environment DG has developed the ILCD handbook. The ILCD handbook's main goal is to ensure quality and consistency of life cycle data, methods and assessments (EC, 2010). The ILCD handbook consists of a set of documents that are in line with the international standards on LCA (ISO 14040/44).

Environmental Extended Input Output Analysis

MICA Mineral Intelligence Capacity Analysis

FACT SHEET

Environmental Extended Input Output Analysis (EEIOA)

Scope

Input-Output Analysis (IOA) is used for various types of economic analyses within and outside government. The object of analysis is the structure of a national economy, described in terms of the monetary exchanges between the elements of the system investigated. These are listed in a so-called IO-table. The use of IO-tables is important for analysing structural changes in the production system of national economies. IOA uses monetary units to describe exchanges between production sectors. Either the sectors or the products they exchange can be the elements in the IOA system. IOA is described in a separate factsheet. This factsheet focuses on Environmental Extended IOA (EEIOA), transforming the economic model into an environmental one by adding environmental extensions (extractions and emissions) to the different elements in the system.

Supply and use tables (SUTs) form the basis of the IO-tables. SUTs are matrices, industry by product, describing the transactions between sectors in products of a national economy in physical as well as monetary terms. Supply and use tables are used to derive the Gross Domestic Product (GDP) of a country. Supply and use are rearranged in a single symmetric table with identical classification of either industries or products employed for both rows and columns. The Input Output Table thus derived from SUTs (SUIOT) can be extended with national environmental accounts per industry/product in physical terms (kg emissions or extraction) (Timmer et al., 2012; EUROSTAT, 2016b; Eurostat, 2011; Eurostat, 2008). A comprehensive explanation on compilation methodologies and possible applications of the tables are provided in the Eurostat Manual of Supply, Use and Input-Output Tables (Eurostat, 2008).

Note that the main focus of SUIOTs is on the production phase. The use phase, like private households' activities, might also be part of the SUIOT. If it is taken into account it generally is much aggregated. All activities are aggregated into a few sectors: households and governments. Additional transformations are necessary to split these sectors up into different household activities. Waste treatment sector is poorly monitored in SUTs. This is mainly because the interactions are based on monetary transactions.

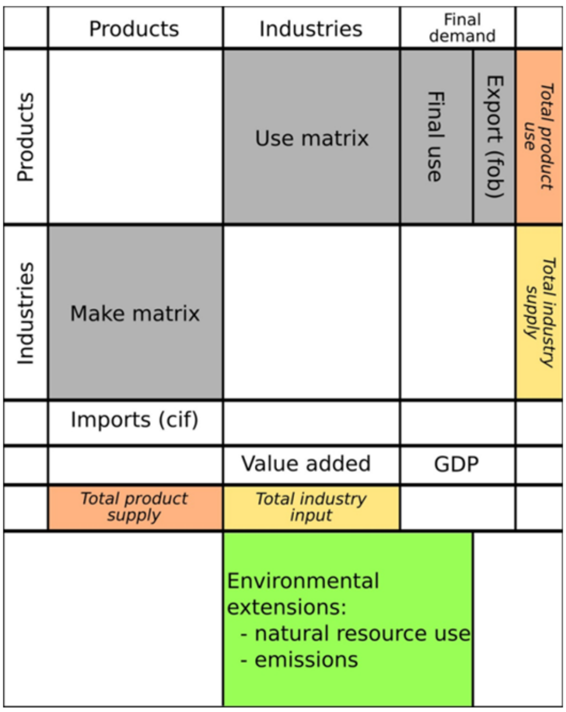

Figure 16 Environmentally Extended Supply Use and Input Output framework.

The construction of SUTs, IOTs and SUIOTs including the environmental information is a statistical activity. Using IOTs as a model is the main activity of Input Output Analysis: the translation of the transactions into transfer coefficients, and of registered emissions and extractions into environmental multipliers in terms of mass per monetary unit. Such a static model can be used to assess the impacts of certain management or regime changes.

Contexts of use, application fields

The main use of IOA, and also of EEIOA, is to display all transactions within an economy; simultaneously illustrating the connection between producers and consumers and the interdependence of industries. The input-output method is thus used to capture the state of the industrial structure. This model permits an analysis of static changes, which helps identify targets which have the most effect on the waste streams and the product/process environment. Pollution and other undesirable external effects of productive or consumptive activities can, for all practical purposes, be considered as a part of the economic system. Due to its goal and scope IOA (and EE-IOA) is mainly used by government and academia.

The EEIOT in first instance is an accounting method. The advantage of the EEIOT is the integrated monitoring of environmental and economic data. For this reason the EEIOA framework is an appropriate method to derive indicators for eco-efficiency and resource efficiency.

If these data are transformed into factors the EEIO accounting framework is transformed into an EEIO model. The EEIO model may be employed in various ways in order to analyze on a macro level both ex-post and ex-ante environmental effects of changes in demand of goods, technology of processes or structure of the economy:

Structural Decomposition Analysis (SDA)
Structural decomposition analysis (SDA) aims at identifying the driving forces of changes in time of an aggregate measure. When dealing with EEIOA, the measure to be decomposed could be the change in environmental pressures exerted by economic activities. The investigation of changes through time requires the availability of data for multiple time periods. Starting from an accounting identity (such as total sectoral environmental pressures defined as $e=wLf$), decomposition aims at identifying the role of each component of the identity keeping the other elements fixed. In the example of environmental pressures, the main drivers could be: (i) changes in environmental intensity (Δe); (ii) changes in the mix of intermediate inputs (ΔL); and (iii) changes in final demand (Δf). The initial identity could be further decomposed in order to identify additional and more specific driving forces (e.g. final demand changes could be split into changes in the composition of final demand and changes in the scale of final demand). For further details on basic concepts of SDA refer to chapter 13 of Miller and Blair (2009).

Consumption vs production perspective
EEIOA allows providing estimates of overall environmental pressures of a country. This can be done based on a territorial or production related assessment: all interventions taking place within the country's geographical boundaries. It can also be done based on a footprint or consumption based assessment: all interventions related to satisfy final demand, whether they take place within the country or outside it. For such a consumption based analysis, a multiregional trade linked EE-SUIO model (MR-EEIOA) is appropriate. MR-EEIOA models are used for footprint analysis of nations, for example for calculating carbon footprints (see Footprint fact sheet).

In order to estimate environmental pressures from the consumption perspective, the EEIO model should be modified by using a worldwide production technology (including both domestic and imported intermediate inputs). Environmental coefficients should be adjusted (if possible) to reflect differences in environmental intensities across trade partners. A review of the methodologies is described in Serrano and Dietzenbacher (2010).

Integrated analysis in economic structure and environmental pressure over time
In an EE-SUIOT the transactions between industries give a description of the structure of the national economy. Comparison of different EE-SUIOT over time might be used to identify changes in this structure, together with changes in the environmental pressure. Environmental pressure may change via various mechanisms: (1) a change in the environmental extensions, for example as a result of end-of-pipe emission reduction, (2) a change in efficiency, enabling a sector to generate the same output with less input, (3) a change in the structure of the economy, enabling a sector to generate the same output with different inputs, and (4) changes in GDP that have an overall impact on the production level. The contribution of these factors can be assessed by a decomposition analysis (see above).

Contribution analysis
With an EE-SUIOT it is possible to do a contribution analysis of the most important sectors contributing to the emissions and extractions of a region, for both a territorial and a footprint based intervention profile.

Scenario analysis and counterfactual analysis
IOA and EEIOA may be used also for ex-ante modelling. Starting from observational data, it is possible to build scenarios or counterfactuals by modifying any of the elements of the three main components of EEIO models: environmental coefficients, Leontief matrix, vector of final demand. This could be useful to compare how different technologies (both in terms of mix of intermediate inputs and in terms of intensity of environmental pressures) and different vectors of final demand (corresponding to different assumptions on behaviors of consumers) affect aggregate environmental pressures.

Price (Ghoshian) models
IOA could be used to describe relative prices of industry output by assuming that quantities are held fixed and price changes are completely transmitted to downstream sectors and to final demand (Oosterhaven, 1996). This category of models could be used to provide some estimate on the effect of changes in the relative prices of a product (possibly due to the

introduction and the diffusion of innovations) on the prices of other products or changes in (carbon) taxation of energy products.

Type(s) of data or knowledge needed and their possible source(s)

Data requirements and availability:
Many countries have databases for IOA, be it of different quality and detail.
The option of employing EEIOA depends on the availability of input-output tables and corresponding environmental extensions (NAMEA -like data, Eurostat, 2016a). Moreover, when dealing with analysis of time series and structural decomposition analysis, such information needs to be available for more than one period. Recent efforts by Eurostat and EU-funded research projects improved data coverage for both input-output tables and environmental extensions.

Environmental Extended Supply Use and Input Output Tables (EE-SUIOT from Eurostat)
Eurostat's EU27 consolidated Environmentally Extended Supply Use and Input Output Tables are a combination of Air Emissions Accounts by activity (NACE industries and households, formerly called NAMEA) (Eurostat, 2016a) and Consolidated supply, use, and input-output tables (product-by-product) at basic prices (Eurostat 2016b,c,d).

The tables come in two resolutions: 60*60 and 6*6 product groups. Data for eight pollutants (CO_2, N_2O, CH_4, SO_x, NO_x, NH_3, CO, NMVOC) are added to the above mentioned consolidated SUTs and IOTs. Due to confidentiality reasons the EE-SUOITs are published only for the aggregated EU27 and euro area. National level time series start in general in 1995. However, the consolidated tables cover the years 2000 to 2006. For a detailed description see the Technical Documentation of EE-SUIOT (Eurostat, 2011, 2014).

World Input Output Database (WIOD)
The World Input Output Database (WIOD) project is funded by the European Commission, Research Directorate General as part of the 7th Framework Programme, Theme 8: Socio-Economic Sciences and Humanities (Timmer, 2012).
The tables have a resolution of 35 sectors. The World Input-Output Database consists of time series of:

- World Input-Output tables and International Supply and Use tables
- National Input-Output tables and National Supply and Use tables
- Socio-Economic Accounts
- Environmental Accounts (air emissions, land use and aggregated material extraction)

The database covers 27 EU countries and 13 other major countries in the world for the period from 1995 to 2009.

EXIOBASE

EXIOBASE[2] is a MR-EEIOA database and model developed in the projects EXIOPOL[3] and CREEA[4] both funded by the European Commission.
The tables have a detailed sector resolution of 160 sectors. The environmental extensions include emissions to air, the use of land and water, and the extraction of a number of specific resources.

EXIOBASE has a global coverage (27 EU countries, 17 other countries and RoW). Time series have been constructed covering 1995 – 2011.

Model used

The IO framework in first instance is an accounting method. Information is collected about interactions between sectors in the economic system. If these data are transformed into multipliers, the IO accounting framework can be transformed into a static linear IO model that can be used to assess the effects of changes.

IOA is expressed in a set of linear equations, followed by an indication of the connection between the purely algebraic solution to the input-output, using the Leontief inverse matrix, and the logical economic content of the round-by-round view of production interrelationships in an economy. For environmental purposes there are three (different) basic categories of models: the Generalised IO Model, the Economic/Ecologic Model and the Commodity-by-Industry Model.

Input-output tables represent the distribution of sectoral gross output in matrix form, in which each row represents the breakdown of sectoral gross output into intermediate consumption (further broken down by the sector) and in final consumption. If the sectoral breakdown of intermediate inputs corresponds to the same sectors in the economy, the matrix representing intersectoral flows is a square matrix (Z). The vector of sectoral gross output (x) is given by the sum of intermediate inputs (Zi, where i is a vector of ones) and final consumption (vector f). An alternative way of representing gross sectoral output is to use a matrix of technical coefficients (A=Z<x>-1)(note: <x> is a square diagonal matrix having the element of the vector x on its diagonal) , with the vector of gross output now defined as x=Ax+f. The final step is to express the vector of gross sectoral output as a function of final demand and technology (in terms of mix of intermediate inputs) only: x=(I-A)-1f where I is the identity matrix. The matrix (I-A)-1 is defined as the Leontief matrix (L).

[2] www.exiobase.eu/

[3] www.feem-project.net/exiopol/

[4] www.creea.eu/

The equation x=Lf fully describes how changes in the vector of final demand (f) reflect in changes in the vector of sectoral gross output (x).

This simple representation of the economy can be easily extended to account for environmental pressures driven by the production of gross output. This extended model is built by pre-multiplying a vector of sectoral coefficients of environmental pressures (w=e<x>-1 where w is the vector of coefficients of environmental pressures and e is a vector of total direct sectoral environmental pressures) to the basic input-output model (x=Lf). The final identity which describes total sectoral environmental pressures is e=wLf. In this equation, changes in the vector of final demand (f) are linked to changes in the vector of sectoral environmental pressures. For a more detailed overview of basic concepts of input-output analysis refer to chapter 2 of Miller and Blair (2009).

System and/or parameters considered

The primary object of analysis in IOA is the monetary exchanges between the elements of the system investigated. These are listed in an IO-table. In EEIOA extractions and emissions are additional objects of analysis.

SUTs and IOTs are composed for national economies. They can be aggregated into larger units, for example the EU, or even the world. Linking national IOTs via trade-flows into Multi-Regional IOTs enables the analysis of international trade flows.

With a MR-EE-IOT framework it is possible to derive two types of environmental intervention profiles for a specific country representing different system boundaries:

- Territorial or production based extractions and emissions, expresses the environmental pressure within the national territory due to the activities in the total national economy
- Footprint or consumption based extractions and emissions; The EEIOT together with the ‘final demand’ of products and services can be used to derive this ‘consumption based environmental intervention profile’ of a total national economy.

IOA follows a region-oriented system definition. It is effect oriented, analysing the changes which occur in the different elements due to a specific change in demand. This tool uses linear algebra which allows all economic activity to be directly related to final demand. With an EE-SUIOT framework it is possible to derive two types of intervention (emission and extraction) profiles for a specific country representing different system boundaries:

- territorial based interventions, expresses the environmental pressure in a region due to the activities in the total regional economy (mainly focused on activities of production, but sometimes also but to a less extend use and waste treatment in the region)

- function based interventions or consumption based interventions; The EEIOT together with the ‘final demand’ of products and services (expressed in monetary terms) can be used to derive this ‘consumption based intervention profile’ of a total regional economy.

Time / Space / Resolution /Accuracy / Plausibility

An input-output model is constructed for a particular economic area, using administrative boundaries. Usually the economic area is a nation state. The economy is divided into a number of sectors. The resolution differs from 10 to 500 sectors. Global MR-EEIOA models distinguish 50–120 sectors. The time resolution is one year. See also section data needs/databases.

Problems with consistency occur especially when linking national IOTs. Discrepancies between country data have to be resolved via a reconciliation procedure that sometimes leads to significant errors. Uncertainties occur especially in the translation from the monetary to the physical. This includes the environmental extensions which often are rather crude. In IOA there are standardized ways to account for uncertainties (see separate fact sheet on Input Output Analysis).

Indicators / Outputs / Units

The type of interventions represented in EEIOA may be resource flows into, or emissions from different economic sectors. Indicators usually have the dimension of resource or eco-intensity, or resource productivity. Using an EEIOA framework it is possible to derive two types of intervention profiles (emissions and extractions) for a specific country:

- production based interventions or territorial based interventions
- consumption based interventions or function based interventions

The environmental satellite account of the EEIOT expresses the environmental pressure in a region due to the activities in the regional economy (activities of production, use and waste treatment in the region) and thus specify the first intervention profile.
In a consumption based emission approach, the emissions are related to the consumption in that region. The EEIOT together with the final demand of products and services (expressed in monetary terms) can be used to derive this consumption based intervention profile, which not only includes the production, domestic as well as foreign, to the extent required for domestic consumption. This can be characterized as a function based or a “footprint” approach (see separate factsheet on footprints). A carbon footprint account of the countries

of the world is available, derived from trade-linked EEIOA, as well as EEIOA derived water footprint accounts are also available (GFN, 2012; Hertwich & Peters, 2009; Hoekstra & Mekonnen, 2012].

Treatment of uncertainty, verification, validation

While the physical measure is perhaps a better reflection of one sector's use of another sector's product, there are enormous measurement problems when sectors actually sell more than one good. For these and other reasons, accounts are generally kept in monetary terms, even though this introduces problems due to changes in prices, which do not reflect changes in the use of physical inputs. Furthermore IOA suffers from limitations of high levels of aggregation in international input-output tables.

As an analytical tool IOA is dependent on the choice of the "right" conditions, i.e., of what is going to be taken into account. The environmental problems that are considered to be relevant can vary from one study to another. Analysis using IOA assumes that the technical and pollution coefficients do not change over time. Clearly this is unrealistic for changes over a long time period.

Problems with consistency occur especially when linking national IOTs. Discrepancies between country data have to be resolved via a reconciliation procedure that sometimes leads to significant errors. Uncertainties occur especially in the translation from the monetary to the physical. This includes the environmental extensions which often are rather crude. In IOA there are standardized ways to account for uncertainties (see separate fact sheet on Input Output Analysis).

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Related methods

Compatibility with other types of information:
Current EEIOA is focused on expanding the scope to cover consumption, disposal, health effects, environmental impacts, etc. Given the region-oriented type of system definition it can be linked to MFA studies.

Hybrid LCA is a combination of LCA and EEIOA. The structure of the two methods is similar, and the combination may overcome some of the drawbacks of either method. LCA has a high resolution but has a limited scope, while EEIOA has a low resolution but represents the total economy (Suh & Nakamura, 2007; Heijungs et al., 2006). To relate micro level changes to effects on the macro level it is necessary to embed the micro system into a macro system. In this sense both methods, LCA and EEIOA, seem to be complementary. In Van Oers et al. (2013) the possibilities of the use of hybrid LCA EEIO models in the EmInInn project is further elaborated.

Some examples of operational tools

Many countries have databases and derived models for EEIOA, be it of different quality and detail, either compiled by national statistical bureaus and/or universities.
Some examples of Multi Regional databases and models are given in the section 'Type(s) of data or knowledge needed and their possible source(s)', like EXIOBASE, WIOD and the EE-SUIOTs from Eurostat.

Key relevant contacts

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Footprint methods

FACT SHEET

Footprint methods

Scope

The term "footprint" was initially introduced by Mathis Wackernagel and William Rees in the early 1990s (Rees and Wackernagel, 1992), when the indicator "Ecological Footprint" was first presented. The Ecological Footprint is an aggregated indicator that calculates the total environmental pressure related to consumption in terms of square meters of land required. "Consumption" can refer to a product, to the annual consumption of a person, or to the annual consumption of a nation. Later additions to the Ecological Footprint are the comparison with the area of bioproductive land for the country-level assessments, and to the addition of land needed to absorb the waste (CO_2) produced (WWF et al., 2012). Ecological Footprints use a consumption-based system, and a global perspective, i.e. they include all biologically productive land world-wide to satisfy consumption, including those embodied in internationally-traded products. (Giljum *et al.,* 2013)

More recently, the term "footprint" is also introduced for other indicators than the land use. These indicators use the same type of consumption based system, but express the pressure of that system in different terms. We now have the following footprints, in addition to the Ecological Footprint:

- Water footprint
- Land footprint
- Materials footprint
- Carbon footprint

Even more recent is the notion that "footprints" can also be calculated for intermediate consumption, turning the system into a cradle-to-gate rather than a cradle-to-grave chain. Recently, the concepts of Product Environmental Footprint (PEF) and Organisation Environmental Footprint (OEF) have been introduced by the JRC as part of the European Platform on Life Cycle Assessment (see http://eplca.jrc.ec.europa.eu/?page_id=104). The PEF in fact is a form of product LCA. The OEF is an indicator of environmental pressure related to the products produced or services delivered by certain organisations. It can therefore be described as a cradle-to-gate LCA with a complex functional unit. The PEF and OEF guide can be found as Annex 2 and 3 of the EC Recommendation on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations (European Commission, 2013). PEF and OEF will not be described further here. Their methodology is Life Cycle Assessment; a description can be found in the LCA fact sheet.

The **water footprint** is the total amount of fresh water that is used directly and indirectly to produce the goods and services which satisfy domestic final consumption. For effective water management the water footprint ideally distinguishes between different types of water flows: (1) water withdrawal and water consumption; the first term being the whole amount of water abstracted from the environment, the second being only the amount which is not returned at all (incorporated in the product) or at much later point in time or to another catchment. (2) Blue and green water; the first being water extracted from surface and groundwater, the second from rainwater. The distinction between the blue and green water footprint is important because the hydrological, environmental and social impacts, as well as the economic opportunity costs of surface and groundwater use for production, differ distinctively from the impacts and costs of rainwater use. Comprehensive water accounts – and the resulting footprint analyses – encompass all these aspects of the appropriation of water by human society (WFN, 2016; Mekonnen & Hoekstra, 2011; Chapagain & Hoekstra, 2004). In an attempt to model closer to the Ecological Footprint, (3) Grey water has been added: the amount of water needed to absorb emissions to water.

The **land footprint** assesses the domestic and foreign land areas, which are directly and indirectly required to satisfy domestic final consumption. It is important to note that land footprint approaches differ from calculations of the ecological footprint, as no weighting of land areas by different bio-productivities is applied. In contrast to the category of materials, no harmonised definition of the land footprint exists so far. Due to data restrictions, land footprint studies have so far often focused on the agricultural and forestry areas.

The **material footprint** illustrates the global, life-cycle wide material extraction and use related to the final consumption of a country, whether occurring within the country or beyond the countries' borders. Material footprint is therefore a newer term for "ecological rucksacks" (Schmidt-Bleek, 1992; Schmidt-Bleek, 2009), which also refer to the life-cycle wide material inputs of products. Material footprints can be focused on used material extraction (resulting in the indicator Raw Material Consumption) or also include unused material extraction (delivering Total Material Consumption). EUROSTAT (2013) and OECD (2007) offer methodological guides for the material footprint indicator.

The **carbon footprint** captures the full amount of greenhouse gas emissions that are directly and indirectly caused by an activity or are accumulated over the life stages of products, which are consumed in a country (Wiedmann, 2011). Three standards for carbon footprinting have been already published, including the PAS 2050 standard (BSI, 2008), the Product Life Cycle Accounting and Reporting Standard by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD) (WRI & WBCSD, 2011), and the International Organisation for Standardisation developed the ISO 14067 on the Carbon Footprint of Products (ISO, 2012).

Each of the above footprints has their own methodology, data needs and indicators. However, the general principle of all the footprint methods is that they take consumption - or function based perspective to calculate environmental impacts, rather than a production- or territorial based perspective. Given this consumption perspective, methodologies such as Life Cycle Assessment (LCA) and Multi-Region Environmental Extended Input Output Analysis (MR-EEIOA) can be used to calculate footprint indicators. For details see factsheets on LCA and EEIOA. Giljum et al (2013) describe three types of methodologies to calculate footprint-type indicators based on IOA, LCA or a hybrid of these two methods. The report also gives an overview of databases that are useful to derive footprint indicators for materials, water, land and carbon (Giljum et al., (2013). For example research is undertaken to use input-output tables as input to calculate Carbon, water, land and materials Footprint accounts (Tukker et al., 2014). This factsheet will now focus on the footprint methodologies that are not based on LCA or IOA.

Contexts of use, application fields

The Ecological Footprint shows whether the current consumption is within the limits of what the earth can sustain (Schaefer et al. 2006). They have a strong communicational and educational strength, are very effective for raising awareness on environmental sustainability and can be used to evaluate personal lifestyles (Giljum et al. 2007). However, the Ecological Footprint has also attracted criticism because of the comparison with this biocapacity indicator, especially in combination with the recent addition of land for CO_2-absorption (see, among others, Van den Berg & Grazi, 2013).

Footprint applications without the carrying capacity dimension are found to be useful at many scale levels. They are used by countries, by persons and by sectors to assess the worldwide impact of their actions, and thus form a valuable addition to the usually territorially bounded environmental information. Such applications have shown that some countries have exported the more polluting stages of the life cycle, and that there are countries that provide the rest of the world with resources. The EU Resource Efficiency Roadmap has defined an indicator set where territorial indicators of material, water and land use and GHG emissions are complemented by footprint indicators for material, water and land use and GHG emissions.

Type(s) of data or knowledge needed and their possible source(s)

1. National Ecological Footprint, based on carrying capacity
The data necessary to calculate the National Ecological Footprint Accounts are mainly from international statistical and scientific agencies. The primary resources are tracked based on FAOSTAT data. The FAO documents data on production, import and export data of many resources. The primary resources embodied in manufactured products are tracked using data from the UN Statistical Department COMTRADE global trade database. An overview of required data is provided in the original guides for calculation of ecological footprints (GFN, 2008a; Wackernagel et al., 2005).

2. Water footprint
All water footprints are based on a basic water balance of a process using the following data

1. Water Evaporation;
2. Water Incorporation into the product;
3. Lost Return flow to the same catchment area, for example, it is returned to another catchment area or the sea;

4. Lost Return flow in the same period, for example, it is withdrawn in scarce period and returned in a wet period.

In addition to calculate grey water footprints information is needed on pollutant loads by a process and standards for maximum acceptable concentration and natural concentration levels of pollutants in the water.
The water footprint network has published the Global Water Footprint Assessment Standard lays out the internationally accepted methodology for conducting a Water Footprint Assessment (http://waterfootprint.org/en/standard/global-water-footprint-standard/). Water footprints which are calculated using the Global Water Footprint Assessment Standard are provided in WaterStat (http://waterfootprint.org/en/resources/water-footprint-statistics/).

3. Land footprint
The data needs for the land footprint are similar to those of the ecological footprint (see first item). However, in the land footprint the land use is not compared to carrying capacity references, and the land for the absorption of CO_2 is not taken into account.

4. Materials footprint
Material footprints are based on Economy Wide Material Flow Aaccounting, see the factsheet EW-MFA. Eurostat produces measures of domestic material consumption (DMC) as part of the EW-MFA accounts. Those statistics however do not provide an accurate picture of global material footprints because they record the international flows of materials differently than the materials extracted from the environment (called domestic extraction in EW-MFA). Imports and exports are recorded in material flow accounts as the actual weight of the traded goods when they cross country borders instead of the weight of materials extracted to produce them. As the former are lower than the latter economy-wide, material flow accounts and the derived DMC underestimate the material footprint. To adjust for this, the weight of processed goods traded internationally is converted into the corresponding raw material extractions they induce. So import and export flows must be expressed in their raw material equivalents (RME). These are estimated with models that are still under development and therefore do not produce official statistics yet.
http://ec.europa.eu/eurostat/statistics-explained/index.php/Material_flow_accounts_-_flows_in_raw_material_equivalents

5. Carbon footprint
The carbon footprints are based on EE-IOA and LCA methodologies: for details please see the respective factsheets.

Model used

1. National Ecological Footprint
The Ecological Footprint accounts consist of a supply side (Biocapacity) and a demand side (Ecological Footprint). The supply side consists of a table. The demand side is calculated by

using square meter multiplyers for each type of consumption, also from a table. These are used to calculate Global Hectares, and then added up to form a total Ecological Footprint at the national level that then is compared to the national bioproductive land area.

2. Water footprint
The water footprint of one single 'process step' is the basic building block of all water footprint accounts. The blue water footprint in a process step is calculated as the sum of blue water evaporation, blue water incorporation in products and a lost return flow. The green water footprint in a process step is equal to the green water evaporation plus green water incorporation. The grey water footprint is calculated by dividing the pollutant load by the difference between the ambient water quality standard for that pollutant and its natural concentration in the receiving water body. The three are then added up to a total water footprint.

3. Land footprint
Land footprints are based on domestic final consumption of products by nations or individuals and multiplies this consumption with land areas necessary to produce these products, similar to the Ecological Footprint. Up until now many land footprints are limited to products from agriculture and forestry.

4. Materials footprint
The material footprint is based on EW-MFA, for details see factsheet EW-MFA. However, the traded flows are converted from kg product into kg Raw Material Equivalents (RME). In order to do this all the raw materials that are extracted along the cradle to gate or cradle to grave chain of the consumed product are aggregated into a mass indicator. Trade flows in RME are estimated by Eurostat based on an environmentally extended hybrid input-output model for the aggregated EU economy. These embedded raw materials in trade products are combined with the domestic extracted raw materials to define the Raw Material Consumption expressed in Raw Material Equivalents (RME).

5. Carbon footprint
The carbon footprints are mostly based on EE-IOA and LCA methodologies; for details please see the respective factsheets. The footprint score is based on an inventory of the emissions of all the greenhouse gasses emitted by the system. The emissions are multiplied with weighting factors that express the relative contribution of the substance emission to global warming. In LCA terminology this is called characterization. The final footprint score is expressed in kg CO_2 equivalents.

System and/or parameters considered

The system of all footprints is consumption based: the total amount of land, water, materials or carbon that is required for the consumption of a person, a product, a country, a sector, or the world. The details differ per application.

1. Ecological Footprint

The Ecological Footprint mostly focuses on the national level. The system of the national footprint is defined as the total amount of land required to fulfill the demand of the nation's population. This land can be located anywhere in the world. The reference, the nation's biocapacity, is the sum of all bioproductive land within the nation's territory.

For the demand side of the accounts, the footprints of renewable resources, built-up area and fossil fuels are calculated. The footprint of built-up area is equal to the foregone agricultural productivity of these areas, under the assumption that built-up areas occupy former cropland. The footprint of fossil fuels is calculated as the bioproductive area needed to sequester the CO_2 emission through afforestation.

For the supply side of the accounts, the biocapacity of a country is calculated. The land area is translated into global hectares using equivalency factors and the national yield factors. The global hectares of the different land categories are then summed to obtain the total national biocapacity (GFN, 2008a).

The Ecological Footprint is also used at the level of an individual. Websites exist where individuals can calculate their Ecological Footprints based on a number of assumptions and some data provided by the individual on their lifestyle. This personal Ecological Footprint then can be compared to the area formed by dividing the total global bioproductive area by the world population. This "fair share" obviously changes over time as the world population grows.

2. Water footprint

Water footprints can be based on different system definitions:

- The water footprint of a product = the sum of the water footprints of the process steps taken to produce the product (considering the whole production and supply chain).
- The water footprint of a consumer = the sum of the water footprints of all products consumed by the consumer.
- The water footprint of a community = the sum of the water footprints of its members.
- The water footprint of national consumption = the sum of the water footprints of its inhabitants.
- The water footprint of a business = the sum of the water footprints of the final products that the business produces.
- The water footprint within a geographically delineated area (for example, a municipality, province, state, nation, catchment or river basin) = the sum of the process water footprints of all processes taking place in the area.

The methodology for calaculation of the water footprints and the data needs are described in detail in the water footprint standard http://waterfootprint.org/en/standard/global-water-footprint-standard/

3. Land footprint
The land footprint refers the domestic and foreign land areas, which are required to satisfy consumption, mostly limited to agricultural and forestry products. “Consumption” can refer to a product, to the annual consumption of a person, or to the annual consumption of a nation.

4. Materials footprint
The materials footprint refers the domestic and foreign extracted raw materials, accumulated over the life stages of products, which are consumed. “Consumption” is mostly related to the annual consumption of a nation, as the method is linked to EW-MFA. Sometimes a per capita or per € ($) dimension is used to enable comparison between countries. MIPS is a similar concept that is applied at the product level.

5. Carbon
The carbon footprint refers the domestic and foreign emitted Green House Gasses (expressed in CO_2-equivalents) accumulated over the life stages of products, which are consumed. “Consumption” can refer to a product, to the annual consumption of a person, or to the annual consumption of a nation. Carbon footprints are also calculated for sectors, and for companies.

Time / Space / Resolution /Accuracy / Plausibility

1. Ecological Footprint
The National Footprint Accounts, 2006 Edition contains the national Ecological Footprint and biocapacity of more than 150 nations from 1961-2003.
www.footprintnetwork.org/gfn_sub.php?content=nrb
National Footprint Account (NFA) results from the 2016 edition are available for 186 countries. Time series data for all nations is not available.
www.footprintnetwork.org/en/index.php/GFN/page/footprint_for_nations/

2. Water footprint
Water footprints are available in Waterstat for the period 1996-2005 for crops, animal products, biofuels, industrial products, national production and national consumption by countries worldwide. waterfootprint.org/en/resources/water-footprint-statistics/

3. Land footprint
Land footprints can be derived for products or the consumption by individuals or the yearly consumption of goods by nations. There are no formalized time series of land footprints for countries available yet.

4. Materials footprint
Eurostat's material flow accounts in RME include a breakdown by four main material categories; biomass, metal ores, non-metallic minerals, and fossil energy materials/carriers, each with several more detailed breakdowns, with a total of 67 categories (including

grouped categories). The Eurostat material footprints are reported yearly for 28 European member states. http://ec.europa.eu/eurostat/statistics-explained/index.php/Material_flow_accounts_-_flows_in_raw_material_equivalents

5. Carbon footprint
Carbon footprints can be derived for products or the consumption by individuals or the yearly consumption of goods by nations.
Yearly carbon footprints are available for nations worldwide (see for example http://carbonfootprintofnations.com/)
There are several carbon footprint tools on the internet that calculate carbon footprints of products or of individual consumption.

Indicators / Outputs / Units

1. Ecological Footprint
The EF is expressed in units of surface (m2, ha or km2). In fact it is surface being used for one year's consumption of a nation, but the "year" dimension has disappeared from the indicator. When compared to the reference, the indicator becomes dimensionless: m2/m2. It then expresses the fraction of the biocapacity that is "used up" (Wackernagel et al. 2005; GFN, 2006 & 2008). www.footprintnetwork.org/en/index.php/GFN/

2. Water footprint
Water footprints at the national level are calculated in terms of m3 water per inhabitant and per year (WFN, 2011). The components of blue, green and grey water are provided separately. Also the contribution of domestic and foreign water use is provided separately.

3. Land footprint
Land footprint is expressed in units of surface (m2, ha or km2). Depending on the system definition it will relate to one year's consumption of a nation or individual, or to the cradle to gate/grave chain of a unit (e.g. kg, piece etc.) of product.

4. Materials footprint
Material footprints are expressed in kg Raw Material Equivalents. Depending on the system definition it will relate to one year's consumption of a nation or individual, or to the cradle to gate/grave chain of a unit (e.g. kg, piece etc.) of product.

5. Carbon footprint
Carbon footprints are expressed in kg CO_2-equivalents. Depending on the system definition it will relate to one year's consumption of a nation or individual, or to the cradle to gate/grave chain of a product.

Treatment of uncertainty, verification, validation

For all footprints, information on uncertainty is scattered and limited. For Material footprints and Carbon footprints, uncertainty estimation is based on their respective methods (EW-MFA, EE-IOA and LCA).

As indicated earlier, there is criticism on the Ecological Footprint preventing a general acceptance of this indicator. This is related to the use of bioproductive land as a reference. A country such as the USA or Australia, with a very high per capita footprint, comes out as sustainable because their consumption doesn't overshoot their bioproductive land. A country such as the Netherlands, densely population but with a much lower per capita footprint overshoots its biocapacity by a factor 3-6. The information this provides for environmental policies is at best confusing. A further point of criticism is the fact that in recent years land to absorb CO_2 emissions has been added to the footprint, in an attempt to increase the scope of the indicator. This has resulted in an indicator that combines actual with virtual land use, rendering the comparison with bioproductive land rather meaningless. A similar addition has been made to the water footprint: the grey water, increasing the scope by including water pollution as the amount of water needed to absorb the pollution, again at the expense of devaluating the straightforward message of the original water footprint.

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Related methods

Given the consumption perspective of the footprint indicators, methodologies like Life Cycle Assessment (LCA) and Environmental Extended Input Output Analysis (EEIOA) can be used to calculate footprint indicators. For details see factsheets on LCA and EEIOA. Giljum et al (2013) describe three types of methodologies to calculate footprint-type indicators based on IOA, LCA or a hybrid of these two methods. The report also gives an overview of databases that are useful to derive footprint indicators for materials, water, land and carbon (Giljum et al., (2013).

Some examples of operational tools

Water footprint

The Waterfootprint network provides different tools to calculate the water footprint, like

- Water Footprint Assessment Tool
- National water footprint explorer
- Product gallery
- Personal water footprint calculator

http://waterfootprint.org/en/resources/interactive-tools/

Key relevant contacts

The most widely used methodology for calculating national Footprints are the National Footprint Accounts by the **Global Footprint Network**. The Global Footprint Network (GFN) is the organization that promotes the application of Ecological Footprint accounts and is supported by more than 90 partner organizations. The National Footprint accounts are calculated annually for more than 150 countries. The Global Footprint standards (GFN 2006b) have been initiated by the Global Footprint Network to reach consensus on a common calculation method for the Ecological Footprints. Partners of the Global Footprint Network are required to comply with the most recent Ecological Footprint standards.
www.footprintnetwork.org/en/index.php/GFN/

The **Water Footprint Network** is an international learning community (non-profit foundation under Dutch law) that serves as a platform for connecting communities interested in sustainability, equitability and efficiency of water use. The organization has two work programmes: a Technical Work Programme and a Policy Work Programme. In addition, there is a Partner Forum which offer partners of the WFN a way of receiving, contributing and exchanging knowledge and experience on water footprint.
waterfootprint.org/en/

Material footprint accounts for the European Union are drafted by **EUROSTAT**
http://ec.europa.eu/eurostat/statistics-explained/index.php/Material_flow_accounts_-_flows_in_raw_material_equivalents
Or by the materialfootprint network
http://materialfootprint.org/materialfootprintnetwork_eng.html#objectives

Carbon footprints of nations are mostly calculated using EE-IOA, see factsheet EE-IOA. Three standards for carbon footprinting have been already published, including the PAS 2050 standard (BSI, 2008), the Product Life Cycle Accounting and Reporting Standard by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD) (WRI & WBCSD, 2011), and the International Organisation for Standardisation developed the ISO 14067 on the Carbon Footprint of Products (ISO, 2012).

Quantitative Risk Assessment

MICA Mineral Intelligence Capacity Analysis

FACT SHEET

Quantitative Risk Assessment (QRA)

Scope

Risk Assessment (RA) is a broad method of estimating and managing health risks. A formal QRA attempts to answer the questions:

1. What can go wrong?
2. How often does it happen?
3. How bad are the consequences?

Based on this information, the decision is made whether the risk is considered acceptable. The approach calculates the chance of some hazardous event and multiplies that with the number of potential casualties if such an event would happen. The result is a theoretical number of casualties per annum, which is then subjected to a comparison with an established acceptable level. RA is relevant for the release of toxic substances into the environment, but is used for incidents rather than prolonged exposure as a result of continuous emissions. It is also used for other disastrous events such as explosions, floods or traffic accidents.

Contexts of use, application fields

A Quantitative Risk Assessment (QRA) is a valuable tool for determining the risk of the production, use, handling, transport and storage of dangerous substances. QRAs are performed if dangerous substances are thought to be present at a location (e.g. industrial sites and transportation routes) in amounts that can endanger health or the environment. A QRA is used in a Safety Report to demonstrate the risk caused by the establishment and to provide the competent authority with relevant information for assessing incremental risk and for enabling decisions on the acceptability of risk related to developments on site of or around the establishment (RIVM, 2005).

A Safety Report should be made if the amount of dangerous substances that can be present in an establishment exceeds a threshold value. The procedure to determine whether a Safety Report has to be made is given in the 'Seveso-III directive', the Directive 2012/18/EU of the European Parliament and of the Council of 4 July 2012 on the control of major-accident hazards involving dangerous substances, amending and subsequently repealing Council Directive 96/82/EC (EC, 2016; EC, 2012). The procedure is outlined in for example the

Dutch Reference Manual Bevi Risk Assessments (RIVM, 2015; RIVM, 2009; RIVM, 2005) and the ARAMIS, developed in an European project, a risk assessment methodology for industries in the framework of the SEVESO II directive (Salvi & Debray, 2014).

The Minerva portal of the Major Accident Hazards Bureau at the European Commission's Joint Research Centre provides a collection of technical information and tools supporting the Industrial Accident policy. (JRC, 2016)

Type(s) of data or knowledge needed and their possible source(s)

Risk assessments are performed for the use, handling, transport and storage of dangerous substances. QRA's are performed for installations or transport routes for these two different applications slightly different models and procedures are used (RIVM, 2015; RIVM, 2009; RIVM, 2005)

Roughly the following information is needed to perform a quantified risk assessment for a static installation:

- Selection of installation to estimate loss of containment events:
  Type and location of installations
- Dispersion of the substance:
  Physical and chemical properties of the substance, meteorological data
- Exposure and damage:
  Toxicological data of the substance
- Individual risk and societal risk assessment:
  information of the people density and distribution at the location

The basic data needed in conducting a QRA for a specific transport route include the:

- Description of the transport route (location, type of route, obstacles present)
- Description of the transport streams (annual number of transport units per substance or category, during daytime and night-time)
- Description of the number of accidents and traffic intensities in order to determine accident frequencies
- Description of the transport units (type of unit, characteristic inventory)
- Description of the ignition sources
- Physical, chemical and toxicological properties of transported (representative) substances
- Terrain classification of the surroundings of the transportation route
- Meteorological data
- Population present in the surroundings of the transportation route

The Minerva portal of the Major Accident Hazards Bureau at the European Commission's Joint Research Centre provides a collection of technical information and tools supporting the Industrial Accident policy. (JRC, 2016)

Model used

In general three steps in the procedure of risk assessment can be distinguished all making use of dedicated models

- methods for determining and processing probabilities are used to derive scenarios leading to a loss of containment event
- models to determine the outflow and dispersion of dangerous substances in the environment
- models to describe the impact on humans of exposure to toxic substances , heat radiation and overpressure (RIVM, 2015; RIVM, 2009; RIVM, 2005)

System and/or parameters considered

Quantitative risk assessment calculates the probability and consequences of an incident either for a static installation or a mobile transport vessel along a transport route. The calculated risks are substance specific, installation specific and site specific.

Time / Space / Resolution /Accuracy / Plausibility

The consequences and probability of the risks are calculated for the present situation. The probability of the incident is mostly based on a year. The risk assessments are made case by case for detailed specified installations and transport routes.

Indicators / Outputs / Units

The results of a QRA are the Individual Risk and the Societal Risk (RIVM, 2015; RIVM, 2009; RIVM, 2005)

- The Individual Risk represents the frequency of an individual dying due to loss of containment events (LOCs). The individual is assumed to be unprotected and to be present during the total exposure time. The Individual Risk is presented as contour lines on a topographic map.

- The Societal Risk represents the frequency of having an accident with N or more people being killed simultaneously. The people involved are assumed to have some means of protection. The Societal Risk is presented as an FN curve, where N is the number of deaths and F the cumulative frequency of accidents with N or more deaths.

Treatment of uncertainty, verification, validation

If the results of a QRA in the decision-making process are to be used, they must be verifiable, reproducible and comparable. These requirements necessitate QRAs made on the basis of similar starting-points, models and basic data. Ideally, differences in QRA results should only arise from differences in process- and site-specific information. To guarantee such a consistency in starting points and procedure the Dutch Committee for the Prevention of Disasters (CPR) has published a number of documents for attaining comparability in the QRA calculations.

The Committee for the Prevention of Disasters (CPR) has issued three reports describing the methods to be used in a QRA calculation, namely the 'Red Book', the 'Yellow Book' and the 'Green Book'. The 'Red Book', describing the methods for determining and processing probabilities, is to be used to derive scenarios leading to a loss of containment event [CPR12E]. The 'Yellow Book' describes the models to determine the outflow and dispersion of dangerous substances in the environment [CPR14, CPR14E], and finally, the 'Green Book' describes the impact on humans of exposure to toxic substances, heat radiation and overpressure [CPR16].

Main publications / references

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Related methods

Environmental risk assessment, see factsheet ERA, is part of the broader family of Risk Assessment. ERA is relevant for the release of toxic substances into the environment, but for prolonged exposure as a result of continuous emissions rather than for incidents.

Some examples of operational tools

ADAM (Accident Damage Analysis Module) is a tool developed by MAHB (Major Accident Hazards Bureau from EC-JRC) designed to assess physical effects of an industrial accident in terms of thermal radiation, overpressure or toxic concentration resulting from an unintended release of a dangerous substance. For such a purpose, suitable models have been used and combined, to simulate the possible evolution of each accident: from the time of release to the final damage. This tool is specifically intended to guide the EU competent authorities for assessing the consequences of potential major accidents.
https://minerva.jrc.ec.europa.eu/en/ADAM/content
However there are numerous other QRA software tools exist, see for example https://en.wikipedia.org/wiki/Quantitative_risk_assessment_software

Key relevant contacts

The Joint Research Centre's Major Accident Hazards Bureau
https://minerva.jrc.ec.europa.eu/en/content/minerva/c76dfa82-97a9-435f-8e0e-39a435aeec3a/who_we_are

Environmental Risk Assessment

FACT SHEET

Environmental Risk Assessment (ERA)

Scope

Environmental Risk Assessment (ERA) studies are carried out to examine the effects of emissions from processes in plants and factories as well as their products in the broadest sense on human health and on ecosystems, enabling a risk management decision to be made. While Risk Assessment (see separate factsheet) is concerned with disastrous events, Environmental Risk Assessment is oriented at the exposure to chemicals due to continuous low-level emissions. The risk is estimated by quantifying exposure and confronting that with some sort of a no-effect or acceptable level. This may lead to risk acceptance or to the implementation of risk reduction measures that reduce the likelihood of the event or reduce the consequences to a satisfactory level.

Approaches to estimate the risks related to substances, processes and technology are either quantitative or qualitative. ERAs vary widely in scope and application. In broad terms ERAs are carried out to examine the effects on humans (Health Risk Assessment, HRA) and ecosystems (Ecological Risk Assessment, EcoRA).

The process of environmental risk assessment includes four steps: hazard identification, hazard characterisation, exposure assessment, and risk characterization and the first two steps are regarded as the process of hazard assessment:

- Hazard Assessment, identifying and characterising the inherent properties of chemical substances is basically the first step of environmental risk assessment. Environmental hazard assessment (hazard identification and hazard characterisation) involves gathering or generating and evaluating data of chemical substances and concluding on their inherent eco-toxicological effects and environmental fate. In this step single species toxicity data are extrapolated to no-effect levels.
- Exposure Assessment, another important step of the environmental risk assessment is to estimate or predict the extent of exposure of chemicals to the target species and/or the environment through its production, use and disposal. Emission rates are translated by distribution models into exposure levels and intakes.
- Risk characterisation, the last step in the environmental risk assessment, is the qualitative and, wherever possible, quantitative determination of the probability of occurrence of the adverse effects of chemicals to the environment under predicted exposure conditions. This process is based on outcomes of the previous steps, i.e. environmental hazard and environmental exposure assessment. In many regulatory frameworks environmental risks are often expressed by ratios between PEC (Predicted Environmental Concentration, derived from environmental exposure assessment) and PNEC (Predicted No Effect Concentrations for target ecosystems, an outcome of environmental hazard assessment. (OECD, 2016)

Projects from EEA provide information on the general aspects of ERA, involving its core concepts, definitions and terminology, its use and application, and its limitations and uncertainties (EEA, 1998).

Contexts of use, application fields

ERA is developed for both industry and authorities (legislators and administrators). The risk assessment focus is on the low-/no-effect end of a hazard scale, and there is a concentrated effort to deal with data requirements supporting this evaluation. Its main application is that it enables risk management.

Usually, ERA only considers the emission of toxic substances. However, there are developments to include the distribution of genetically modified organisms into the ERA framework.

ERA is the main method used by the EU in the REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) system. EC Regulation 1907 / 2006 (EC, 2006) contains detailed descriptions of the methodological steps, required data and interpretation, as well as long lists of substances and their risk classification.

Type(s) of data or knowledge needed and their possible source(s)

Dependent on the amount and the quality of available data, and considering the details required, risk assessment studies have developed into a tiered, step-wise process. A distinction can be made between:

1. a screening phase based on a restricted amount of data, relatively close to the EUbase- set requirements for notification of new chemicals,
2. a refined assessment as an "in-between" stage, carried out by using more details for the exposure as well as the effect descriptions. This is followed by:
3. a comprehensive (or full) risk assessment, which is very demanding on data and documentation. Only a few full scale risk assessment studies have actually been made for individual chemicals (e.g., for some important pesticides), whereas an assessment at this level ought to be the rule rather than an exception when dealing with assessments according to the Seveso-directive.

The risk characterisation based on the PEC/PNEC-ratio is derived from monitoring data, realistic worst cases scenarios and predictive modelling techniques. The gathering of data is a complex task and includes data on release, transport, fate mechanisms and effect/toxicity of a great number of substances. There is a wide range of available databases used in the risk assessment process. The REACH&CLP Helpdesk (2016) gives an overview of a number of databases from the European Chemical Agency and European and other international databases:
www.reach.lu/mmp/online/website/menu_vert/documentation/546/550/index_EN.html

REACH is a regulation of the European Union, adopted to improve the protection of human health and the environment from the risks that can be posed by chemicals. ‘Information on Chemicals’ from the ‘European Chemicals Agency’ is unique source of information on the chemicals manufactured and imported in Europe. It covers their hazardous properties, classification and labelling, and information on how to use them safely. As from 20 January 2016, information on up to 120 000 chemicals is enriched and structured in three layers: infocard, brief profile and detailed source data. See http://echa.europa.eu/information-on-chemicals for more details

Model used

In general two types of models are used in environmental risk assessment both making use of dedicated models:

- environmental fate models: models to determine the dispersion and fate of hazardous substances in the environment from the point of emissions, via transport through air, water or groundwater
- exposure models: models to estimate the resulting exposure of humans and/or ecosystems through intake via air, water or food
- effect models: models to estimate the toxic, carcinogenic, mutagenic and teratogenic effects of exposure to hazardous substances on humans, or the effects of exposure on plant and animal species in ecosystems.

To derive no-effect levels, all quantitative toxicity assessments are based on the dose-response concept, which is first of all based on laboratory tests using test organisms. Epidemiological data may also be used, however, such data are most often not available. In the absence of data, sometimes models are used as an approximation: QSAR models, based on the physical and chemical properties of the substances.

Generally, ERA methods and software are based on steady state modelling.

System and/or parameters considered

ERA analysis emissions of substances by processes, technologies and activities. The main focus is on the assessment of risks derived from substances and how they pose risks to human health and to ecosystems. The system is built around the emitting plant or product and includes the affected surroundings. Although local, it has no set geographical system boundaries. Neither does the system have temporal boundaries. Although the emission can be described as emissions in a period of time, the effects taken into account are often long-term.

Time / Space / Resolution /Accuracy / Plausibility…

ERA is usually a "here-and-now"-evaluation: time and location specific. ERA may, however, also deal with exposures over wider spatial scale, e.g. as can be observed for the regional or global distribution of acidifying, ozone depletion or climate changing air pollutants. In the assessment of risks of existing chemicals, the distribution from diffuse sources is also evaluated. This is part of the so-called generic Risk Assessment studies which are the objectives of EU directive 793/93.

Indicators / Outputs / Units

ERA indicators include the emissions, the environmental concentrations, the intake of the substance, and no-effect levels or acceptable levels of environmental concentrations or intake. To derive no-effect levels, all quantitative toxicity assessments are based on the dose-response concept, which is first of all based on laboratory tests using test organisms. Epidemiological data may also be used; however, such data are most often not available.

Treatment of uncertainty, verification, validation

Limitations:
The techniques quite often take only one chemical at a certain time into account, focusing on one location, but also considering one up- or downstream process. In addition, generic risk assessment studies are also being performed for a whole region, taking all emission sources into account. It should be noted that risk ERA, although focusing at the local level, is a modelling approach still quite far removed from the prediction of actual environmental impact.

Handling of uncertainties:
Uncertainties are both related to the availability of data and to the uncertainty of the data themselves. In the exposure assessment, uncertainties arise because it is difficult to model the amount of a pollutant in the environment over time, and to assess how much is taken in by individuals. In the effect assessment, uncertainties arise from variability in biological experiments and observations as well as when the findings are extrapolated from animals to humans, or from test organisms to ecosystems. For ecological risk assessment the uncertainties deal with the extrapolation of data for a small number of species to effects on bio-diversity in total. For this purpose different extrapolation methods are available. Uncertainties connected to lack of knowledge and indeterminacies intrinsic to the effects description or the uncontrolled or accidental dissemination of chemicals is generally not included in risk characterisation and assessment procedures.

Main publications / references

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Related methods

Quantitative Risk Assessment (QRA) is a broader method of estimating and managing health risks. The approach calculates the chance of some hazardous event and multiplies that with the number of potential casualties if such an event would happen. The result is a theoretical number of casualties per annum, which is then subjected to a comparison with some sort of agreed on acceptable level. RA is relevant for the release of toxic substances into the environment, but is used for incidents rather than prolongued exposure as a result of continuous emissions. It is also used for other disastrous events such as explosions, floods or traffic accidents.

Life Cycle Assessment uses information of ERA to populate its toxicity related impact categories in Life Cycle Impact Assessment.

ERA can be linked to Substance Flow Analysis when the SFA contains an analysis of environmental flows as well as flows through society.

Some examples of operational tools

Software availability:
A variety of risk assessment software models are available. In general the models are divided into transport/fate/exposure models, effect models and risk management models. There are well over 500 such models in existence for different applications.
In the OECD Environmental Risk Assessment Toolkit a summary table is given of tools and models developed and used in OECD member countries for environmental risk assessment.

www.oecd.org/chemicalsafety/risk-assessment/summarytableofavailabletoolsforriskassessment.htm

Also the REACH website gives a short overview of the tools needed or helpful to fulfill obligations under REACH (Registration, Evaluation, Authorisation and restriction of Chemicals) and CLP (Classification Labelling Packaging).
www.reach.lu/mmp/online/website/menu_vert/outils/624/index_EN.html

Key relevant contacts

Formal status:
Guidelines for risk assessment have been developed by OECD, the EU and US EPA. A number of academic societies such as SETAC, ECETOC, SRA are dealing with HRA and/or ERA. Until now ERA has not been formally standardised by ISO. In the REACH program of the EU, a high level of standardization has been obtained.

5. Fact sheets of Economic methods

Econometric methods

FACT SHEET

Econometrics

Scope

Econometrics is the application of statistical methods to economic, environmental and social data. Such methods aim to find connections and patterns in data to test hypotheses, explain a variety of economic, environmental and social phenomena, and derive quantitative estimates of the relationship between variables. Econometrics allows, for instance, to estimate the effects of mineral policies on mineral use, the impact of mineral prices on firms' performance, and forecast future environmental pressures associated with the use of mineral. As such, econometrics is a tool for applied sciences and thus also relevant in the context of minerals.

The outcome of applying econometric methods to data is estimates of model coefficients. These estimates represent the isolated effect from one variable on another, i.e. what is the effect of changing one variable on another keeping all other relevant variables constant (the so-called notion of *ceteris paribus*). Given certain assumptions, some of which are outlined below, econometrics allows to make causal inference – e.g. by how much will my revenues change due to an increase in mineral prices by 1%, while everything else remains unchanged? Therefore, econometrics provides powerful methods to empirically support decision making for policy makers and private companies.

Before using econometric techniques, one first needs to consider an adequate model to describe the hypothesis, phenomenon or relationship to be investigated. The model can be derived from economic theory, previous studies or be based on new ideas and intuition. Moreover, relevant data is essential to apply any econometric method. Depending on the type of data (cross-sectional, time-series or panel data, which are explained in greater detail in the data section) as well as assumptions underlying the model, different estimation methods can be applied. The 'default' estimation method is called ordinary least squares (OLS). OLS is a wide-spread econometric method, because it is conceptually accessible to a broad audience, and it produces optimal, i.e. unbiased and efficient, estimates under the standard assumption outlines below.

The application of econometric methods can be exemplified by a simplistic model that relates greenhouse gas (GHG) emissions to material use (e.g. domestic material consumption, DMC) for the EU-28 aggregate between 2000 and 2014. This example is based on the economic model of a 'production function', i.e. an input, in this example materials; produce an output, in this example GHG emissions. Formally, the model to be estimated can be described as follows.

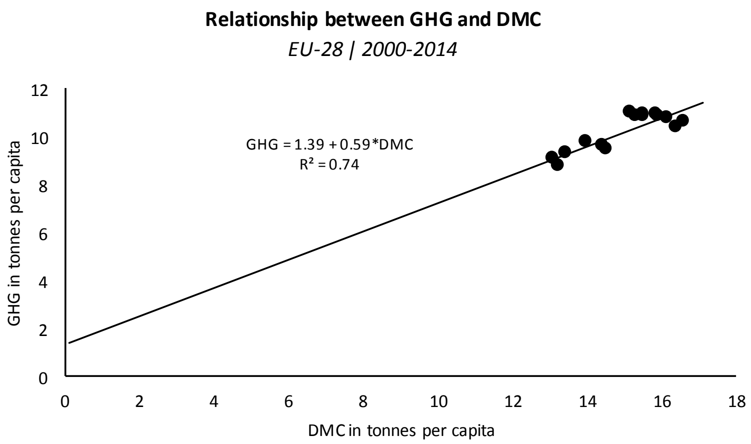
$$GHG_{t,i} = \alpha_{t,i} + \beta_{t,i} DMC_{t,i} + \varepsilon_{t,i}$$

where $GHG_{t,i}$ describes GHG emissions, $\alpha_{t,i}$ is the constant/intercept, $\beta_{t,i}$ the coefficient of the effect of DMC on GHG, $DMC_{t,i}$ represents DMC, and $\varepsilon_{t,i}$ is the error term, i.e. contains all other factors that explain GHG and are not included in the model. The subscripts t stands for the years 2000-2014 and i for the EU-28.

Applying the OLS method to this model is essentially about fitting a line between the data points of the GHG emissions and DMC for the EU-28 between 2000 and 2014, so that the distance between the line and all data points is minimised (the method actually minimises the squares of the distance). The estimated coefficients are the following.

$$GHG_{t,i} = 1.39 + 0.59 * DMC_{t,i}$$

The results indicate that increasing DMC by one tonne per capita, GHG emissions increase by 0.59 tonnes per capita. The graph below illustrates how the application of econometric methods, in this example OLS, can help to quantify the relationship between two variables.



While applying econometric methods appears to be straight forward, estimating optimal, i.e. unbiased and efficient, estimates requires certain assumptions to hold. The assumption in this example would need to comply with the standard assumptions for the simple regression models (e.g. Wooldridge J.M. (2015). Introductory Econometrics: A Modern Approach. 6th edition. Cengage Learning. Boston, USA).

1. The relationship needs to be linear.
2. The sample observations need to be random, i.e. representative for the overall population, and vary, i.e. they cannot take only one value.
3. The error term ($\varepsilon_{t,i}$) has to be 0 on average, thus no additional variable that is not included in the model is allowed to systematically affects the dependent variable (in this example GHG emission).
4. The model has no heteroscedasticity, i.e. the variance of the error term remains constant, and no autocorrelation, i.e. the error term is uncorrelated between observations.

In case any of these assumptions are violated, either other estimation methods than OLS should be applied or the estimations are not optimal anymore. While this simplistic example clearly violates some of these assumptions, it was presented only for illustrative purposes.

Contexts of use, application fields

Econometrics allows considering all types of topics for which sufficient data exists – may it be to test a hypothesis, explain a phenomenon or derive quantitative estimates of the relationship between variables. As such, the range of topics for which econometrics can be used is vast. This can comprise economic, environmental or social topics, or any combination of them. Also, econometric methods can be applied to the macroeconomic, i.e. economy-wide, the microeconomic, i.e. firms or individuals, or the intermediate level, i.e. industry. Moreover, it allows studying individual or groups of countries, industries, firms, etc. at a specific point in time or across time (e.g. over days, months, years). This depends on the availability of data and/or the specific aspect to be investigated. However, one has to keep in mind that the type of data at hand and the model in mind jointly determine the exact econometric method to be applied, for which different assumptions have to be considered.

Type(s) of data or knowledge needed and their possible source(s)

Even though econometric methods allow the user to investigate a broad range of topics, in practice, data requirements often limit such possibilities. This is particularly relevant for minerals, as only limited comparable data across units (individuals, firms, countries) and time is publically available. Before turning to publically accessible databases, the following outlines the different types of data that exist and partly determine the specific econometric method to be applied in order to account for the special features each data type entails.

1. Cross-sectional data consists of a several units (individuals, firms, industries, countries, etc.) at a given point in time, e.g. during a specific day, month or year. While the specific feature of cross-sectional data is that the data is collected for a specific point in time, the type of information that is analysed is not limited. For instance, a cross-sectional data on firms in 2016 could comprise their revenue, the number of employees, export activity, spending on R&D, among others. This type of data allows investigating patterns in data for a specific point in time.
2. Time series data consists of one or a few variables over long periods of time. An aggregated mineral price index of the last ten years would be a good example for time series data. The specific feature of this type of data is that it considers variables across long time periods and thus allows analysing changes and developments over time. One of the challenges of time series data with regards to econometric methods is to take the dependence of observations over time into account, e.g. this year's economic activity is likely to be influenced by last year's economic activity. This requires several assumptions to hold in order to estimate meaningful coefficients.
3. Panel data consists of several units (individuals, firms, industries, countries, etc.) over time, thus combining the features of cross-sectional and time series data. This type of data comprises several variables across long time periods. This allows investigating development both between variables and across time. The units that are being considered in panel data remain the same throughout the dataset. While panel data provides the 'fullest' set of information, one also needs to deal with multiple challenges, including dependencies over time and units, resulting in multiple assumptions that need to be complied with.

Several publically available databases exists, often provided by international and national statistical offices, international organisations (e.g. the World Bank, the International Monetary Fund, the United Nations), universities, research institutes and geological surveys as well as the private sector (e.g. associations, federations).

For international data on minerals and resource more generally, the following databases are particularly relevant.

- Eurostat's economy-wide material flow accounts
- SERI/WU material flow database
- The United States Geological Survey
- The World Bank database
- IMF primary commodity prices

Model used

At all times, econometrics uses mathematical models to test hypotheses, explain a variety of economic, environmental and social phenomena, and derive quantitative estimates of the relationship between variables. As illustrated by the practical example above, such mathematical models are typically derived from economic theory, previous investigations or based on new ideas and intuition.

System and/or parameters considered

Econometric methods can be applied to all sorts of systems and parameters. They can range from individuals, firms, cities, industries, countries to the entire world. Which boundaries and measures are considered depend entirely on the data that is being analysed. Thus, econometric methods allow studying input and output variables, stocks and flows, variables in monetary and mass units, commodities and final products, all of which can be studied at specific points in time or across time. The possibilities are vast, but often limited by the availability of data.

Time / Space / Accuracy

Econometric methods can be applied to all sorts of temporal (seconds, days, months, years) as well as special units (individuals, firms, countries). The accuracy of the estimates depend on the type of data, the quality of the data and the application of the specific econometric method according to the underlying assumptions. This is highly dependent on the data and the particular model in mind.

When it comes to forecasting, econometrics allows making near future predictions about variables. Since such predictions are based on past data, the accuracy of those predictions heavily depend on the quality and length of data, while unexpected events (e.g. unforeseeable economic, environmental and social shocks) are challenging to be accounted for. Thus, econometric forecasts can provide relevant predictions for those types of scenarios for which we have sufficient knowledge and data for.

Indicators / Outputs / Units

Econometric methods allow to use all kinds of indicators, for instance on minerals, for which sufficient data is available. Hence, econometric methods are not limited to a specific kind of data, but rather analyses available data.

The output of an econometric estimation is model coefficients. These estimates represent the isolated effect from one variable on another, i.e. what is the effect of changing one variable on another keeping all other relevant variables constant (the so-called notion of *ceteris paribus*). Additionally, information on the so-called confidence interval, i.e. how precise the coefficient is estimated, is usually provided. In economics, coefficients are typically considered to be statistically significant if they are estimated within the 95% confidence interval, which represents a range of numbers of which the average is the coefficient output. Essentially, this interval states that the estimated coefficient is expected to be within the confidence interval in 95% of the times if the coefficient would be re-estimated in numerous replicated scenarios. It thus provides a measure of certainty to the estimated coefficient.

Units play an important role in interpreting the estimated coefficients, while the application of econometric methods is not restricted by them. In practice, existing data is often transformed by the natural logarithm, which allows the estimated coefficients to be interpreted as elasticities, i.e. the ratio of change. This simplifies the interpretation of results since they become independent of specific units. For example, the estimated coefficients can thus be interpreted as a percentage change in the dependent variable (in the example above GHG emissions) due to a 1% increase in the independent variable (in the example above DMC).

Treatment of uncertainty, verification, validation

Uncertainty is an important issue in applying econometric methods. This concerns the quality of data, the model underlying the estimation, and the estimation method itself. First, the coefficient estimates can only be meaningful if the data, on which the estimates are based on, is of acceptable quality. Systematic biases, a lack of comparability and uncertainty on the reliability of the data jeopardises the quality and relevance of the output of econometric estimations. Second, the model underlying the estimation needs to be reasonable. This is why a lot of estimations are based on developed theories or previous investigations. Third, each estimation method has to comply with certain assumptions for an estimation method to provide meaningful estimates. Such assumption need to be considered carefully in any econometric analysis.

As a statistical tool to measure the certainty of the estimates, information on the so-called confidence interval, i.e. how precise the coefficient is estimated, is usually provided. In economics, coefficients are typically considered to be statistically significant if they are estimated within the 95% confidence interval, which represents a range of numbers of which the average is the coefficient output. Essentially, this interval states that the estimated coefficient is expected to be within the confidence interval in 95% of the times if the coefficient would be re-estimated in numerous replicated scenarios. It thus provide a measure of certainty to the estimated coefficient.

Usually, each estimation's robustness is tested by changing the model's specification (including/excluding model parameters), assumptions and even the econometric method itself to investigate whether the estimated coefficients are sensitive to a specific estimation technique. Moreover, the results' robustness is tested by restricting the sample to certain time periods (e.g. excluding times of crisis) or units (e.g. specific sectors) in order to get a sense of the reliability of the estimates. At all times, the effect of potential outliers on the results needs to be considered.

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Related methods

The closest method to econometrics is statistics. Many concepts used in econometrics are based on statistical methods. Additionally, computable general equilibrium (CGE) techniques are related to econometrics. Generally, since econometrics itself does not generate new data but rather analyses existing data, all data-generating methods (e.g. material flow analysis, life-cycle analysis) can be linked to econometrics.

Operational tools

- Stata (programme & journal)
- R (programme & journal)
- EViews
- SPSS
- MATLAB

Key relevant contacts

Empirical economists, social scientists, mathematicians and statisticians are most likely to provide further expertise on the issue. These experts can be found in governmental departments and statistical offices, international organisations, European institutions, financial institutions, consultancies and non-governmental organisations, universities and research institutes.

In particular, such expertise on econometric methods combined with knowledge on topics related to minerals can found in the following organisations.

- Most interdisciplinary university or research institute conducting empirical research on resources/minerals
- Most multilateral development banks (especially in the offices of the chief economist or research departments)
- The European Commission (e.g. the Joint Research Centre and Eurostat)
- Knowledge-based consultancies and non-governmental organisations.

Computable General Equilibrium Modelling

FACT SHEET

Computable General Equilibrium Modelling

Scope

A Computable General Equilibrium (CGE) model is a quantitative method to assess the economy-wide impact of policy scenarios. It is computable because the model generates numeric solutions to specific policy questions. It is general because the model accounts for all the important markets and flows in the economy. It is an equilibrium model because demand equals the supply in every single market.

A CGE model is a large-scale numerical model that reproduces the economic structure of the whole economy and therefore the economic transactions between the different agents of the economy (e.g. enterprises, households, government and foreign sector). The economy-wide perspective captured by CGE models make them a useful tool to evaluate policies which effects are expected to spread through different channels. Therefore, a CGE model is useful for policy design evaluating counter-factual scenarios compared to a business and usual baseline.

A CGE model consists on behavioral equations that describe the economic behavior of each agent in the model (based on microeconomic foundations), identity equations that impose constraints in the model to ensure market clearing, macro closure rules that determine the macroeconomic equilibrium conditions of the model and a detailed empirical database consistent with the model equations.

Contexts of use, application fields

Sub-national, single country, regional and global CGE models have been applied to study a wide range of economics problems. Among the most common applications are:

- Tax policies
- Trade and development policies
- Poverty and income distribution policies
- Trade liberalization
- Agricultural policies
- Climate change, mitigation and adaptation policies

Type(s) of data or knowledge needed and their possible source(s)

The backbone of a CGE model is the Social Accounting Matrix (SAM). A SAM records the flows of all economic transactions that take place in a particular economy and in a single year. The SAM is based on the input-output tables, national account data and household income and expenditure data.

A CGE model explains the economic transactions of a Social Accounting Matrix. Two types of parameters are required. *Behavioral parameters* related to the cost structure, income and expenditure structure, trade structure, saving and tax rates among other. *Elasticity parameters* that define the shape of structural functions such as production, utility, import demand and export supply among others.

Model used

A CGE model is a large system of simultaneous non-linear equations. A few software packages are used to code and run most CGE models; these are GAMS, GEMPACK and GAMS/MPSGE.

Most CGE models are based on Walrasian general equilibrium theory characterized by utility-maximizing consumers and profit-maximizing firms. The economy is modelled as a perfectly competitive economy with flexible prices and market clearing conditions.

System and/or parameters considered

CGE models are constructed according to the detail observed in the Social Accounting Matrix. While single country CGE models provide more detail on sectoral and income distribution aspects, global CGE model are constrained by the availability of global data and have less detail. Global CGE models consider just one representative household in each region.

Time / Space / Resolution / Accuracy

Static CGE models are used to evaluate future policies; this requires calibrating the model to a hypothetical equilibrium in the future and then applied the policy shocks. Dynamic CGE models are able to trace the path of adjustment to the new equilibrium point. Thus, dynamic models provide a better understanding of the adjustment process in response to a policy shock.

CGE models vary in geographical resolution from sub-national studies to global economic modelling. While some analyses that aim to capture production and expenditure linkages among households require village-town CGE models, global phenomena such a climate change require a global economic modelling.

Indicators / Outputs / Units

Standard output variables in CGE models are:

- Macroeconomic variables (e.g. regional GDP, consumption, savings, investment, imports, exports)
- Industry output and prices
- Demand and price for endowments
- Regional income and welfare
- Sectoral and regional CO_2 emissions

Treatment of uncertainty, verification, validation

CGE modes are deterministic. However, uncertainty related to the true value of the model parameters such as elasticities are explored via a systematic sensitivity analysis such as Monte Carlo analysis or Gaussian Quadrature procedure.

Main publications / references

Handbook of computable general equilibrium modelling, edited by Peter Dixon and Dale Jorgenson (www.sciencedirect.com/science/handbooks/22116885).

Related methods

- Input – Output Models
- Integrated Assessment Models

Operational tools

- GAMS (www.gams.com/)
- GEMPACK (www.copsmodels.com/gempack.htm)
- GAMS/MPSGE (www.gams.com/solvers/mpsge/)

Key relevant contacts

The most widely used single country and global CGE models are:
- IFPRI model (www.ifpri.org/publication/standard-computable-general-equilibrium-cge-model-gams-0)
- GTAP model (www.gtap.agecon.purdue.edu/models/current.asp)

Input Output Analysis

FACT SHEET

Input-Output Analysis

Scope

Input-output analysis refers to an analytical framework of economic analysis based on the model developed by the Russian economist Leontief in the 1930s. In its basic terms, the input-output model the interdependences between different sectors of the economy. Each sector or industry both produces goods (outputs) and consumer goods from other industries (inputs) in order to produce their own outputs. The complexity of the model varies from the consideration of few industries to detailed description of sectors and subsectors of an economy. The mathematical foundation of the model consists of a set of n linear equations that represent the transaction of each sector with the rest of the sectors that can then be combined in a matrix. The data required for the elaboration of an input-output model is observed data from a determined economic area (i.e. country, region, etc.). The economic area is divided into several sectors of activity. The dataset should include the flows of goods from each sector (as producers) to the rest of the sectors (as buyer) in monetary terms for a specific period of time. As sectors both produce good but require goods for the production, the transitional flows show the interconnections between the different sectors of the economy. In addition, there are a number of buyers in an economy that are more exogenous to the industrial sectors producing goods. These actors, such as households, government or foreign trade are generally referred to as final demand, as they are likely to be the final users of the produced goods rather than producers of goods to be used by other industrial sectors.

Considering that there are n sectors in an economy, the output of sector i can be denoted as X_i and the final demand for the goods (outputs) of the sector is represented by f_i, then the distribution of sector i outputs can be represented by the following equation:

$$x_i = z_{i1} + \cdots + z_{ij} + \cdots + z_{in} + f_i = \Sigma z_{ij} + f_i$$

Considering n sectors of the economy, the transactional flows could be represented as following:

$$x_i = z_{i1} + \cdots + z_{ij} + \cdots + z_{in} + f_i$$
$$\cdots$$
$$x_n = z_{n1} + \cdots + z_{nj} + \cdots + z_{nn} + f_n$$

This can be easily transformed into matrix notation, to ease calculations.

In the matrix notation, columns represent the inputs, purchases of products from other sectors and rows are the outputs from each sector, sales of the sector to other sectors. All this information can be summarized using matrix notation as:

$$X = Zi + f$$

In addition to the inputs acquired from other industrial sectors, an industrial sector also pays for other factors of productions to transform the inputs into outputs, such as capital and labour. These are referred to the value added. Moreover, a sector can also purchase imports as inputs for the sector. All these purchases are summed in what is referred to as payments sector.

		Processing Sectors 1	2	Final Demand				Total Output ($\mathbf{x}$)
Processing Sectors	1	z_{11}	z_{12}	c_1	i_1	g_1	e_1	x_1
	2	z_{21}	z_{22}	c_2	i_2	g_2	e_2	x_2
Payments Sectors	Value Added ($\mathbf{v}'$)	l_1	l_2	l_C	l_I	l_G	l_E	L
		n_1	n_2	n_C	n_I	n_G	n_E	N
	Imports	m_1	m_2	m_C	m_I	m_G	m_E	M
Total Outlays ($\mathbf{x}'$)		x_1	x_2	C	I	G	E	X

Source: Miller and Blair, 2009.

In input-output models, it is considered that inter-industrial flows between sectors in a determined period of time depend on the output of the sectors for that period. This is the same as to say that the input-output analysis assumes that total inputs equal total outcomes, in a sort of economic mass balance. It is therefore assumed that the economy operates under constant returns of scale and no economies of scale are considered. It is also assumed that factors and inputs are used in a fixed proportion.

Given these assumptions, technical coefficients can be calculated. The technical coefficients represent the input from a sector needed for the production of the output of another sector. Given zij and xj – for example, input of steel (i) bought by car manufacturers (j) over the last period and total car manufacture for the period, the technical coefficient would be:
Aij = zij xj = value of steel bought by car manufacturers/ value of car manufacturing
One core element of input-output analysis is the calculation of the 'Leontief inverse'. The Leontief inverse enables to understanding of relevant questions such as the amount of inter-industrial flows required to produce a unit of output to final demand, considering direct and indirect requirements. In order to calculate the inverse matrix, we need first to calculate the matrix of direct intermediate requirements (A) or technical coefficients. Each element in A denotes the amount of inter-industrial inputs directly needed to produce a unit of output. To calculate it, we divide each element of the matrix of inter-industrial flows (Z) by the total output (x) of the sector to which it contributes, as we did when calculating the technical coefficients.

Departing from matrix A, the next step is the multiplication of matrix A by the vector of total outputs (x) obtaining the difference between total outputs and final demand. This then represents the total inter-industry flows:

$A * x = x – y$

Through a number of equivalence operations we calculate the Leontief Inverse:

$Y = x – Ax$

$Y = x (I – A)$

$$x = (I - A)^{-1} * y$$

where I is the identity matrix (with 1s along the diagonal and zeroes everywhere else) and $(I - A)^{-1}$ is the Leontief Inverse. By multiplying the Leontief inverse by final demand y, we obtain the total outputs.

Input–output analysis has also been extended to account for other topics such as social aspects and environmental impacts of industrial activity. Leontief himself addressed the issue of how to modify input-output analysis to address the environmental impacts associated to the economic structure (Leontief, 1970):

"*Frequently unnoticed and too often disregarded, undesirable by-products (as well as certain valuable, but unpaid-for natural inputs) are linked directly to the network of physical relationships that govern the day-to-day operations of our economic system. The technical interdependence between the levels of desirable and undesirable outputs can be described in terms of structural coefficients similar to those used to trace structural interdependence between all the regular brances of production and consumption*"

Contexts of use, application fields

Input-output analysis has multiple applications in a number of different areas. As noticed before, the key application of input-output analysis is to the understanding of the interdependences between different sectors that conform an economy. It has been traditionally used in regional and national economic planning as a way to better understand the impact of policies and economic changes in the economic structure. Furthermore, the Leontief Inverse Matrix is useful to identify key sectors in an economy. As Leontief puts it: "The total amount of that particular type of pollution generated by the economic system as a whole, equals the sum total of the amounts produced by all its separate sectors" (Leontief 1970, 264).

The extension of IOA to account for topics such as environmental pollution also provides insights into the impacts of economic structure and industrial flows on environmental problems such as climate change and pollutant emissions. Using Leontief inverse in an environmentally extended IOA, we can address issues such as the impact of meat consumption on pollution, independently of when this happens in the industry, including direct and indirect effects.

Traditionally, IO models have been developed for national economies. However, given the global scale of economic operations, multi-regional IO models have been developed to account for the structure of trade interdependencies. This is of special relevance for the analysis of environmental impacts associated to the economic structure. For example, in 2011 traded goods account for over 22% of the CO_2 emissions (EU: Open, 2010).
World input-output tables are an extension of this and the main difference with input-output national tables is that the use of products is disaggregated by their origin. Therefore, each

product can be produced by a national industry or a foreign industry. This allows knowing for example in which country an import originates and where are the exports being used.

Type(s) of data or knowledge needed and their possible source(s)

National statistics generally include detailed IO tables. In Europe, Eurostat develops IOT up to the year 2011. Also, MSs are requested to provide Five-yearly symmetric input-output tables (with the breakdown between domestic production and imports).

The World IO database (WIOD) is a main source of data for the production of MRIOT. They distinguish 40 countries and a region 'rest of the world'. The dataset is accessible through the WIOD 7FP project at www.wiod.org/new_site/database/wiots.htm

The EXIOBASE dataset provides relevant datasets for environmental extensions.

See the factsheet on Environmental Extended Input Output Analysis for more details.

Model used

Mathematical foundations of the IOM are based on matrix calculations as briefly detailed in the scope section. For more details, see the factsheet on Environmental Extended Input Output Analysis.

System and/or parameters considered

As noted in earlier sections IOA can be used at different levels ranging from regional to national and multiregional models.
The models vary in complexity such as the number of sectors of activity considered and can be extended to account for social metrics and environmental impacts.

Time / Space / Accuracy

IOT are routinely elaborated by national statistic services in most European countries every year. Eurostat also elaborates yearly tables and has established a compulsory transmission of tables by the European Member States. The level of resolution is macro and can be complemented by more detailed analysis at the regional or local level.

Indicators / Outputs / Units

Multiple indicators can be calculated using IO tables such as:

- Do a policy Impact Analysis
- Calculate Output Multiplier
- Calculate Income Multiplier
- Calculate Employment Multiplier
- Calculate Input (or Supply) Multiplier

Treatment of uncertainty, verification, validation

Uncertainty is an important issue in IOA. Leontief himself recognised that '[f]irst of all, there is the immediate problem of the numerical accuracy of the individual entries' in IOA but he also emphasised that "numerical accuracy unfortunately cannot be answered as simply and directly as it can be posed. In order to know how inaccurate are the figures presented in published tables, one would have to possess the true measures of the magnitudes in question; but if these were available, they certainly should have been used in the first place' (Leontief, 1955).

Uncertainty in IOA is certainly caused by a number of different elements including errors generated during data sampling and compilation, aggregation into sectors, monetary exchange rates, concordance between different industries and the consideration and aggregation of the region 'rest of the world'. There may also be problems of uncertainty associated with the estimation of trade flows and intermediary flows.

Main publications / references

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Related methods

Input Output Analysis has been expanded for environmental analysis to Environmental Extended Input Output Analysis. A separate factsheet can be found in the Industrial Ecology Methods section.

Related methods further include:

- Material flow analysis
- LCA
- CGE models

Operational tools

There are a number of free software to perform input output analysis (such as IRIOS, PyIO, IO REAL) but in most cases, general software such as STATA or excel can be used for the calculations.

Key relevant contacts

FACT SHEET

Cost Benefit Analysis

Scope

Cost-benefit analysis (CBA) is a systematic approach to decision-making to assess whether a particular policy, investment, business or financial opportunity promotes efficiency, understood in economic terms. At the most general and comprehensive level, CBA is an aggregator of all impacts, to all affected parties, at all points in time. The impacts, both positive and negative, are converted into a common monetary unit, and then adjusted for their time-value to obtain correct estimates and the cost-benefit criterion is simply a test of whether the benefits exceed the costs. If the net benefits are positive, it is assumed that the policy or investment has a net positive contribution to economic efficiency (Kotchen 2010). Benefits to costs ratio and other indicators are used to conduct such analyses. Different approaches follow different approaches to assess welfare gain. Some more restrictive approaches follow the Pareto principle of welfare gain by which the policy or project should be undertaken if some win and nobody loses. This is understood as a positive net benefit and implies that compensation is paid to the losers. However, this is rarely feasible to do in the practice. Instead, Hicks-Kaldor criterion is generally preferred, which indicates that a project should be implemented if the winners could in principle compensate the losers even if this does not happen in reality (Layard and Gleiser, 2012).

Broadly, CBA is used for two fundamental purposes : (i) to determine all costs and benefits involved in a particular opportunity or proposal, so as to provide a decision or justification for the project; Iii) to determine the strengths and weaknesses of a particular opportunity and its alternatives to better understand the costs and benefits of each option against the other. There are two main types of CBA: 1) ex-ante CBA and 2) ex-post CBA. The first one allows assessing whether a project represents an efficient use of resources, while the latter assesses whether the investment, project or policy managed to achieve the expected outcomes. The broad goal of CBA is to assist in decision-making, not necessarily in terms of producing the ideal project but simply by proposing the optimum solution out of a spectrum of possibilities.

CBA exercises involve generally two stages: 1) value of all the costs and benefits of a project or investment along its life cycle in monetary terms and 2) obtain a net present value of the project by aggregating all benefits and costs and discounting them to present time. In the policy area, CBA should include all benefits and costs incurred by different actors and the society as a whole at different stages of the project life cycle. It is also important to note that the discount rate is of crucial importance and its determination should be part of an open policy process. In most cases, the social discount rate may differ from the private discount rate (Layard & Glaister, 2012).

There are several similar decision-making frameworks i.e. cost-effectiveness, cost-utility analysis, risk assessment that are often compared with cost-benefit analysis. The key difference between these frameworks and CBA lies in the monetization of the costs and benefits and their discount to present value. These values are adjusted for the time value of money, so that all flows of benefits and flows of project costs over time are expressed on a common basis of the Net Present Value. While the CBA is often criticised for its reliance on aggregate, monetised benefits, that exclude more nuanced arguments about equality and fairness (Heinzerling and Ackerman 2002); it is also often lauded for its rational and systematic use of monetary value that produces evidence-based results. It is said to provide a more transparent and objective process, especially in the public policy domain (Sartori et al 2014).

Contexts of use, application fields

Although often referenced as a tool for business decision making, the theoretical origins of CBA date back to welfare economics. Its implementation has been traced back to the formal requirement for costs and benefits to be compared in water-related investments in the USA in the 1930's, so that public finds were utilized efficiently (Pearce et al. 2006). It is still recognized as a major appraisal technique in public investments and public policy and used across various policy domains. These include health, education, housing, transport, natural resources (i.e. energy and water efficiency) and the environment, and recreation.

Undertaking a CBA in the policy domain requires a consideration of net impacts of a project on society. This entails going beyond typical revenue and costs generated by the project to take into account benefits and costs that might not be captured by market prices i.e. externalities borne by third parties that are not involved in the consumption or production of the project (Wai Yang and Yong Long 2015).

In the EU for instance, CBA is constantly promoted for major infrastructure projects. CBA is used to appraise an investment decision in order to assess the welfare change attributable to it and, in so doing, the contribution to EU cohesion policy objectives. The EU cohesion policy aims to deliver growth and jobs together with the targets and objectives contained within the Europe 2020 strategy. Choosing the best quality projects which offer best value for money and which impact significantly on jobs and growth is a key ingredient of the overall strategy. In this framework, CBA is explicitly required, among other elements, as a basis for decision making on the co-financing of major projects included in operational programmes (OPs) of the European Regional Development Fund (ERDF) and the Cohesion Fund (Sartori et al. 2014).

Type(s) of related input data or knowledge needed and their possible source(s)

Every CBA will be different, using appropriate methodologies and required assumptions, as per the project, policy or proposal in question. There are nevertheless some fundamental data and information needs that are common to most applications of CBA (HM Treasury 2014; Sartori et al. 2014).

1. Details about the body responsible for the implementation and its capacity.
2. Description of investment and its location
3. Timetable for planned investment and financing plan
4. Identifying costs: includes data on capital costs, revenue costs and in-kind costs;
5. Feasibility studies, including options analysis
6. Monetising benefits: includes data and information on fiscal benefits (money savings); and public value benefits (economic and social benefits)

Discounting the future: identifying a discount rate is a key feature of CBA that can significantly affect results. When costs and benefits occur at different points in time, discounting makes adjustments to facilitate intertemporal comparisons. Discounting, in effect, is the opposite of compounding interest on an investment, and it converts all future costs and benefits into their present value. The cost-benefit criterion is then a question of whether the present value net benefits are positive.

Certain assumptions and decisions need to be made to determine some of the input data. It is important to ensure that the assumptions and methodological approach are consistent for the various projects being compared.

Model used

The mathematical foundations of CBA are relatively simply. In order to assess whether a project/ investment or policy is implemented requires: 1) the identification of all costs and benefits over the life cycle of the investment; 2) the calculation of the present value of all those benefits and costs and 3) the comparison of all aggregated present value of costs and

aggregated present value of benefits. To convert all cash flows to the present, one needs to define a discount rate. The discount rate represents the willingness of the society or companies to give up consumption/welfare in the present for consumption or welfare in the future. The higher the discount rate the lower would be the value put on the future. This has clearly implications for aspects such as ecosystem services and other natural resources with substantially longer cycles than humans.
The calculation of the net present value follows the following formula:

$NPV = \sum X_t/(1 + r)t$

where Xt represents the cash flow in year t, for a specific time period T generally considered in years, and r is the discount rate, where If NPV ≥0, the project or policy is recommended ; If NPV <0 the project should be rejected.

The simplicity of the calculation does not rest complexity to the elaboration of CBA. Issues such as the selection of the discount rate, estimation of future benefits and costs require several assumptions and depending of the type of the project are subjected to different levels of uncertainty. In the assessment of environmental and welfare policies increased complexity is linked to the calculation and use of shadow prices to account for intangible benefits or costs where there is no applicable market from which to derive a price.

System and/or parameters considered

In any CBA several stages must be conducted; specific stages can differ based on the type of project or proposal under review but in general, the following systems and parameters should be included in all analysis (Hanley and Splash 1993; HM Treasury 2014).

1. Definition of project: This is an essential first step so that clarity about what is being appraised exists. This stage also includes determining the boundaries of the analysis. Two key system and boundary conditions need to be determined
   - Details of the reallocation of resources being proposed. For instance, will the enquiry into the construction of a new nuclear power station in the UK will include appraisal of UK energy policy, EU energy policy or restrict to local impacts only.
   - The population over which costs and benefits are to be aggregated, so that winners and losers can be considered. For instance, implications for communities in the immediate vicinity of a new power station or affected persons at regional, national and international levels.
2. Identification of project impacts: identification of all impacts resulting from the implementation. This includes listing of all the resources needed, effects on local employment/unemployment, impacts on traffic, effects on property prices, impacts on quality of landscape, impacts on educational facilities among others. Concepts such as additionality (new impacts of a policy or project) and displacement (changes and to what extent of existing policies, projects and communities) are also important to be considered.

3. Identification of economically relevant impacts: selection of projects that add to the social utility by increasing value of consumables by more than any associated depletion in the levels of other utility-generating goods.
4. Quantification of relevant impacts: determining physical amounts of cost and benefit flows and identifying when in time they will occur. Here varying levels of uncertainty will be incorporated.
5. Monetary valuation of relevant effects: valuation in common units which are essentially monetary units. Prices carry valuable information and a CBA will have to predict prices for value flows in the future, correct market prices where necessary, and calculate prices where they don't exist.
6. Calculate present values Calculating present value (PV) and discounting values that occur in future years. Present value costs and benefits were then summed across years to obtain the total present value costs and benefits.
7. Calculate the net present value (NPV). The net present value (NPV) of each option.
8. Calculate the benefit cost ratio (BCR) and internal rate of return (IRR). The results of a CBA can also be represented by two other indicators of a project's worth (in addition to NPV). These are the benefit cost ratio (BCR) and the internal rate of return (IRR). The IRR is the discount rate at which a project's NPV becomes zero. If the IRR exceeds the discount rate, the project generates returns in excess of other investments in the economy, and can be considered worthwhile.
9. Conduct sensitivity analysis. Information on the monetary values of costs and benefits of alternative options will often not be known with absolute certainty. Uncertainty over the values or assumptions included in the analysis leads to the results also being uncertain. One such area is the discount factor applied.
10. Select option. Based on the information generated on the NPV of each option, the sensitivity of the results, the distribution of impacts, and additional non-monetary information, a decision maker can select the most preferred option.

Time / Space / Accuracy

The definition of the time/space and boundaries of the project are flexible in CBA and need to be defined in accordance to the scope and purpose of the study. The longer the timeline though the higher uncertainty that will be introduced in the system. Also the discount of future costs and benefits would introduce biases towards short term cost and benefits.

Indicators / Outputs / Units

The main key indicator derived from CBA is the benefit cost ration (BCR). This ratio relates the befits of the project against the costs and calculated by aggregating the total discounted benefits of a project/ policy over its entire life cycle and dividing it by the total discounted costs of the project.

Benefit Cost Ration (BCR):

BCR= $\Sigma[B/(1+r)^t]/\Sigma[C/(1+r)^t]$

If the BCR>1 it means that the benefits outweighs the costs of the project, and therefore should be implemented, while BCR<1 means that the project's costs outweighs its benefits.

Incremental Benefit Cost Ratio: This method helps to determine the margin by which a project is more beneficial or costly than any other project. It is used to compare alternative options to help determine which is more feasible over the other(s).

Return on Investment (ROI) is another indicator that compares the net benefits (total discounted benefits minus total discounted costs) to the costs. This indicator provides an idea of the how much of an investment can be expected to be received as a benefit. The ROI is calculated as follows:

ROI: $\Sigma\{[B/(1+r)^t]-\Sigma[C/(1+r)^t]\}/\Sigma[C/(1+r)^t]$

If the ROI>1 the benefits exceed the costs and the investment/policy should be implemented.

The Payback Period: This is the time period required for the total discounted costs of a project to be surpassed by the total discounted benefits. This can be done by calculating the cumulative discounted benefits and cumulative discounted costs of a project for each consecutive year of a project. The year that the cumulative benefits exceed the cumulative costs is the payback period year of the project. In other words, the year following the project payback period will see net profits or benefits to the project (WHO 2016).

Treatment of uncertainty, verification, validation

Estimates of future CBAs are always subject to varying degrees of uncertainty. The overall source of uncertainty is due to cost-estimating methods used and also inherent uncertainties in a system. Although uncertainties cannot be entirely eliminated, it is useful to identify their associated risk issues and attempt to quantify the degree of uncertainty as much as possible. There are a number of variables that form an important part of a CBA analysis but which represent either a decision or a judgement. These can often lead to varying uncertainties in the output. For instance, decisions on discount rates can significantly alter the end result of a CBA analysis. Some of this uncertainty can be understood through sensitivity analyses, formal qualitative risk analysis, or probabilistic risk analysis. The objective of estimating uncertainty is to ensure that the CBA is appropriately understood, to clearly inform the alternative comparison process and the use of such estimates when planning future budgets.

Some of the key methods used to understand key risks and plan for them are (Sartori et al 2014):

- Sensitivity analysis: The calculated benefits and costs of a project may vary depending on different assumptions about the input data and methodology applied in the CBA. The range of potential outcomes for differing inputs can be gauged using a sensitivity analysis. Sensitivity analysis enables the identification of the 'critical' variables of the project. Such variables are those whose variations, be they positive or negative, have the largest impact on the project's financial and/or economic performance. The analysis is carried out by varying one variable at a time and determining the effect of that change on the NPV.
- Qualitative risk analysis: The qualitative risk analysis aims shall include identification of a list of adverse events to which the project is exposed; a risk matrix for each adverse event, an assessment of acceptable levels of risk and finally, a description of mitigation measures for the risks.
- Probabilistic risk analysis: This type of analysis assigns a probability distribution to each of the critical variables of the sensitivity analysis, defined in a precise range of values around the best estimate, used as the base case, in order to recalculate the expected values of financial and economic performance indicators.

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Related methods

Related methods include:

- LCC
- WLC

Operational tools

There are a number of free software to perform CBA and methodological guidelines but in most cases, general software such as STATA or excel can be used for the calculations

Key relevant contacts

Life Cycle Costing

MICA Mineral Intelligence Capacity Analysis

FACT SHEET

Life Cycle Costing (LCC)

Scope

Life Cycle Costing (LCC) is a tool for assessing and comparing the costs of an asset along its whole life cycle. The tool allows decision-makers to have a comprehensive picture of the costs associated with the acquisition, operation and disposal of specific assets. While the initial cost of an asset is generally well known and clearly defined, operational and end of life costs are not always well represented when evaluating alternative options.

A major driver for the introduction of LCC is the possibility to provide a more accurate picture of the costs associated with an asset from a longer-term perspective, and move away from decision-making based purely on initial outlay costs. This for example would encourage considering assets with overall lower costs, even when they require a higher initial investment.

Buildings and the built environment in general have been an area where LCC has been applied more consistently. A standardised methodology has been developed for building and constructed assets under BS ISO 15686-5 (2008) standard. This Standard defines LCC as a 'a technique which enables comparative cost assessments to be made over a specified period of time, taking into account all relevant economic factors, both in terms of initial costs and future operational costs'. The standard covers the following areas:

- Principles of LCC
- Definitions, terminology and data sources
- LCC calculations and methods of economic assessment
- Defining the scope of LCC studies
- Risks and uncertainties
- Integration of LCC in the Whole life costing assessment process
- Links to wider environmental and social assessments

Although in some contexts LCC is used interchangeably with Whole Life Costing (WLC), the concepts although related are different. The definition of Whole Life Costing in the BS ISO 15686-5 is the following: "LCC is a methodology for the systematic economic consideration of all the whole life costs and benefits over the period of analysis, as defined in the agreed scope". LCC in its origins has been a traditional accounting method to rank investment alternatives by taking into account different costs originated at different stages of the life cycle of an asset. Despite applications in the environmental area, LCC does not generally account for environmental costs, and, therefore, the WLC may be a more appropriate concept when considering an environmental perspective (Gluch and Baumann, 2004). A number of other concepts that attempt at providing alternative accounting techniques at the corporate level to incorporate the environmental dimension into the companies' decision making have been developed since the 1990s. In Table 4 some of these environmental accounting methods can be seen. Close to the concept of WLC is that of Life Cycle Costing Assessment (LCCA). LCCA is a hybrid method between LCCA where the environmental consequences are taken into account and assigned a monetary value.

Table 4 Summary of environmental accounting methods related to LCC.

CONCEPT	DEFINITION	SCOPE
Full cost accounting (FCA)	Calculates the possible environmental, social and economic costs and benefits of a proposed plan through incorporating direct and indirect costs. It refers to the triple bottom line.	Accounts for hidden costs and externalities; overhead and indirect costs, past and future outlays and incorporates costs throughout the life-cycle of the product.
Total Cost Accounting (TCA)	It refers to a long-term, comprehensive financial analysis of the full account of internal costs and savings.	Accounts for internal costs as well as savings associated with an investment
Life Cycle Costing (LCC)	LCC is a systematic approach that enables to compare alternative investments by taking into account all relevant economic costs and revenues of a investment over its whole life cycle, including initial purchase, maintenance and other operational costs.	Accounts for initial costs, maintenance and operation costs. Does not generally consider environmental costs.
Whole life costing (WLC)	Used sometimes interchangeably with TCA or LCC. It generally refers to a systematic framework for the analysis of all relevant costs and revenues associated with an asset, including its acquisition, operational and environmental costs.	Similar to LCC but it generally also includes environmental costs or an estimation of those.

Source: author's elaborated based on Gluch and Baumann, 2004.

In summary, most of these concepts share similarities and differ mainly in the scope and ways in which environmental costs are considered.

Contexts of use, application fields

LCC can be regarded as a counterpart to LCA: cost information related to a product or service over its life cycle. Although not an environmental accounting method in its origin, LCC has been extended and adapted to account for environmental costs and has been used in the context of corporal environmental accounting. The facts that the method factors all costs in monetary terms have encouraged its adoption by corporate organisations. Buildings and the built environment in general are an area where LCC has been applied more extensively given the relatively long use life of buildings and the difference between initial and operational costs. In this case, the method has been standardised under BSI ISO 15686, providing clear guidance on how LCC needs to be performed. BSI has also developed in the UK a number of supplements that provide practical guidance and instructions in the implementation of LCC in construction procurement.

LCC is also one of the methods referred to under the EU procurement rules (2014) for GPP. LCC is recommended as a way to incorporate all relevant costs associated with a purchase during the whole life cycle of the product/ service. Article 68(2) of Directive 2014/24/EU and Article 83(2) of Directive 2014/25/EU provide further details as how to use LCC in the context of GPP.

Existing pieces of regulation at the EU level have also tried to encourage the use of LCC in the investment decision-making. For example, the Clean Vehicle Directive 2009/33/EC also requires contracting authorities and entities to take into account consumption and emissions when purchasing road transport vehicles and in its annex provides some guidance on how this costs can be calculated within the LCC.

LCC provides a systematic way to respond to the following questions ?

- What investment alternatives may be more relevant if the whole life cycle is considered?
- How do I measure environmental effects and impacts in a monetary way?
- How do I make sure that environmental costs are considered in the corporate/ public decision making process?

Type(s) of data or knowledge needed and their possible source(s)

In order to carry out an LCC analysis we will need to gather information from a diversity of sources to account for all costs of a system over its whole life span. Data requires may include the following:

- Economic data associated with an asset during its entire life cycle, include (i) initial costs linked to purchasing costs and acquisition, design and development costs; (ii) operating and maintenance costs of the asset (i.e. cost of repairs, spares, downtime, maintenance costs); and (iii) disposal costs
- Financial data which may need to refer to interest rates, depreciations, discount rates
- Environmental data expressed in monetary terms. While some of the environmental costs are easier to estimate based for example on taxes or costs of licenses and permits, others may require of specific valuation techniques for environmental goods/ services (i.e. impact on an ecosystem)

Sources to cover data needs will need to consider all actors linked to different phases of the life cycle of the asset, including suppliers, manufacturers, users and disposal/ treatment facilities. Some relevant data sources may be the following:

- Data from producers association
- Statistical data and datasets from national statistics office
- Data from modelling exercises i.e. modelling of energy consumption
- Data from manufacturers, suppliers, users, maintenance services, etc.

Model used

A number of LCC models are currently available and used. These include both generic and specific models. Authors generally classify models into different categories, which vary. Dhillon (2013) presents three categories; (i) Heuristic models (ii) Conceptual models (iii) Analytical models

Analytical models are typically the most applicable and are generally based on mathematical relationships. They can include, total cost models, design trade models logistic support models, steady state models, comparative state equilibrium models, quasi-dynamic models, dynamic models among others. Heuristic models are less structured; and conceptual models hypothesise variables given in qualitative fashion and tend to be flexible.

A key step in analytical models is the analysis of cost data. The following methods are typically used and their use is dependent on the availability of data (NSW Treasury 2004).

(i) Engineering cost method: is used where there is detailed and accurate capital and operational cost data for the study. It involves direct estimation of a particular cost element by examining the asset component-by-component. It uses standard established cost factors (eg. firm engineering and/or manufacturing estimates) to develop the cost of each element and its relationship to other elements (known as Cost Element Relationships - CER).

(ii) Analogous cost method: provides the same level of detail as the Engineering Cost Method but draws on historical data from components of other assets having analogous size, technology, use patterns and operational characteristics.

(iii) Parametric cost method: is employed where actual or historical detailed asset component data is limited to known parameters. This available data from existing cost analyses is used to develop a mathematical regression or progression formula that can be solved for the cost estimate required. Parametric models are the easiest to use but are known to be less accurate.

There is no single accepted standardised LCC method. This is largely because in most cases, it is appropriate to develop a model for a specific application. This can depend on the intended use environment, existence of differing cost data collection systems, different types of equipment, maintenance concept, maintenance and support scenarios. The variability of these factors often raises concerns about the potential feasibility of having a standardised life cycle cost model.

System and/or parameters considered

Any LCC analysis should begin with development of a plan, which addresses the purpose, and scope of the analysis. The nature and scope of the LCC is a direct result of the definition of the project/program at the time the estimate is prepared. It is especially important to clearly define the LCC boundaries, not just with respect to the specific estimate being developed, but also its association to other affected projects or programs. This includes clearly identifying critical and specific inclusions, exclusions, and assumptions. A systematic scoping will include:

1. Define, document and understand the main purpose of the analysis
2. Identify the initial scope of the analysis
3. Identify the period of analysis
4. Any specific inclusions and exclusions
5. How the analysis relates to the overall business case or strategic option appraisal

Once the system boundaries and scope are identified, key parameters to be included in the analysis can be identified. This will vary on the type of analysis being conducted. For instance, analysis in the public sector domain may be constrained by institutional requirements regarding standard options to be considered, method of economic evaluation or discount rates applied. Analysis in the business domain on the other hand, may have different constraints including internal requirements on investment returns or market needs. In general, all LCC analysis should include for the following key parameters:

- Costs: All relevant costs from purchase to disposal should be considered. The decision to include or exclude certain costs (such as incomes from rent or sale of renewable energy) are taken depending on the client or project at hand.
- Period of analysis: the time-scale selected for the analysis should be selected. It can be a long-term cradle to grave approach or short-term period linked with shorter-term investment returns.
- Project and asset requirements: This may include general parameters such as physical characteristics, performance requirements, design/device life etc.
- Methods of economic evaluation to be used: identifying appropriate interest rates and discount rates, which can have significant impacts on the outcome of the analysis.
- Extent of environmental and sustainability impact: could be a high-level assessment or specific impacts such as costs associated with specific environmental provisions like renewable energy targets or achieving performance ratings.
- Risk and sensitivity analysis: due to the high level of uncertainty present in an assessment of life cycle costs, it is important to include for varying options based on risk, and perform sensitivity analysis to assess the impacts of changing key variables such as discount rates, inflation among others.

Indicators / Outputs / Units

The key output is to identify the full consequences, whether environmental or economic arising out of production of a product or service across its whole life-cycle. It allows for alternatives to be compared on the same basis. It can be used in the research, development and design stages, during the beginning of the project and anytime until completion. The outputs of LCC will assist in assessing the cost performance of initial work, aimed at facilitating choices where there are alternative means of achieving the objectives and where those alternatives differ, not only in their initial costs but also in their subsequent operational costs. For example, environmental considerations are often viewed as obstacles to business development, particularly in the short term. LCC allows for comparisons between environmental policies and measures as applied in different business situations. Outcomes of such analyses might be revealing, and allow for more resource-efficient choices. The strategic argument for LCC, from an environmental point of view is that having such a method, technological development can be guided in a more rational direction, optimising the trade-off between environment and economy (Hunkeler et al., 2003).

Treatment of uncertainty, verification, validation

Estimates of future LCCs are always subject to varying degrees of uncertainty. The overall source of uncertainty is due to cost-estimating methods used and also inherent uncertainties in a system. Although uncertainties cannot be entirely eliminated, it is useful to identify their associated risk issues and attempt to quantify the degree of uncertainty as much as possible. There are a number of variables that form an important part of a LCC analysis but which represent either a decision or a judgement. These can often lead to varying uncertainties in the output. For instance, decisions on discount rates, can significantly alter the end result of a LCC analysis. Some of this uncertainty can be understood through sensitivity analyses or a formal quantitative risk analysis. The objective of quantifying estimate uncertainty is to ensure that the full range of potential LCCs is appropriately understood, to clearly inform the alternative comparison process and the use of such estimates when planning future budgets.

A sensitivity analysis will examine the impact of variations to assumptions and cost element uncertainties on LCC model results. Particular attention should be focused on cost drivers, assumptions related to asset usage and different discount rates. In practical terms, it shows how estimated cost would change if one or more assumptions change. In good sensitivity analyses, the cost drivers are not changed by arbitrary plus/minus percentages but rather by a careful assessment of the underlying risks. Sensitivity analysis is useful for identifying critical estimating assumptions, but it has limited utility in providing a comprehensive sense of overall uncertainty.

In contrast, quantitative risk analysis can provide an overall assessment of variability in the cost estimate. In quantitative risk analysis, selected factors (technical, programmatic, and cost) are described by probability distributions. When estimates are based on cost models derived from historical data, the effects of cost estimation error may be incorporated into the range of considerations included in the cost risk assessment. Risk analyses assess the aggregate variability in the overall estimate that stems from the variability in each input probability distribution— typically through Monte Carlo simulations. It is then possible to derive an estimated empirical probability distribution for the overall LCCE. This allows the analyst to describe the nature and degree of variability in the estimate (USDE 2014).
For any system, sensitivity and risk analyses also have uses beyond addressing the uncertainty in cost estimates. These analyses can help managers understand what can go wrong with a program and thus focus appropriate attention on risk areas.

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Related methods

When used as a counterpart to Life Cycle Assessment, many methodological choices can be derived from the LCA methodological framework, especially related to system boundaries, but also to methodological choices such as allocation.

Operational tools

Not applicable

Key relevant contacts

Criticality Assessment

FACT SHEET

Resource Criticality Assessment

Scope

The basic concept of resource criticality assessment, as it has been applied on resource management till now, has some roots in the traditionally used basic risk assessment. In the risk assessment, which could be applied on any subject e.g. manufacturing or production facilities, the probability or risk of an incident to happen causing releases of dangerous substances and exposure to environment is being considered. In traditional risk assessment studies, the analysis relies on two main issues being evaluated. The first is the probability of an incident and the second is the consequences such an incident could have. In the resource criticality assessment studies, a similar approach could be observed. Here, the first parameter is the assessment of risk/probability of a disruption in resource supply. The second one is the importance of such a disruption in the supply of a resource or the vulnerability of affected systems, economies or technologies to such a disruption (Habib and Wenzel 2015).

In the context of raw materials, the first resource criticality assessment was conducted in 1939 by American administration for raw materials with military relevance (NRC 2008) . Based on that study, the US army decided to build of up a stock for 42 raw materials, which were considered critical for military applications. This was enforced through the law "Critical Material Stockpiling Act". The aim of this process was to ensure US independent access to raw materials of military use in emergency case. After the Cold war, although the geopolitical situation has been relaxed, the stockpiling of military relevant resources has continued until today. Although, the origin of resource criticality assessments is the national policy and military sectors, the focus today is much wider, covering issues of supply chain security both by the public and private sectors. So, one may find criticality assessments in the scope of corporates or manufacturing companies. The geographical focus of these studies has also widened to include global, regional level, specific technologies or whole industry branches. In the recent years, in addition to supply restriction and importance of raw materials, other factors have been considered within assessment methodologies. A number of studies have tried to evaluate the criticality through a combination of ecological, political, social, ethical and technical perspectives. This goes through the development of a complex matrix containing the relevant metrics. Today, resource criticality assessment covers an integral and complex scope, which could be applied on any encountered heterogeneous research field (Achzet and Helbig 2013a). The picture below illustrates an example of an integrated approach developed to address key factors in resource criticality assessments and a selection of possible scopes, which could be country, company or a technological sector.

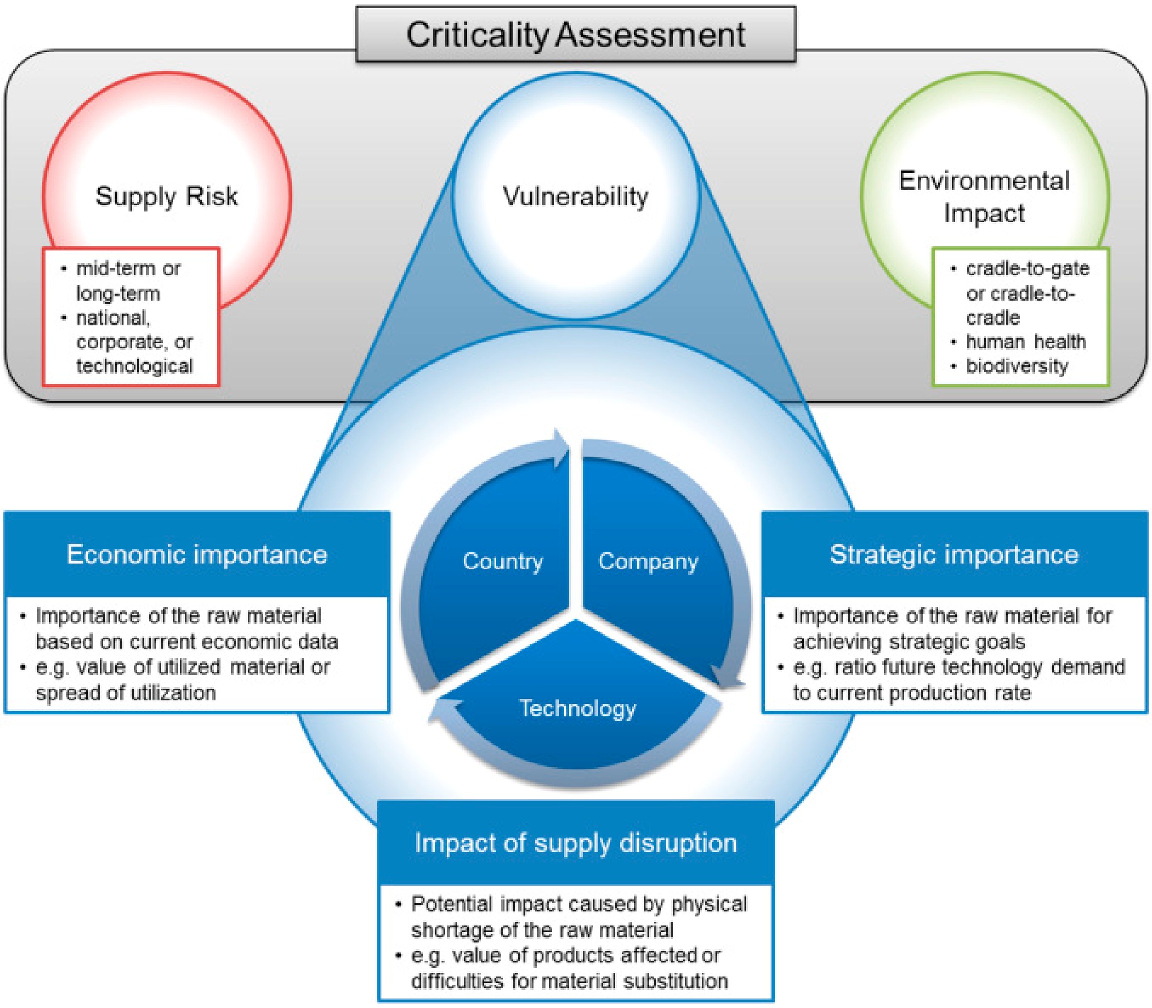


Figure 17 Characteristics of a resource criticality assessment. Source: (Helbig et al. 2016).

Contexts of use, application fields

Concerns over resource availability are not new. The reliance of modern societies primarily on non-renewable resources has raised the question of scarcity. Ever since the industrial revolution, many researchers and scientists considered whether or not the limited availability of resources would put constraints on future growth (Neumayer 2002).
After World War II, and the growth of military industries, for the first time the term 'critical materials' was used in the context of raw materials with a military application (Achzet and Helbig, 2013) in the context of the aforementioned, the Strategic and Critical Material Stock Piling Act. However, stockpiling critical materials by the United States has continued until today. In a 2005 revision, the Act extended the definition of strategic and critical materials to include industrial applications in addition to materials with military applications (U.S. National Research Council, 2008). The European Union (EU) has also launched a working group in the EU Raw Material Initiative to identify and analyse critical raw materials at the EU level (EU Commission, 2010). Similarly, other countries such as Germany and Japan have initiated specific studies to address concerns regarding the scarcity of critical materials (Defra, 2012).

An alternative point of reference for examining material criticality is the issue of 'accessibility' rather than 'availability' (Rosenau-Tornow et al. 2009). Social, economic and environmental constraints all could potentially affect the accessibility of resources (Lloyd et al. 2012). For example, the Democratic Republic of Congo is a key region supplying cobalt and the conflict there in the 1970s led to the 'cobalt crises' (Alonso et al. 2007). Another example is the increasing interest that has been shown in rare earth elements as China currently dominates the supply of these elements even though many studies demonstrate that, geologically, they are not particularly rare (National Research Center, 2008).
In recent years several studies have considered the issue of critical materials required for the energy sector, focusing in particular on the materials required for low-carbon energy technologies (Moss et al. 2011a; Zepf V et al. 2014). It is anticipated that the deployment of low-carbon technologies will increase in response to climate change policies. The main target in these studies is to investigate whether there may be any problems of scarcity/ accessibility of materials to deploy low-carbon technologies at the scale required, and, further, how the supply of these materials may be affected by the consequent increase in demand.

Type(s) of data or knowledge needed and their possible source(s)

There are a number of different databases and data needs required for undertaking of a criticality assessment. As there is not a unified methodology, studies may use a range of different metrics to assess criticality. International institutions such as the World Bank or United Nations Environment Programme (UNEP) have also developed in recent years metrics. Researchers may also develop their own metrics to measure the criticality depending on the study focus. An example of such metrics is the measure of the proportion of reserves to production. Table 5 summarises key metrics and databases used in resource criticality assessment studies.

Table 5 Databases and metrics.

No.	Factor	Unit / Metric	Main Data Base
1	Supply Concentration	[%] HHI (Herfindahl–Hirschman Index)	USGS, Raw Materials Group
2	Geopolitical Risk	WGI,FSI Qualitative	World bank , Fund for the peace , Expert assessment
3	Recycling/Recycling Potential	Ratio, [tons]	USGS , UNEP
4	Substitutability	Qualitative	Expert assessment, European Commission (2010b)
5	Environmental Issue	EPI, LCA studies.	The Yale Centre for Environmental Law & Policy, Any LCA database e.g Ecoinvent
6	Reserve: Production Ratio	Ratio , Year, Depletion time ,	USGS, Graedel (2012)
7	Demand Growth	Ratio, Qualitative, Third parties scenarios	Expert citation, available projections
8	Economic Importance	GDP, GVA, Qualitative assessment	World Bank, Mining Journals
9	By-Product Dependency	[%]	Raw materials group

The metrics and parameters will be reviews in the following sections.

Model used

There are three key studies which have developed a robust model for assessing material criticality (NRC 2008; EC 2010; Graedel et al. 2012): 1) the study by the National Research Council (2008) in the US; 2) A study by the European Commission (2010) and 3) an academic-led study by Graedel et al. (2012) at Yale University. In addition to developing a framework, the NRC (2008) and EC (2010) applied their framework to the U.S. economy and European Union 'megasector'[5] respectively..

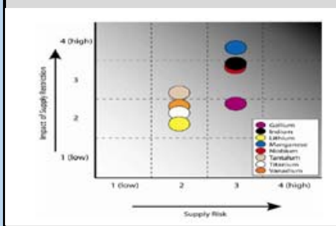
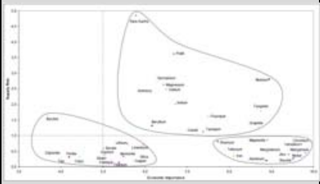
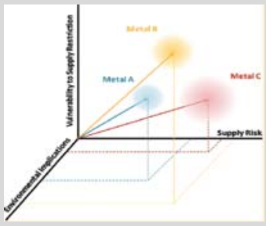
The overarching concept for all existing frameworks is a type of 'criticality matrix', which may have two or more dimensions. The frameworks rank each material depending on the score obtained in each dimension. The dimensions are defined by a selection of metrics in

[5] According to the definition of 'megasector' by European commission, it refers to 17 sectors which cover almost 90% of total value added for EU's manufacturing sector (EC 2010)

accordance to the scope and timeframe of the study. The scores for each dimension are then aggregated into a single final score for the material that is plotted on the matrix. A threshold encompassing a two dimension area (or volume) on this matrix is finally defined to assess whether or not a material is to be considered critical.

The detail of these three studies is summarised in Table 6 with the metrics each used to assess the 'supply risk' and the 'impact' dimensions. The 'supply risk' dimension includes investigation of concentration of material within specific geographic areas and analysis of identified resources. The 'Impact' dimension refers to consequences of scarcity of materials within the scope of the study, which could be the national economy or a specific sector. While all three studies use a matrix-based framework, Graedel et al. (2012), in contrast to NRC (2008) and EC (2010) studies, relies upon an additional dimension. The authors include 'environmental implications' as a separate dimension in the criticality matrix. The 'environmental dimension' covers the impact of materials extraction and recycling on the environment. All three methods incorporated a quantitative approach to analyse the supply risk. The NRC (2008) used expert elicitation to measure how different factors affect the supply risk. The other two studies used pre-developed metrics such as Herfindahl-Hirshman Index (HHI) and World Governance Index (WGI) to assess the supply risk (EC 2010; Graedel et al. 2012). In the following section, these indexes will be reviewed in detail.

Table 6 Modelling frameworks.

	NRC (2008)	EC(2010)	Graedel et al (2012)
			
Basic concept	Criticality matrix	Criticality matrix	Criticality space
Main dimension	Supply risk, Impact of supply restriction	Supply risk, Economic Importance (Impact)	Supply risk , Vulnerability to supply restriction, Environmental implications
'Supply Risk ' dimension	Semi-quantitative: scale of 1–4, expert judgements considering five determinants: geologic, technical, environmental and social, political, economic	Quantitative: theoretical scale of 1–10, product of monopoly supply (HHI), political stability (WGI), recycling rate and substitutability indices	Quantitative: scale of 0–100, weighted average of depletion time (reserves), companion metal fraction, policy potential index, human development index (both related to producing countries), political stability (WGI), supply concentration (HHI)
'Impact' dimension	Semi-quantitative: scale of 1–4 by sector, weighted by decimal value of usage, considering substitution,	Quantitative: scale 1–10,'economic importance' judged by 17 'EU mega-sectors', as	Quantitative: scale of 0-100, end-use fraction multiplied by weighted average of metrics covering importance,

	importance of end use nationally, to society and to emerging technologies	product of share of EU consumption and value added to the EU economy, divided by gross domestic product (GDP)	substitutability and ability to innovate, precise metrics depend on perspective
Aggregation method	Single estimate for impact of supply restriction | Algorithm for supply risk	Algorithm for both dimension	Algorithm for all dimensions

System and/or parameters considered

As it was described in Figure 17, the resource criticality assessment may be applied at different scales such as global, national, corporate or technological sector and scopes. The scope of the project defines the parameters and metrics to assess the criticality. Below the main parameters are reviewed.

Supply concentration
Most studies consider supply concentration to be a crucial factor for assessing the criticality of a material. Supply concentration examines whether there is a high level of concentration of production or reserves in a few countries. Generally, studies use either the amount of production or the reserves. For measuring the concentration most studies apply either the sum of the one to three largest producers, number of reserves countries or the Herfindahl–Hirschman Index (HHI). In most of studies all producing countries are including in the analysis. However, in some cases (i.e. Moss et al. (2011) studies use the number of producing countries which make up at least 50 % of the world's annual production.

The HHI is a standard economic concept widely applied in competition law, technology management and antitrust actions (Achzet and Helbig 2013b) . It is calculated as the sum of the square of all countries' market shares (as a ratio of global production) of a given material as expressed in Equation 1:

$$HHI(a) = \sum_{i=1}^{N}(a_i{}^2)$$
Equation 1

Where N is the number of producing countries, and a_i is the share that a given country or company has of the total global annual production of that material.

A typical example of raw material with a high HHI index is the group of REE. Most of these elements are mined in China. For example, China accounts for 46% of global annual production of molybdenum, and up to 97 % for some other materials in the REE group (USGS 2013).

The U.S. Department of Justice and the Federal Trade Commission have published a guideline on how to use the HHI index (U.S. Department of Justice and the Federal Trade Commission concentrations 2010). They give a threshold HHI concentration as < 0.15 – '*un-concentrated*'; between 0.15 and 0.25 – 'moderately concentrated'; and > 0.25 – 'highly concentrated'. However, there is some disagreement on these figures. For example, the German Federal Ministry of Economics and Technology indicates that any materials with HHI values above 0.15 and to be considered critical (Rosenau-Tornow et al. 2009).

Geopolitical risk
To evaluate the geopolitical risk, studies normally combine political risk metrics with production or reserve data for each of the countries. Metrics that are used for the quantification of geopolitical risk are usually based either on the 'World Governance Index' produced by the World Bank, the 'Global Political Risk Index' (GPRI) produced by the Eurasia Group, the 'Policy Potential Index' (PPI) produced by the Fraser Institute, or the 'Human Development Index' (HDI) produced by the United Nations Development Programme (Achzet and Helbig 2013b).

In addition to geopolitical risk, Graedel et al. (2012) evaluate social and regulatory risks by including the Policy Potential Index (PPI) and the Human Development Index (HDI). The PPI calculates the attractiveness of a country for exploration of raw materials based on an assessment of taxes, ecological regulation, infrastructure, labour market and socio-economic parameters. The HDI, more generally, measures the life expectancy of the population, its education and income (UNDP 2014).
The most common approach is a combination of one of these metrics with the HHI index (Equation 1).

$$Country\ risk_{HHI}(a) = \sum_{i=1}^{N}(\propto_i \times a_i^2)$$
Equation 2

Where $\propto_i$ either represents the World Governance Index (WGI), the Policy Potential Index (PPI), Human Development Index (HDI), or the Political Risk Index (GPRI) and a_i : The share country/ company has of the annual production

A threshold for criticality of the geopolitical risk is given by Rosenau–Tornow et al. (2009), which evaluate a country risk of 5.5 and above as critical (on a scale from 0 to 10). Graedel et al. (2012) use the country risk in its general algorithm for assessing the supply risk and Moreley and Etherlley (2008) prefers to use a relative country risk index in its study and dividing countries into three divisions based on their associated risk.

Reserve: Production ratio
The relationship between the volume of reserves of a material remaining and production is used by some studies in their definition of criticality, although generally in different ways. The meaning of 'reserves' is commonly taken from the U.S Geological Survey definition for 'Reserve' and 'Reserve base'. Figure 18 illustrates the definition of these terms. According to this, 'reserves' refers to deposits which could be identified and could be economically extracted as of today. The 'reserve base' additionally covers the raw materials, which could

be extracted sub-economically or with marginal benefit. However, since 2013, USGS no longer uses the term 'reserve base' in its publications. Instead it uses 'marginal reserves' and 'sub-economic resources' (USGS 2013). These changes have been reflected in material criticality studies.

Most of the studies use the 'static reserve production ratio', which is obtained by dividing current annual production by volume of reserves (Figure 17). Some studies have proposed adaptations of this metric. Morley & Eatherley (2008) uses a dynamic method for its calculation using possible future production scenarios that extend to the year 2050 and a wider reserve base (see Figure 18) instead of current production and reserves levels (Morley and Eatherley 2008).

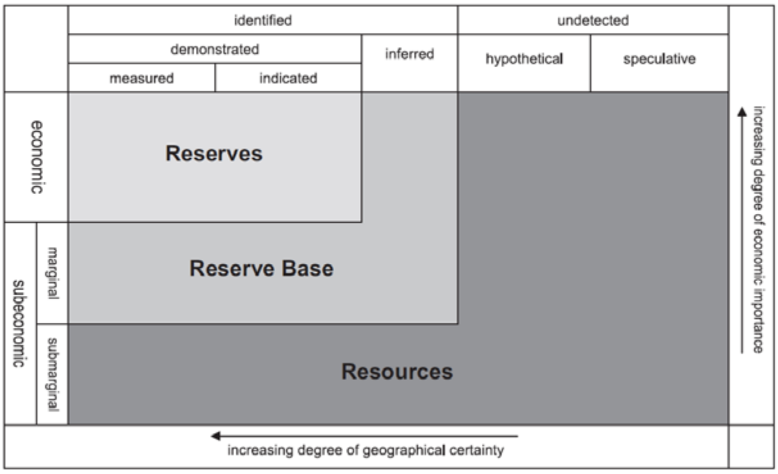


Figure 18 Definition of Reserve, Reserve base and resource. Figure from Achzet & Helbig 2013.

Graedel et al (2012) has developed an algorithm called depletion time (DT). DT includes a dynamic approach which covers reserve, the demand trend, and recyclability of the material (Graedel et al. 2012). It adds the recycling component to the commonly used reserves to production ratio. It covers the distribution of the material life cycle and material losses from extraction to product. The recycling rate is incorporated using the end of life recycling rate (EOLRR) (Graedel et al. 2012).

While no specific threshold for criticality assessment of depletion time is given by Graedel et al. (2012), in another independent study by the same research group where they applied their method to the copper family, 50 % is used as the limit of criticality (Nassar et al. 2012). TD algorithm has also been used by other studies. For example, the Cologne Institute of Economic Research uses it to assess the criticality of materials for Bavarian companies, working with 12.5 % as their threshold for criticality (Achzet and Helbig 2013b).

Recyclability

Recyclability and recycling potential has also been used by a number of recent studies and as a possible solution in the case of rapid demand growth to reduce supply risk.
Concerning the assessment of recyclability, two different terms, 'new scrap' and 'old scrap' have been used by the studies. New scrap refers to recycling the production waste and

returning it to the production process while old scrap refers to the recycling process at the product's end of life (Graedel et al. 2011). For example, in the energy sector, indium is used for photovoltaic panel production, and a considerable amount of indium that could be recycled as new scrap is wasted in the manufacturing process.

The solar panels produced can, however, also be recycled at the end of their life cycle. This is the potential for old scrap recycling and is calculated by the 'end-of-life recycling rate' (EOL-RR), which includes the whole recycling process. The EOL-RR is generally measured as the relation between potentially collectible old material and the actually recycled secondary material (Graedel et al. 2011). The most common database for EOL-RR is the UNEP and USGS report on the recycling rate of materials.

Substitutability
The substitutability of material is an important factor in material criticality studies as it concerns the vulnerability of a material in the event of supply restrictions. Different studies have measured substitutability using qualitative or quantitative approaches. For example, Duclos et al. (2010) in a study for General Electric, assess the substitutability of raw materials qualitatively using expert assessments. On the other hand, the European Commission has developed a quantitative method for assessing the substitutability (EC 2010). The equation below shows the formula used for evaluating the substitutability in the latter study.

$$\sigma_i = \sum_{n=i}^{N} A_{is}\sigma_{is}$$
Equation 3

Where A_{is} specifies which share of the raw material (i) is demanded by each application (s) and σ_{is} quantifies the substitutability of material (i) for each application (s) with 0 (substitutable), 0.5 (substitutable only at high expenses) and 1 (not substitutable).
Due to the high degree of uncertainty the investigation of substitutability can be exceptionally complex, especially with multifunctional raw materials, which have many applications. Therefore, it is not a straightforward process to analyse substitutability (Achzet and Helbig 2013b). Another important factor is that substitutability is not only dependant on the raw material, but it can depend on the substitution potential of a technology and/or application (Lloyd et al. 2012)

By-product dependency
The by-product dependency is used by some studies as a factor to assess the criticality associated with the supply risks. The term 'by-product' refers to a mineral or a raw material that is producible only at the time of production of a main metal. It is possible that, after necessary intermediate steps, the by-product raw material can be economically extracted (Achzet and Helbig 2013b). Some studies refer to this issue using different terms. For example, Graedel (2011) describes the by-product dependency by a parent metal and daughter metal definition. Parent metal refers to metal that can be found in relatively high concentration in good-sized deposits, while daughter material are those whose concentration is less than 1 ppm occurring in the ores of material with similar physical and chemical properties (Graedel 2011). An example of by-product dependency in the energy

sector is indium and cadmium which are used for the manufacturing of photovoltaics (Speirs and Contestabile 2013). Both of these materials are a typical by-product of the zinc extraction process. One of the challenging issues in criticality assessment studies is that extraction and processing of the main metal could directly affect the elasticity of the supply of the by-product (Hagelüken and Meskers 2010). Figure 19 illustrates the concept of by-product dependency.

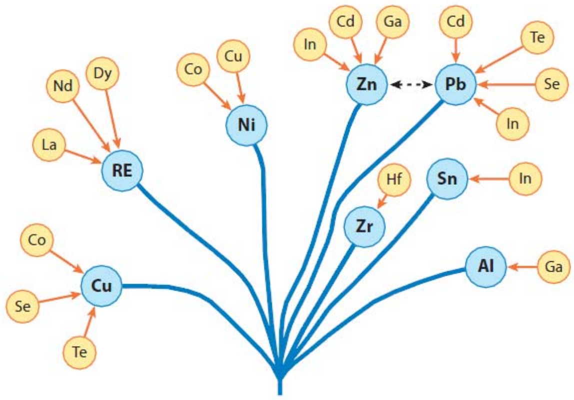


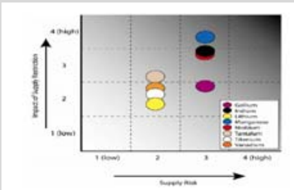
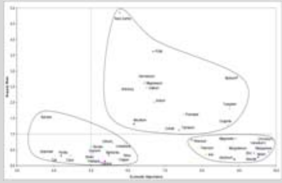
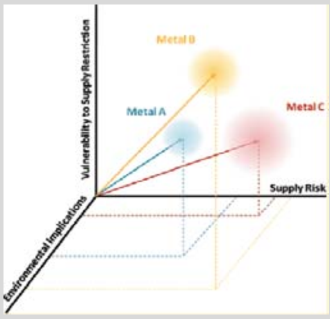
Figure 19 By-product dependency. Source: Hagelüken & Meskers 2010 and Graedel 2011.

To measure by-product dependency most of studies have used a qualitative approach while Graedel et al. (2012) and NRC (2008) measure the ratio of by-production to the total production in their algorithm.

Time / Space / Resolution /Accuracy

Based on the scope of the project the criticality assessment could be apply on Global level, national level, a single company or a technological sector. One of the key elements of criticality is the demand projection. Therefore, it would be important to have a clear understating of the timeframe of the project while the future demand scenarios are being developed. Table 7 shows how the three main modeling frameworks developed for material criticality considered the timeframe and scope of their study.

Table 7 Time frame and scope of the studies.

	NRC (2008)	EC(2010)	Graedel et al (2012)
			
Basic concept	Criticality matrix	Criticality matrix	Criticality space
System under study	Economy	Economy	A group of material / in any sector/ in any scope
Scope	Scope	EU	Global, National or Company
Time Frame	<10 Years	<10 Years	Short-term<10 Yr. Long-term 10-100 yr.

Indicators / Outputs / Units

Resource criticality assessments report their results in different ways. It could be qualitative low-mid-high scales; explicit numerical scales; or criticality matrices. Where criticality matrices are used the assessed factors are generally split into two groups and expressed into two separate axes. In more sophisticated methodologies the matrix can be represented by three separate axes. For example, Graedel *et al*. (2012) present a three axes matrix, with *environmental implications* represented on the third axis, capturing the environmental implications of using a particular metal, including human health and ecosystem impacts.

Figure 20 illustrate some example of reporting resource criticality.

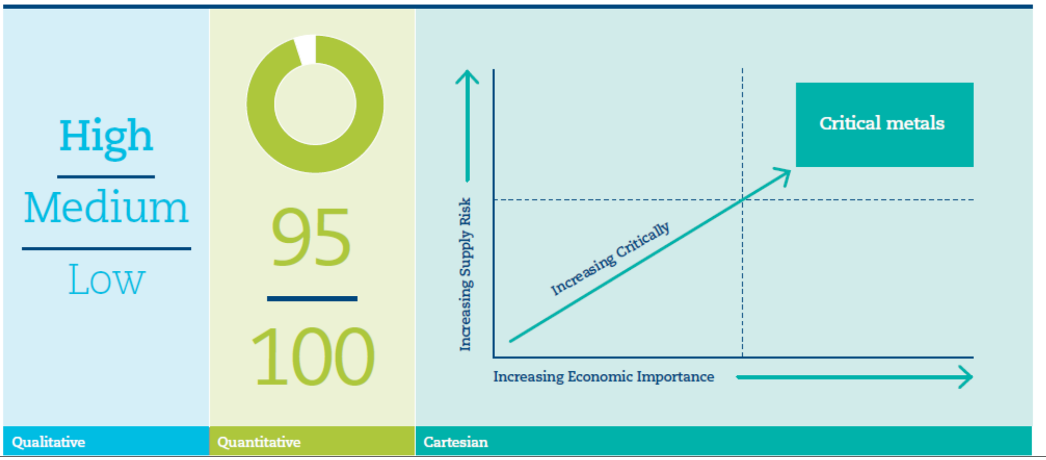


Figure 20 Example of types of criticality scoring. Source: (Speirs and Contestabile 2013.

Treatment of uncertainty, verification, validation

One key shortcoming in criticality assessments is the issue of uncertainty, which has rarely been addressed. There are a number of sources of uncertainty, which can derive, in evident variation between studies.

For example, in the case of critical materials for energy sector, an important source of uncertainty is material intensity of energy technologies with a potentially significant impact on the results. **Fejl! Henvisningskilde ikke fundet.** shows different values for material intensity reported by previous studies. Among the previous studies, only Graedel et al. (2012) consider uncertainty analysis, using the Monte Carlo simulation, which assess how the variation in the metrics used may affect the aggregated results. It is, however, essential that all material criticality assessments acknowledge the inherent uncertainty of results and to some extent attempt to quantify or understand the level of uncertainty. One may suggest that methods should be applied iteratively, reviewing initial results and appropriately adjusting the methods to ensure that they reflect the underlying concerns.

Table 8 Material intensities for energy technologies.

Material Intensity	SEI (2012) (Kg/MW)	WWF (2014) (Kg/MW) in 2009	WWF (2014) (Kg/MW) in 2050	SOTA (2011) (Kg/MW)
Indium for PV	110-2.5	12.5	3	5.32-7.95
Tellurium for PV	142-22	7.75	2	90.38
Neodymium for wind turbines	185-122	400	121	19.6-171.5

Going back to our example on the energy sector (Table 8), one reason that may explain substantial differences in reported values could be the issue of substitution. If the substitution analysis differs, it directly affects their material intensities for different technologies. Therefore, one of the main sources of uncertainty may be the potential substitution in technologies or materials.

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Related methods

Not applicable

Operational tools

Not applicable

Key relevant contacts

Institute / Organisation	Link/ main contact
Critical Materials Institute / U.S Départment of Ennery / Ames laboratory	https://cmi.ameslab.gov/about
U.S. Geological Survey	www.usgs.gov/ Contacts: Klaus Schulz, kschulz@usgs.gov and Dwight Bradley, dbradley@usgs.gov
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British Geological Survey	www.bgs.ac.uk/mineralsuk/statistics/criticalRawMaterials.html Contact : Paul Lusty plusty@bgs.ac.uk
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