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Environmental Systems Analysis

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1.1 Introduction

Throughout history, engineers were always expected to provide innovative solutions to various societal challenges, and these expectations continue to the present day. However, nowadays, we are facing some unprecedented challenges, such as climate change, growing energy demand, resource scarcity, and inadequate access to food and water, to name but a few. With a fast-growing population, it is increasingly clear that the lifestyles of modern society cannot be sustained indefinitely. Growing scientific evidence shows that we are exceeding the Earth's capacity to provide many of the resources we use and to accommodate our emissions to the environment (IPCC, 2013; UNEP, 2012).

Engineers have a significant role to play in addressing these sustainability challenges by helping meet human needs through provision of technologies, products, and services that are economically viable, environmentally benign, and socially beneficial (Azapagic and Perdan, 2014). However, one of the challenges is determining what technologies, products, and services are sustainable and which metrics to use to ascertain that.

Environmental systems analysis (ESA) can be used for these purposes. ESA takes a systems approach to describe and evaluate the impacts of various human activities on the environment. A systems approach is essential for this as it enables consideration of the complex interrelationships among different elements of the system, recognizing that the behavior of the whole system is quite different from its individual elements when considered in isolation from each other. The "system" in this context can be a product, process, project, organization, or a whole country.

Many methods are used in ESA, including:

- Energy and exergy analysis
- Material and substance flow analysis (SFA)
- Environmental risk assessment (ERA)
- Environmental management systems (EMS)
- Environmental input–output analysis (EIOA)
- Life cycle assessment (LCA)
- Life cycle costing (LCC)
- Social life cycle assessment (S-LCA)
- Cost–benefit analysis (CBA).

These methods are discussed in the rest of this chapter.

1.2 Environmental Systems Analysis Methods

In addition to the methodologies that underpin them, ESA methods differ in many other respects, including the focus, scope, application, and sustainability aspects considered. This is summarized in Table 1.1 and discussed in the sections that follow.

1.2.1 Energy and Exergy Analysis

Energy analysis is used to quantify the total amount of energy used by a system and to determine its efficiency. It can also be used to identify energy "hot spots" and opportunities for improvements. Exergy analysis goes a step further, and, instead of focusing on the quantity, it measures the quality of energy or the maximum amount of work that can be theoretically obtained from a system as it comes into equilibrium with its environment. Exergy analysis can be used to determine the efficiency of resource utilization and how it can be improved.

Although energy analysis has traditionally focused on production processes, it is also used in other applications, including energy analysis at the sectorial and national levels. However, the usefulness of exergy analysis is questionable for non-energy systems. Furthermore,

Handbook of Environmental Engineering, First Edition. Edited by Myer Kutz.

Table 1.1 An overview of methods used in environmental systems analysis.

Method	Focus	Scope/system boundary	Sustainability aspects	Application
Energy/exergy analysis	Production processes, supply chains, regions, countries	Production process, sectorial, regional, national	Energy	Process or project analysis, energy efficiency, identification of energy "hot spots"
Material flow analysis	Materials	Regional, national, global	Natural resources	Environmental accounting, preservation of resources, policy
Substance flow analysis	Chemical substances	Regional, national, global	Environmental pollution	Environmental accounting and protection, strategic management of chemicals, policy
Environmental risk assessment	Products, installations	Product or installation, local, regional, national	Environmental, health and safety	Risk analysis, evaluation of risk mitigation measures, financial planning, regulation
Environmental management systems	Organizations	Organization	Environmental	Environmental management
Environmental input–output analysis	Product groups, sectors, national economy	Sectors, supply chains, national economy	Environmental and economic	Environmental accounting, policy
Life cycle assessment	Products, processes, services, activities	Life cycle/supply chain	Environmental	Benchmarking, identification of opportunities for improvements, eco-design, policy
Life cycle costing	Products, processes, services, activities	Life cycle/supply chain	Economic	Benchmarking, identification of opportunities for improvements
Social life cycle assessment	Products, processes, services, activities	Life cycle/supply chain	Social	Benchmarking, identification of opportunities for improvements, policy
Cost–benefit analysis	Projects, activities	Project, activity	Socioeconomic and environmental	Appraisal of costs and benefits of different projects or activities

many users find it difficult to estimate and interpret the meaning of exergy (Jeswani et al., 2010).

1.2.2 Material Flow Analysis

MFA enables systematic accounting of the flows and stocks of different materials over a certain time period in a certain region (Brunner and Rechberger, 2004). The term "materials" is defined quite broadly, spanning single chemical elements, compounds, and produced goods. Examples of materials often studied through MFA include aluminum, steel, copper, and uranium. MFA is based on the mass balance principle, derived from the law of mass conservation. This means that inputs and outputs of materials must be balanced, including any losses or stocks (i.e. accumulation).

As indicated in Figure 1.1, MFA can include the entire life cycle of a material, including its mining, production use, and waste management. In addition to the material flows, MFA also considers material stocks, making it suitable for analysis of resource scarcity. Material flows are typically tracked over a number of years enabling evaluation of long-term trends in the use of materials. MFA can also serve as a basis for quantifying the resource productivity of an economy, but it is not suitable for consideration of single production systems (Jeswani et al., 2010).

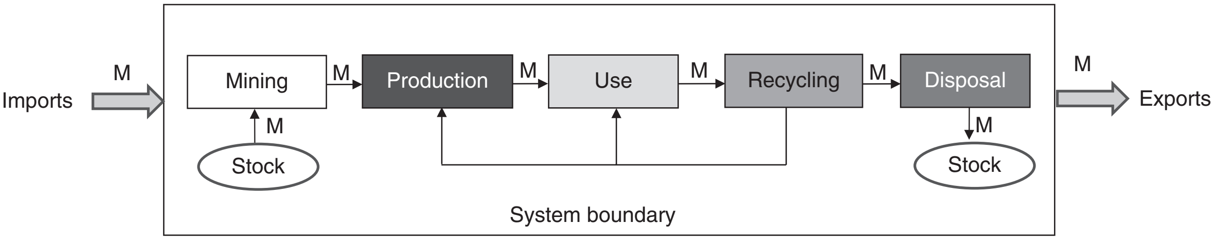


Figure 1.1 Material flow analysis tracks flows of materials through an economy from "cradle to grave." (M – flows of material under consideration).

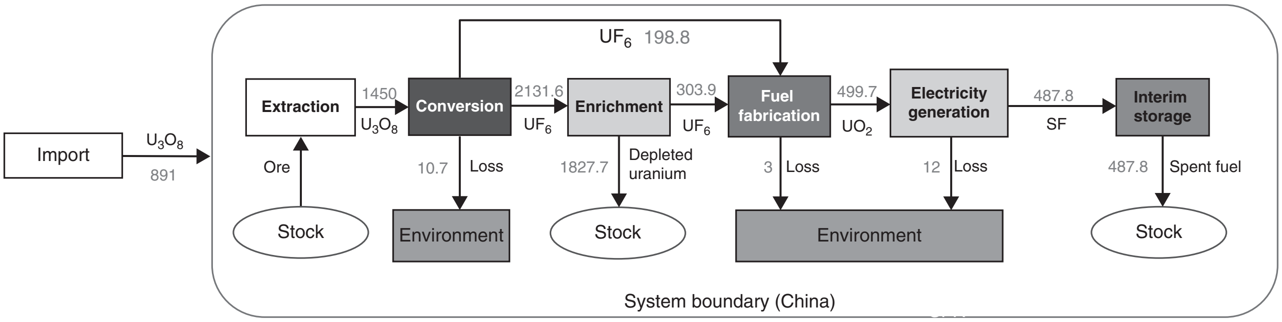


Figure 1.2 Material flow analysis of uranium flows and stocks in China in tonnes per year. *Source*: Adapted from Yue et al. (2016).

An example of MFA applied to uranium in China is given in Figure 1.2. As can be seen, the annual flows and stocks of uranium, which is used as a fuel in nuclear power plants, are tracked within the country along the whole fuel life cycle. This includes extraction of the ore, conversion and enrichment of uranium, fuel fabrication, and electricity generation. Thus, MFA helps to quantify the total consumption of uranium over time and stocks of depleted uranium that could be used for fuel reprocessing. It can also help with the projections of future demand and estimates of how much uranium can be supplied from indigenous reserves and how much needs to be imported.

1.2.3 Substance Flow Analysis

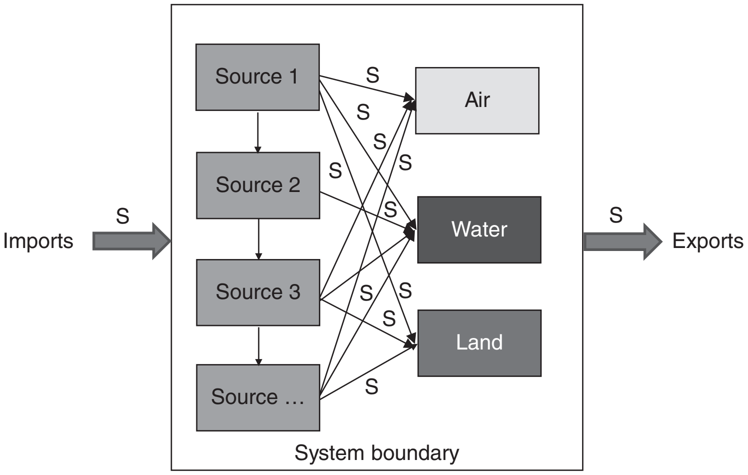
SFA is a specific type of MFA, focusing on chemical substances or compounds. The main aim of most SFA studies is to provide information for strategic management of chemical substances at a regional or national level (van der Voet, 2002). SFA can be also applied to track environmental pollution over time in a certain region. The latter is illustrated in Figure 1.3, which shows emissions of the pollutant of interest from different sources to air, water, and land in a defined region. However, the distinction between MFA and SFA is often blurred, and sometimes the two terms are used interchangeably.

1.2.4 Environmental Risk Assessment

ERA is used to assess environmental risks posed to ecosystems, animals, and humans by chemicals, industrial installations, or human activities. The risks can be physical, biological, or chemical (Fairman et al., 1998).

Many types of ERA are used, including pollution, natural disaster, and chemical risk assessment. The assessment covers emissions and related environmental impacts in the whole life cycle of a chemical or an installation. For chemicals, this includes their production, formulation, use, and end-of-life management. For industrial installations, construction, operation, and decommissioning must be considered. ERA aims to protect the atmosphere, aquatic, and soil organisms as well as mammals and birds further up in the food chain. It is used by industry not only to comply with regulations but also to improve product safety, financial planning, and evaluation of risk mitigation measures.

Figure 1.3 Substance flow analysis tracks the flows of pollutants into, within and out of a region (S – flows of substance under consideration). *Source*: Adapted from Azapagic et al. (2007).



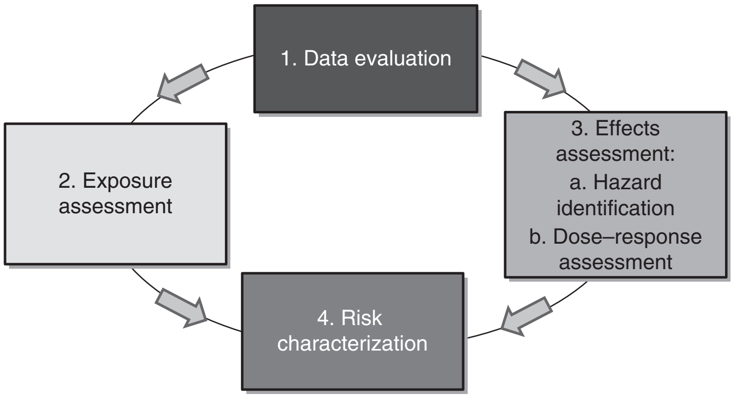


Figure 1.4 Environmental risk assessment steps according to the EUSES. *Source*: Based on Lijzen and Rikken (2004).

There are many methods and tools for carrying out an ERA. One such tool used in Europe is the European Union System for the Evaluation of Substances (EUSES) that enables rapid assessments of risks posed by chemical substances (EC, 2016). As indicated in Figure 1.4, EUSES comprises the following steps (Lijzen and Rikken, 2004):

1) Data collection and evaluation
2) Exposure assessment: estimation of the concentrations/doses to which the humans and the environment are exposed
3) Effects assessment comprising:
   a) Hazard identification: identification of the adverse effects that a substance has an inherent capacity to cause
   b) Dose–response assessment: estimation of the relationship between the level of exposure to a substance (dose, concentration) and the incidence and severity of an effect
4) Risk characterization: estimation of the incidence and severity of the adverse effects likely to occur in a human population or the environment due to actual or predicted exposure to a substance.

EUSES is intended mainly for initial rather than comprehensive risk assessments. The EUSES software is available freely and can be downloaded from the European Commission's website (EC, 2016). In the United States, ERA is regulated by the US Environmental Protection Agency (EPA); for various methods, consult the EPA guidelines (EPA, 2017). For a review of other ERA methods, see Manuilova (2003).

1.2.5 Environmental Management Systems

An EMS represents an integrated program for managing environmental impacts of an organization, with the ultimate aim of helping it improve the environmental performance. The most widely used EMS standard is ISO 14001 (ISO, 2015). This EMS follows the concept of plan–do–check–act, an iterative process aimed at achieving continual improvement.

The main steps of the ISO 14001 EMS outlined in Figure 1.5 are:

1) Planning
2) Support and operation
3) Performance evaluation
4) Implementation.

The EMS is set up and driven by the organization's leadership who are responsible for its implementation. The EMS must be congruent with and follow the organization's environmental policy.

1) *Planning*: In the planning step, the organization must determine the environmental aspects that are relevant to its activities, products, and services. The aspects include both those the organization can control and those that it can influence, and their associated environmental impacts, considering a life cycle perspective (ISO, 2015). Significant environmental impacts must be addressed through appropriate action, also ensuring compliance with legislation.
2) *Support and operation*: This step involves providing adequate resources for the implementation of the EMS and appropriate internal and external communication. The organization must also establish and control the processes needed to meet EMS requirements. Consistent with a life cycle perspective, this must cover all relevant life cycle stages, including procurement of materials and energy, production of product(s) or provision of services, transportation, use, end-of-life treatment, and final disposal of its product(s) or services.
3) *Performance evaluation*: This step involves monitoring, measurement, analysis, and evaluation of the environmental performance. This is typically carried out over the period of one year.
4) *Implementation*: The information obtained in the previous step is then used to identify and implement improvement opportunities across the organization's

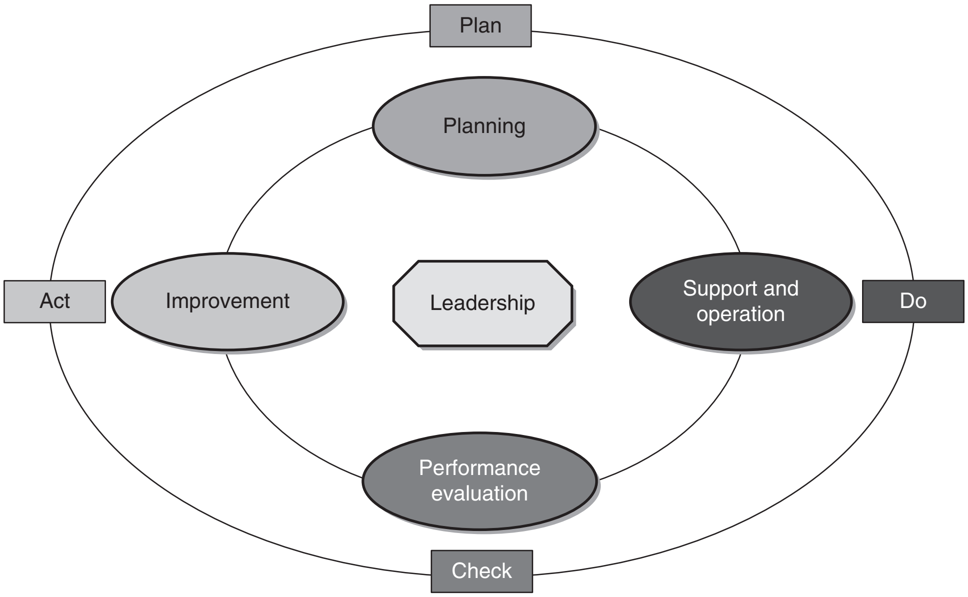


Figure 1.5 Main steps in the ISO 14001 environmental management system. *Source*: Based on ISO (2015).

activities (Figure 1.5). This whole process is repeated iteratively, typically on an annual basis, helping toward continuous improvement of environmental performance.

An alternative to the ISO 14001 is the Eco-Management and Audit Scheme (EMAS) developed by the European Commission. For details, see EC (2013).

1.2.6 Environmental Input–Output Analysis

EIOA represents an expansion of conventional input–output analysis (IOA). While the latter considers monetary flows within an economic system, EIOA combines environmental impacts with the conventional economic analysis carried out in IOA. Environmental impacts are considered either by adding environmental indicators to IOA or by replacing the monetary input–output matrices with those based on physical flows (Jeswani et al., 2010). Different environmental indicators can be considered in EIOA, including material and energy inputs as well as emissions to air and water, and waste. Social aspects, such as employment, can also be integrated into EIOA (Finnveden et al., 2003).

EIOA is suitable for determining the environmental impacts of product groups, sectors, or national economies. While this can be useful for environmental accounting and at a policy level, EIOA has many limitations. First, the data are too aggregated to be useful at the level of specific supply chains, products, or activities. It also often assumes an identical production technology for imported and domestic products, that each sector produces a single product, and that a single technology is used in the production process (Jeswani et al., 2010). Furthermore, allocation of environmental impacts between different sectors, products, and services is proportional to the economic flows.

1.2.7 Life Cycle Assessment

LCA applies life cycle thinking to quantify environmental sustainability of products, processes, or human activities on a life cycle basis. As shown in Figure 1.6, the following stages in the life cycle of a product or an activity can be considered in LCA:

- Extraction and processing of raw materials
- Manufacture
- Use, including any maintenance
- Re-use and recycling
- Final disposal
- Transportation and distribution.

LCA is a well-established tool used by industry, researchers, and policy makers. Some of the applications of LCA include (Azapagic, 2011):

- Measuring environmental sustainability
- Comparison of alternatives to identify environmentally sustainable options
- Identification of hot spots and improvement opportunities
- Product design and process optimization
- Product labeling.

The LCA methodology is standardized by the ISO 14040/44 standards (ISO, 2006a, b) that define LCA as

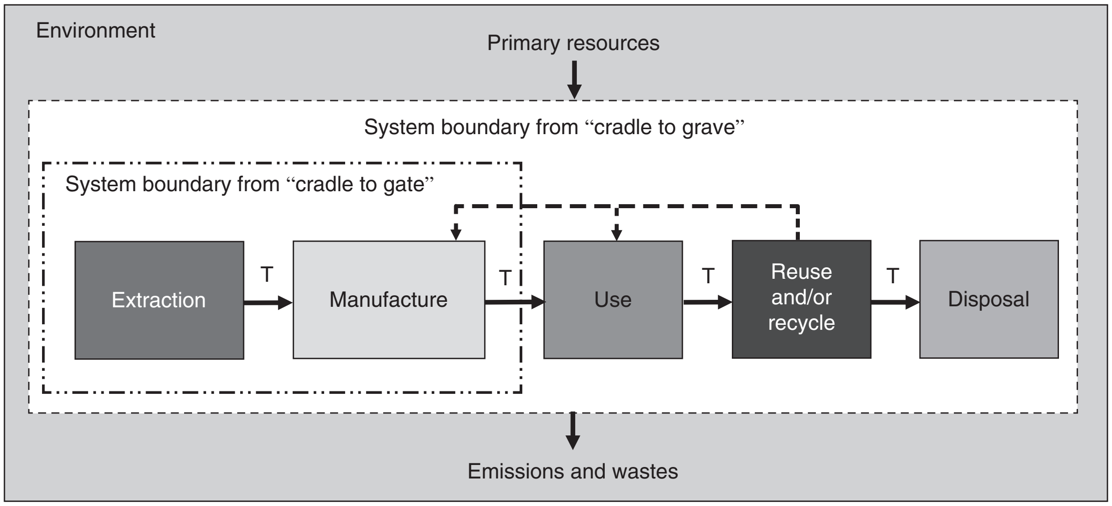


Figure 1.6 The life cycle of a product or an activity from "cradle to gate" and "cradle to grave." *Source*: Based on Azapagic (2011).

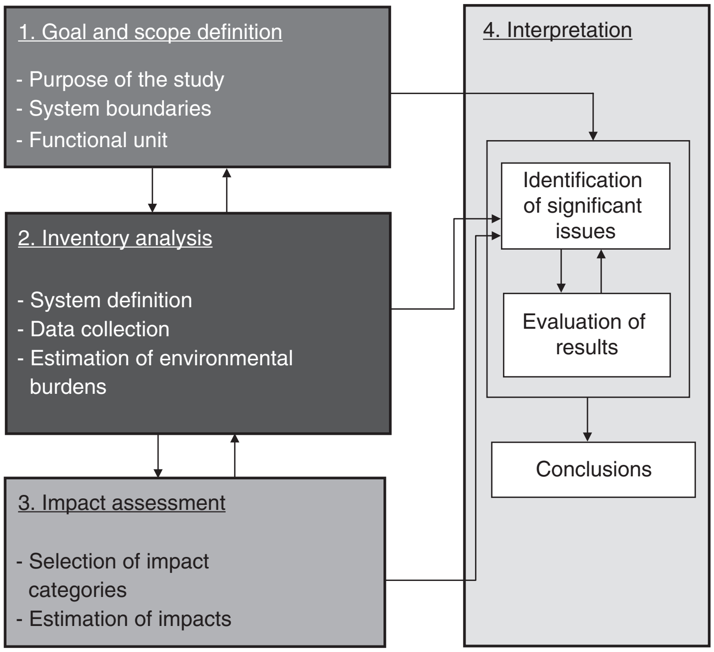


Figure 1.7 LCA methodology according to ISO 14040 (ISO, 2006a).

"…a compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product throughout its life cycle." According to these standards, LCA comprises four phases (Figure 1.7):

1) Goal and scope definition
2) Inventory analysis
3) Impact assessment
4) Interpretation.

1) *Goal and scope definition*: An LCA starts with a goal and scope definition that includes definition of the purpose of the study, system boundaries, and the functional unit (unit of analysis). As indicated in Figure 1.6, the system boundary can be from "cradle to grave" or "cradle to gate." The former considers all stages in the life cycle from extraction of primary resources to end-of-life waste management. The "cradle-to-gate" study stops at the factory "gate" where the product of interest is manufactured, excluding its use and end-of-life waste management. Definition of the system boundary depends on the goal and scope of the study. For example, the goal of the study may be to identify the hot spots in the life cycle of a product or to select environmentally the most sustainable option among alternative products delivering the same function.

Defining the function of the system is one of the most important elements of an LCA study as that determines the functional unit, or unit of analysis, to be used in the study. The functional unit represents a quantitative measure of the outputs that the system delivers (Azapagic, 2011). In comparative LCA studies it is essential that systems are compared on the basis of an equivalent function, i.e. the functional unit. For example, comparison of different types of drinks packaging should be based on their equivalent function that is to contain a certain amount of drink. The functional unit is then defined as "the quantity of packaging material necessary to contain a specified volume of a drink."

2) *Inventory analysis*: This phase involves detailed specification of the system under study and collection of data. The latter includes quantities of materials and energy used in the system and emissions to air, water, and land throughout the life cycle. These are known as environmental burdens. If the system has several functional outputs, e.g. produces several products, the environmental burdens must be allocated among them. Different methods are used for this purpose, including allocation on a mass and economic basis (ISO, 2006b).
3) *Impact assessment*: In this phase, the environmental impacts are translated into different environmental impacts. Example impacts considered in LCA include global warming, acidification, eutrophication, ozone layer depletion, human toxicity, and ecotoxicity. A number of life cycle impact assessment methods are available but the most widely used are CML 2 (Guinee et al., 2001) and Eco-indicator 99 (Goedkoop and Spriensma, 2001). The former is based on a "midpoint" approach, linking the environmental burdens somewhere in between the point of their occurrence (e.g. emissions of CO_2) and the ultimate damage caused (e.g. global warming). Ecoinvent 99 follows a damage-oriented approach that considers the "endpoint" damage caused by environmental burdens to human health, ecosystem, and natural resources. An overview of the CML 2 and Eco-indicator 99 methods can be found in Boxes 1.1 and 1.2. The ReCiPe method (Goedkoop et al., 2009) is gradually superseding CML 2 as its updated and broadened version. In addition to the midpoint approach, ReCiPe also enables calculation of endpoint impacts, thus combining the approaches in CML 2 and Eco-indicator 99.
4) *Interpretation*: The final LCA phase involves evaluation of LCA findings, including identification of significant environmental impacts and hot spots that can then be targeted for system improvements or innovation. Sensitivity analysis is also carried out in this phase to help identify the effects that data gaps and uncertainties have on the results of the study. Further details on the LCA methodology can be found in the ISO 14040 and 14044 standards (ISO, 2006a, b).

Numerous LCA databases and software packages are available, including CCaLC (2016) and Gemis (Öko Institute, 2016), which are freely available, and Ecoinvent (Ecoinvent Centre, 2016), Gabi (Thinkstep, 2016), and SimaPro (PRé Consultants, 2016), which are available at a cost.

1.2.8 Life Cycle Costing

Like LCA, LCC also applies life cycle thinking, but, instead of environmental impacts, it estimates total costs of a product, process, or an activity over its life cycle. Thus, as indicated in Figure 1.8, LCC follows the usual life cycle stages considered in LCA. LCC can be used for benchmarking, ranking of different investment alternatives, or identification of opportunities for cost improvements. However, unlike LCA, LCC is yet to become a mainstream tool – while microeconomic costing is used routinely as a basis for investment decisions, estimations of costs on a life cycle basis, including costs to consumers and society, are still rare.

Although there is no standardized LCC methodology, the *code of practice* developed by Swarr et al. (2011) and largely followed by practitioners is congruent with the ISO 14040 LCA methodology, involving definition of the goal and scope of the study, inventory analysis, impact assessment, and interpretation of results. Inventory data are similar to those used in LCA, but in addition they include costs and revenues associated with the inputs into and outputs from different activities in the life cycle (Figure 1.8).

The comparable structure, data, system boundaries, and life cycle models provide the possibility of integrating LCA and LCC to assess simultaneously the economic and environmental sustainability of the system of interest and to identify any trade-offs. This also enables estimations of the eco-efficiency of products or processes by expressing environmental impacts per unit of life cycle cost or vice versa (Udo de Haes et al., 2004).

1.2.9 Social Life Cycle Assessment

S-LCA can be used to assess social and sociological aspects of products and supply chains, considering both their positive and negative impacts (UNEP and SETAC, 2009). There is no standardized methodology for S-LCA. In an attempt to ease implementation of S-LCA and make it congruent with LCA, UNEP and SETAC

Box 1.1 CML 2 method: Definition of environmental impact categories (Azapagic, 2011)

Abiotic resource depletion potential represents depletion of fossil fuels, metals, and minerals. The total impact is calculated as:

$$\mathrm{ADP} = \sum_{j=1}^{J} \mathrm{ADP}_j B_j \quad (\mathrm{kg\,Sb\,eq.})$$

where B_j is the quantity of abiotic resource j used and ADP_j represents the abiotic depletion potential of that resource. This impact category is expressed in kg of antimony used, which is taken as the reference substance. Alternatively, kg oil eq. can be used instead for fossil resources.

Impacts of land use are calculated by multiplying the area of land used (A) by its occupation time (t):

$$\mathrm{ILU} = A \times t \quad (\mathrm{m}^2.\mathrm{yr})$$

Climate change represents the total global warming potential (GWP) of different greenhouse gases (GHG), such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), etc. GWP is calculated as the sum of GHG emissions multiplied by their respective GWP factors, GWP_j:

$$\mathrm{GWP} = \sum_{j=1}^{J} \mathrm{GWP}_j B_j \quad (\mathrm{kg\,CO_2\,eq.})$$

where B_j represents the emission of GHG j. GWP factors for different GHGs are expressed relative to the GWP of CO_2, which is defined as unity. The values of GWP depend on the time horizon over which the global warming effect is assessed. GWP factors for shorter times (20 and 50 years) provide an indication of the short-term effects of GHG on the climate, while GWP for longer periods (100 and 500 years) are used to predict the cumulative effects of these gases on the global climate.

Stratospheric ozone depletion potential (ODP) indicates the potential of emissions of chlorofluorohydrocarbons (CFCs) and other halogenated hydrocarbons to deplete the ozone layer and is expressed as:

$$\mathrm{ODP} = \sum_{j=1}^{J} \mathrm{ODP}_j B_j \quad (\mathrm{kg\,CFC\text{-}11\,eq.})$$

where B_j is the emission of ozone depleting gas j. The ODP factors are expressed relative to the ozone depletion potential of CFC-11.

Human toxicity potential (HTP) is calculated by taking into account releases toxic to humans to three different media, i.e. air, water, and soil:

$$\mathrm{HTP} = \sum_{j=1}^{J} \mathrm{HTP}_{jA} B_{jA} + \sum_{j=1}^{J} \mathrm{HTP}_{jW} B_{jW} + \sum_{j=1}^{J} \mathrm{HTP}_{jS} B_{jS} \quad (\mathrm{kg\,1,4\text{-}DB\,eq.})$$

where HTP_{jA}, HTP_{jW}, and HTP_{jS} are toxicological classification factors for substances emitted to air, water, and soil, respectively, and B_{jA}, B_{jW}, and B_{jS} represent the respective emissions of different toxic substances into the three environmental media. The reference substance for this impact category is 1,4-dichlorobenzene.

Ecotoxicity potential (ETP) is also calculated for all three environmental media and comprises five indicators ETP_n:

$$\mathrm{ETP}_n = \sum_{j}^{J} \sum_{i=1}^{I} \mathrm{ETP}_{i,j} B_{i,j} \quad (\mathrm{kg\,1,4\text{-}DB\,eq.})$$

where n ($n = 1$–5) represents freshwater and marine aquatic toxicity, freshwater and marine sediment toxicity, and terrestrial ecotoxicity, respectively. $\mathrm{ETP}_{i,j}$ represents the ecotoxicity classification factor for toxic substance j in the compartment i (air, water, soil), and $B_{i,j}$ is the emission of substance j to compartment i. ETP is based on the maximum tolerable concentrations of different toxic substances in the environment by different organisms. The reference substance for this impact category is also 1,4-dichlorobenzene.

Photochemical oxidants creation potential (POCP) is related to the potential of volatile organic compounds (VOCs) and nitrogen oxides (NO_x) to generate photochemical or summer smog. It is usually expressed relative to the POCP of ethylene and can be calculated as:

$$\mathrm{POCP} = \sum_{j=1}^{J} \mathrm{POCP}_j B_j \quad (\mathrm{kg\,ethylene\,eq.})$$

where B_j is the emission of species j participating in the formation of summer smog and POCP_j is its classification factor for photochemical oxidation formation.

Acidification potential (AP) is based on the contribution of sulfur dioxide (SO_2), NO_x and ammonia (NH_3) to the potential acid deposition. AP is calculated according to the equation:

$$\mathrm{AP} = \sum_{j=1}^{J} \mathrm{AP}_j B_j \quad (\mathrm{kg\,SO_2\,eq.})$$

where AP_j represents the AP of gas j expressed relative to the AP of SO_2 and B_j is its emission in kg.

Eutrophication potential (EP) is defined as the potential of nutrients to cause over-fertilization of water and soil, which can result in increased growth of biomass (algae). It is calculated as:

$$\mathrm{EP} = \sum_{j=1}^{J} \mathrm{EP}_j B_j \quad \left(\mathrm{kg\,PO_4}^{3-}\,\mathrm{eq.}\right)$$

where B_j is an emission of species such as N, NO_x, NH_4^+, PO_4^{3-}, P, and chemical oxygen demand (COD); EP_j represent their respective EPs. EP is expressed relative to PO_4^{3-}.

See Guinée et al. (2001) for a full description of the methodology.

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Box 1.2 Eco-indicator 99: Definition of the damage (endpoint) categories (Azapagic, 2011)

1. Damage to Human Health

This damage category comprises the following indicators:

- Carcinogenesis
- Respiratory effects
- Ionizing radiation
- Ozone layer depletion
- Climate change.

They are all expressed in disability-adjusted life years (DALYs) and calculated by carrying out:

1) Fate analysis, to link an emission (expressed in kg) to a temporary change in concentration
2) Exposure analysis, to link the temporary concentration change to a dose
3) Effect analysis, to link the dose to a number of health effects, such as occurrence and type of cancers
4) Damage analysis, to link health effects to DALYs, using the estimates of the number of years lived disabled (YLD) and years of life lost (YLL).

For example, if a cancer causes a 10-year premature death, this is counted as 10 YLL and expressed as 10 DALYs. Similarly, hospital treatment due to air pollution has a value of 0.392 DALYs/year; if the treatment lasted 3 days (or 0.008 years), then the health damage is equal to 0.003 DALYs.

2. Damage to Ecosystem Quality

The indicators within this damage category are expressed in terms of potentially disappeared fraction (PDF) of plant species due to the environmental load in a certain area over certain time. Therefore, damage to ecosystem quality is expressed as $\text{PDF}\cdot\text{m}^2\cdot\text{year}$. The following indicators are considered:

- Ecotoxicity is expressed as the percentage of all species present in the environment living under toxic stress (potentially affected fraction [PAF]). As this is not an observable damage, a rather crude conversion factor is used to translate toxic stress into real observable damage, i.e. convert PAF into PDF.
- Acidification and eutrophication are treated as one single impact category. Damage to target species (vascular plants) in natural areas is modeled. The model used is for the Netherlands only, and it is not suitable to model phosphates.
- Land use and land transformation are based on empirical data of occurrence of vascular plants as a function of land use types and area size. Both local damages in the area occupied or transformed and regional damage to ecosystems are taken into account.

For ecosystem quality, two different approaches are used:

1) Toxic, acid, and the emissions of nutrients go through the following three steps:
   a) Fate analysis, linking the emissions to concentrations.
   b) Effect analysis, linking concentrations to toxic stress or increased nutrient or acidity levels.
   c) Damage analysis, linking these effects with the PDF of plant species.
2) Land use and transformation are modeled on the basis of empirical data on the quality of ecosystems, as a function of the type of land use and area size.

3. Damage to Resources

Two indicators are included here: depletion of minerals and fossil fuels. They are expressed as additional energy in MJ that will be needed for extraction in the future due to a decreasing amount of minerals and fuels. Geostatical models are used to relate availability of a mineral resource to its remaining amount or concentration. For fossil fuels, the additional energy is based on the future use of oil shale and tar sands.

Resource extraction is modeled in two steps:

1) Resource analysis, which is similar to fate analysis, as it links an extraction of a resource to a decrease in its concentrations (through geostatical models)
2) Damage analysis, linking decreased concentrations of resources to the increased effort for their extraction in the future.

More detail on Eco-indicator 99 can be found in Goedkoop and Spriensma (2001).

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(2009) have developed an S-LCA method that follows the ISO 14040 structure. Therefore, according to this method, S-LCA involves the same methodological steps as LCA: goal and scope definition, inventory, impact assessment, and interpretation. However, while the impacts in LCA represent quantitative indicators, S-LCA also includes qualitative indicators. In total, there are 194 social indicators, grouped around five groups of stakeholder: workers, consumers, local community, society, and value chain actors. The main impact categories applicable to different stakeholders are listed in Table 1.2, with each impact category comprising a number of social indicators; for the details of the latter, see UNEP and SETAC (2009).

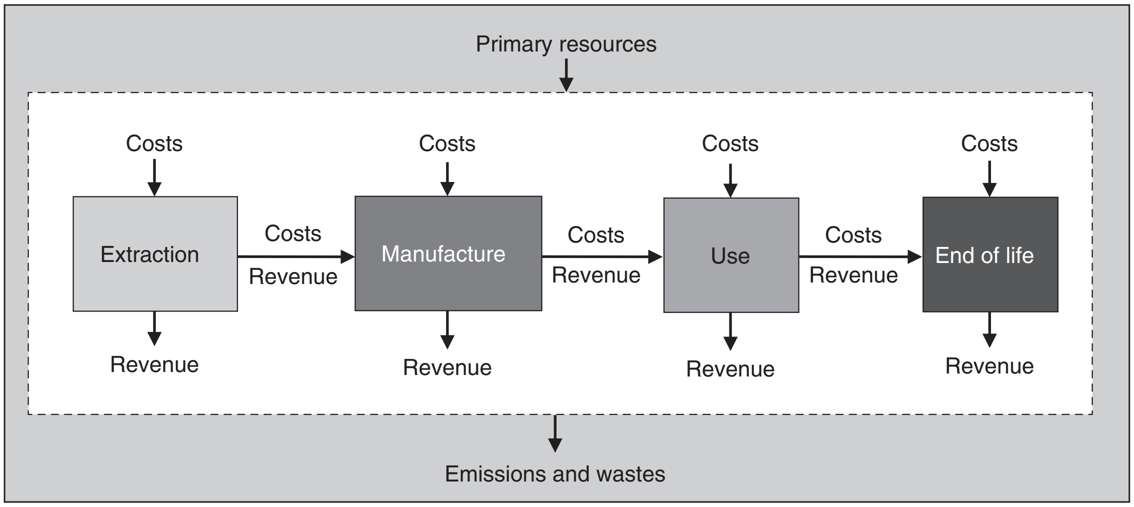

Figure 1.8 Life cycle costing estimates total costs in the life cycle of a product or an activity.

Table 1.2 The UNEP–SETAC framework for social impact categories (UNEP and SETAC, 2009).

Stakeholder group	Impact category
Workers	Freedom of association and collective bargaining
	Child labor
	Fair salary
	Working hours
	Forced labor
	Equal opportunities/discrimination
	Health and safety
	Social benefits/social security
	Feedback mechanism
Consumers	Consumer privacy
	Transparency
	End-of-life responsibility
	Access to material resources
	Access to immaterial resources
	Delocalization and migration
	Cultural heritage
Local community	Safe and healthy living conditions
	Respect of indigenous rights
	Community engagement
	Local employment
	Secure living conditions
Society	Public commitments to sustainability issues
	Contribution to economic development
	Prevention and mitigations of armed conflicts
	Technology development
	Corruption
Value chain actors	Fair competition
	Promoting social responsibility
	Supplier relationships
	Respect of intellectual property rights

As can be inferred from Table 1.2, a significant proportion of the indicators are qualitative and could be highly subjective; hence, their assessment poses a challenge. Another challenge associated with S-LCA is data availability and reliability, particularly for complex supply chains. Furthermore, geographic location of different parts of the supply chain of interest is fundamental for the assessment of social impacts, requiring specific data as generic data may be a poor substitute (Jeswani et al., 2010). However, collecting site-specific data is resource demanding and may hinder a wider adoption of the method.

1.2.10 Cost–Benefit Analysis

CBA is used widely for assessing costs and benefits of a project or an activity and to guide investment decisions. In ESA it is used for weighing environmental and socioeconomic costs and benefits of different alternatives (Jeswani et al., 2010).

CBA is based on the idea of maximum net gain – it reduces aggregate social welfare to the monetary unit of net economic benefit. So, for example, given several alternatives, the CBA approach would favor the one in which the difference between benefits and costs is the greatest. CBA has some similarities with LCC when applied to products (Finnveden and Moberg, 2005).

The most widely applied CBA technique in ESA is contingent valuation (CV). In CV, participants are asked to say how much they would be prepared to pay to protect an environmental asset. This is known as the "willingness to pay" approach. Alternatively, participants can be asked how much they would be willing to accept for loss of that asset, which is known as the "willingness to accept" method.

One of the advantages of CBA is that it presents the results as a single criterion – money – that can be easily communicated (Jeswani et al., 2010). However, measuring the expected benefits, or placing monetary value on the benefits in a simplistic way is often problematic (Ness et al., 2007). In particular, the results of the analysis largely depend on the way the questions are asked and whether the participants are familiar with the environmental asset in question. It is more likely that people who know nothing about the asset will place a nil value on it, although the life of others may depend on it. Furthermore, the value that people place on the environment strongly depends on their individual preferences and self-interest that does not serve as a firm foundation for environmental decision-making.

1.3 Summary

This chapter has presented and discussed various methods used in ESA. Broadly, they can be divided into those that take a life cycle approach and those that are more narrow in their perspective. They can also be distinguished by their focus and application, with some tools being applicable to individual products, technologies or organizations, and others to regional or national-level analyses. A further distinguishing feature is the sustainability aspect they consider: environmental, economic, and social, or their combination. Which method is used in the end will depend on the specific decision-making context and on the question(s) being asked by those carrying out the analysis. Nevertheless, the general trend in legislation and engineering practice is toward application of life cycle methods that integrate all three aspects of sustainability – the environment, economy, and society – in an attempt to balance them and drive sustainable development. Different approaches can be used to help integrate environmental, economic, and social indicators used in different ESA methods. One of the probably most useful approaches is multi-criteria decision analysis (MCDA). In MCDA, relevant stakeholders are asked to state their preferences for different sustainability aspects that are then used to aggregate the considered sustainability indicators into an overall sustainability score, allowing easy comparisons of alternative products, technologies, etc. For further details on MCDA used in ESA, see Azapagic and Perdan (2005a, b).

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