Life Cycle Thinking for Improved Resource Management: LCA or?

46

Björn Frostell

Abstract

Life cycle assessment (LCA) has become one of the most widely applied scientific and industrial methods for estimating environmental impacts of products and services. While the necessity to adopt a life cycle perspective as such was rather quickly accepted, the practical application of LCA has met considerable doubt and lagged behind. Strong contributing factors for this slow adaptation have been (i) a poor understanding of the LCA idea as such, (ii) a lack of useful tools for routine application of LCA, (iii) a lack of useful data and databases, (iv) poorly developed practices and processes for monitoring and data acquisition in industry and society in general, and (v) a general resistance to introduce a new concept. Now that these barriers gradually are being overcome, there is a need for some second and critical thoughts around the usefulness and practical applicability of LCA as a standard routine procedure in society. While doubtlessly having contributed to a revolution in systems thinking, the practical current application of LCA has several shortcomings: (i) There is a poor link between estimated emissions and (ia) the geographical location of them and (ib) the occurrence in time of them, (ii) an LCA rarely discusses the total emissions from a production site or service system since emissions are reported and discussed in relation to the functional unit, (iii) the methodology for LCA demands both categorization of material and energy flows into a large number of impact categories while in practice only a few are selected and sometimes in a rather arbitrary way, based more on the availability of data than based on relevance, (iv) the necessity to pull the assessment through the impact stage requires considerable extra skills and work by the assessing

B. Frostell
Assistant Professor Industrial Ecology, Department of Industrial Ecology, School of Industrial Engineering and Management KTH – Royal Institute of Technology, Stockholm, Sweden
e-mail: frostell@kth.se

J. Kauffman, K.-M. Lee (eds.), *Handbook of Sustainable Engineering*,
DOI 10.1007/978-1-4020-8939-8_50,

industry or agent, (v) when gradually more complex systems are being assessed, the system boundaries become more difficult to identify and the assessor faces the challenge to assess life cycles in different dimensions. The chapter describes the gradual development of life cycle thinking, LCA, and other life cycle thinking tools. It argues for a more differentiated application of life cycle thinking in practical tools in order to increase the practical usefulness of this important approach.

1 Introduction

Sustainable development is a vision of a positive development allowing economic, environmental, and social ambitions to be met both by those living now and by coming generations (cf. WCED 1987). The last worldwide Summit on general aspects of environment and development in Johannesburg (UN 2002) adopted in its General Assembly a resolution on Sustainable Development. Here it was decided to

> adopt sustainable development as a key element of the overarching framework for United Nations activities, in particular for achieving the internationally agreed development goals, included those contained in the United Nations Millennium Declaration, and to give overall political direction to the implementation of Agenda 21 and its review (UN 2002).

Many large international companies have formulated policies and strategies adopting the ideas of sustainable development. The World Business Council for Sustainable Development (WBCSD) is a CEO-led, global association of some 200 companies dealing exclusively with business and sustainable development (WBCSD 2012). Local governments are on their way, and universities cooperate nationally and internationally to foster education for sustainable development.

Two important – and conflicting – results seem evident from the more than 30 years of intensive discussion of sustainable development and efforts to reach it:

Overall, the economic development as calculated in the form of global GDP has increased rapidly and in total the global economic turnover has increased to 72.3 trillion dollars in 2009 (World Bank 2012). This is at least four times the 1975 level depending on the method of calculation. During the same period, the world population has increased from 4.1 to 6.8 billion, an increase by 67%. It may thus be concluded that economically, the world is far better off now than in 1975. On the other hand, much evidence points at the fact that during the same period, the physical global metabolism has increased very rapidly (raw material extraction, emissions of materials, and heat).

Perhaps the most pressing current challenge from an overall sustainable development point of view is the ecological. In recent years, a large amount of scientific evidence sends warning signals to the global community on the increasing risks of current development. Vitousek et al. (1997) concluded the following:

1. Between one-third and one-half of the land surface has been transformed by human action.

2. The carbon dioxide concentration in the atmosphere has increased by nearly 30% since the industrial revolution.
3. More atmospheric nitrogen is fixed by humanity than by all natural terrestrial sources combined.
4. More than half of all accessible surface freshwater is put to human use.
5. About one quarter of the bird species on Earth have been driven to extinction.
6. Approximately two-thirds of major marine fisheries are fully exploited, overexploited, or depleted.

In a thorough discussion of human impact on the ecological systems of the planet, Lubchenko (1998) concluded that:

> The individual and collective changes described above are so different in magnitude, scale and kind from past changes that even our best records and models offer little guidance concerning the scale or even the character of likely responses to these challenges. The future is quite likely to involve increasing rates of change; greater variance in system parameters; greater uncertainty about responses of complex biological, ecological, social, and political systems; and more surprises. The world at the end of the 20th century is a fundamentally different world from the one in which the current scientific enterprise has developed. The challenges for society are formidable and will require substantial information, knowledge, wisdom, and energy from the scientific community. Business as usual will not suffice.

During the last decade, much focus in the environmental debate has been on the risks for increasing costs of climate change mitigation (cf. Stern Review 2006). This has actually overshadowed both the other challenges and more seriously the compound challenge of all changes as a whole.

Life cycle assessment (LCA) of products and services is a very recent approach to estimate, analyze, and discuss the environmental impact of products and services. The start of this development in the late 1960s has been described by Boustead (1996), and a recent broad survey was published by Finnveden et al. (2009). A widely used practical guide to LCA was published by Baumann and Tillman (2004).

Invented and improved by engineers, LCA has later been standardized by the International Standards Organization (latest version ISO 2006a, b). LCA has become one of the most widely applied scientific and industrial methods for estimating environmental impacts of products and services. While the importance to adopt a life cycle perspective was rather quickly accepted, the practical routine application of LCA in industry and society has lagged behind. Strong contributing factors to this slow adaptation have been (i) a poor understanding of the LCA idea as such, (ii) a lack of useful tools for routine application of LCA, (iii) a lack of useful data and data bases, (iv) poorly developed practices and processes for monitoring and data acquisition in industry and society in general, and (v) a general resistance to introduce a new concept.

In this chapter, life cycle thinking as a basis for and broader concept than LCA will be presented and discussed, together with possible applications of life cycle thinking besides LCA.

2 Aim and Objectives

The main aim of this chapter is to inspire and encourage engineers, economists, and others to devote more effort to life cycle thinking and a more holistic and systems oriented work with (mainly) quantitative methods and tools to account for material and energy flows in connection to human activities. Important objectives of the work are to:

- Present a pathway of original thinking on how to make the vision of (ecologically) sustainable development more operational
- Describe and define the term life cycle thinking and its application in practice with the use of different tools and methods
- Discuss possible explanations to the slow penetration of knowledge from life cycle thinking to practice
- Suggest a development path for a mandatory more extensive use of life cycle thinking tools for improved overall resource management

3 Sustainable Development: From Vision to Work?

Traditionally, the SD vision has been presented and discussed as the so-called triple bottom line approach (Elkington 2004; cf. Clift 1998). The term “triple bottom line” refers to taking responsibility for three different pillars of a sustainable development: economic, ecological, and social aspects. Typically, this is expressed as three partially overlapping circles, intuitively giving equal weight to the three aspects of sustainable development. Later, this view has been questioned and other interpretations given (Giddings et al. 2002; cf. Strandberg and Frostell 2006).

In Fig. 46.1, an idea transformation path from traditional technical/economic development to operational sustainability work is presented, showing:

(a) The traditional thinking emphasizing technical/economic development only
(b) The triple bottom line interpretation of sustainable development as based to equal shares on technical/economic, social, and ecologic issues
(c) A nested interpretation (Giddings et al. 2002), emphasizing the ultimate dependence of both the economic and the social system on the ecological capacity of the global system
(d) A more detailed interpretation of the nested principal picture, showing the physical metabolic interaction between human activities (including the formal economy) and the global system as well as the social interaction between human activities and the economy

Interpreting sustainable development using the last model in Fig. 46.1d allows us to start discussing necessary actions to support sustainable development. In Fig. 46.2, the metabolic expression of sustainable development is shown in more detail.

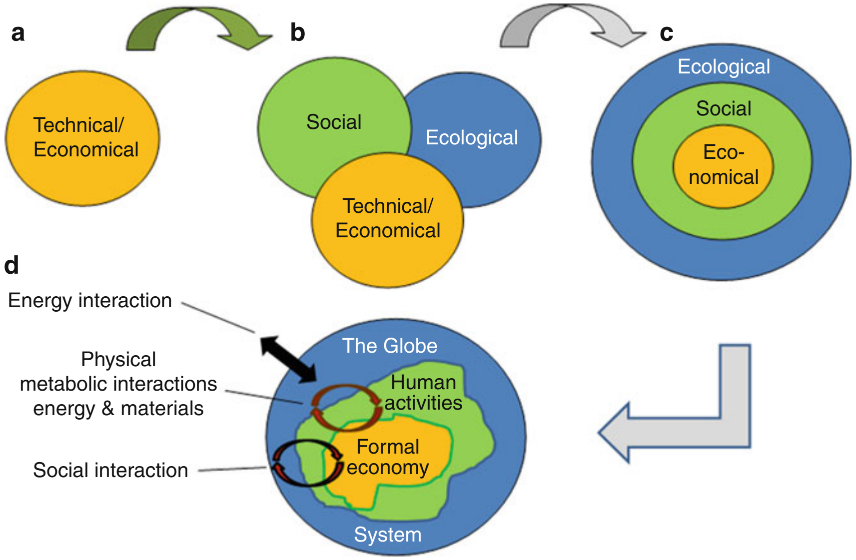

Fig. 46.1 A thought path from traditional strive for technical/economic development (**a**) to the *triple bottom line* approach to sustainable development (**b**), a nested sustainable development view where economy is dependent on society and both on the environment (**c**) arriving at an operational view of sustainability challenges in the form of both a physical metabolic interaction between human activities and the global system and social interactions between the three parts of the global system

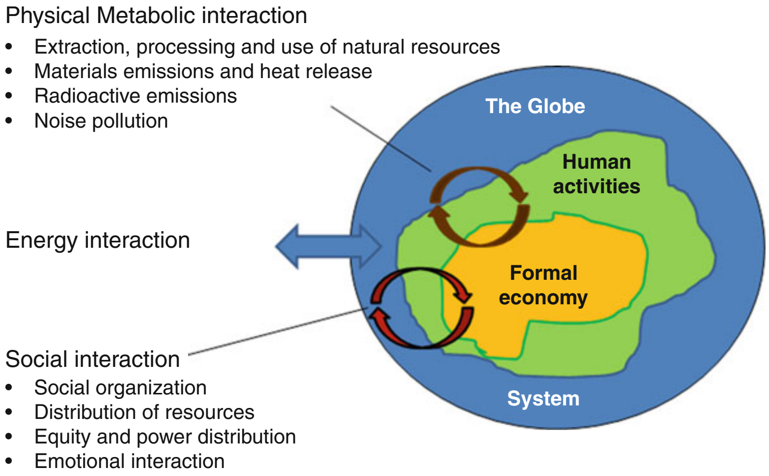

Fig. 46.2 More detailed explanation of important interactions between different subsystems of the overall global system. In this way of viewing the global system, it comprises human activities as a subsystem and this in turn comprises the formal economy as a subsystem. Physical metabolic interaction occurs between the global system and the entire human system (including the formal economy). The formal economy is exchange of goods and services for money. Life cycle thinking aims to include as many aspects as possible of the interactions between the human activities and the global system into resource management and thus into the formal economy

4 Life Cycle Thinking: A Broader Consideration of Interactions

4.1 Life Cycle Thinking

Life cycle thinking is a strive to think in a more holistic way and consider a broader set of interactions between human activities and the global system, be they of physical, economic, or social character. Life cycle thinking tries to understand (i) physical resource interactions and (ii) social resource interactions between (ia and iia) human individuals and different social groups and entities in the formal economy, (ib and iib) the formal economy and other human activities, and (ic and iic) human activities and the global system. Social interactions could be, for example, formal business activities between different parties, but also well-being during a mountain hike or fear for wild animals when walking in the forest. Life cycle thinking is strongly linked to resource management in all aspects relevant to consider and is thus economy in its broadest sense. In a sustainable development context, it involves considering economic, ecologic, and social aspects in an integrated and preferably quantitative way, but also using qualitative considerations when quantification cannot be achieved. In Fig. 46.3, some currently used methods in the three core pillars of the triple bottom line approach to sustainable development are shown.

Life cycle thinking is in practice almost impossible to implement in a satisfactory way. This is because of the following:

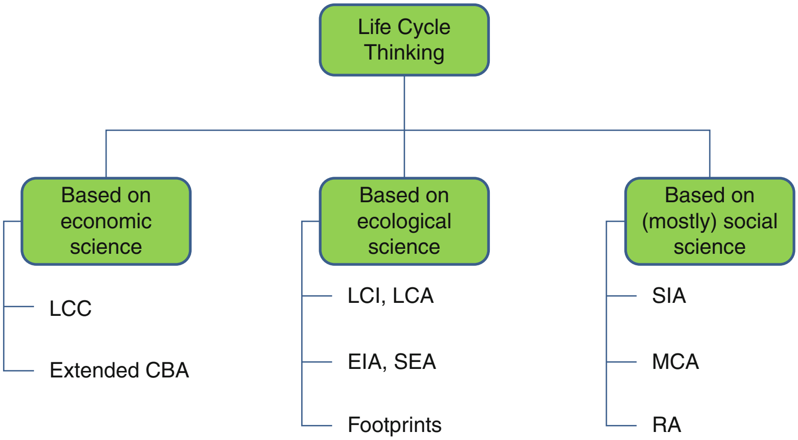

Fig. 46.3 Important life cycle thinking oriented methods – life cycle costing (LCC), cost-benefit analysis (CBA), life cycle inventory (LCI), life cycle assessment (LCA), environmental impact assessment (EIA), strategic environmental assessment (SEA), ecological footprint metrics (Footprints), social impact assessment (SIA), multi-criteria analysis (MCA), and risk assessment (RA)

- The global system (the world including atmosphere, lithosphere, and biosphere with society) is such an incredibly large and complex entity that we know only very little about its details and the interactions between different sub-entities.
- A large part of the interactions in the overall global system are of a social character between individuals, groups of individuals, or based on feelings, where our understanding of the detailed mechanisms and outcomes is still and perhaps forever impossible to predict quantitatively and/or with reliability.
- Only very recently have individuals and groups of individuals started to practice life cycle thinking and thus there is still a subcritical mass of people seeing the values of it.
- The results and suggestions for change emerging from life cycle thinking many times stand in contradiction to personal and group interests and thus are very difficult to accept for individuals and groups that may lose influence and resources.
- Life cycle thinking favors long-term thinking over short term and therefore is in contradiction to many aspects of current formal economy.

It is here recognized that life cycle thinking as defined above is extremely broad and impossible to cover satisfactorily here. For this reason, combined with a belief that the physical aspects of life cycle thinking – the world's physical metabolism of energy and materials – are the most burning issues for social stability and welfare in the next decades, the following discussion will be focused on life cycle thinking for improved resource management, here named physical resource life cycle thinking (PR Life Cycle Thinking).

PR life cycle thinking emphasizes that raw materials and energy may be used and emissions produced in many different places and parts of the world as a consequence of operating a production and consumption system. It is thus not enough to discuss the raw material use and emissions in a specific place. Instead, all the different phases in a combined production and consumption chain need to be recognized. In PR life cycle thinking, energy as well as materials metabolism as well as broader implications of them, such as environmental impacts and economic and social implications, are considered. From early life cycle–oriented research, it has become clear that an increased reuse and recirculation of products and materials will result in a lower overall resource use and emissions and thus higher overall efficiency. In the future, a decreased raw material use, decreased waste production, and increased recycling of materials may therefore be foreseen as illustrated in Fig. 46.4.

In Fig. 46.4, the traditional picture of a life cycle of a product system is depicted. It is important to note that this way of illustrating the life cycle has no spatial (geographical) connection or definition. This fact – that the traditional LCA does not locate the resource use and the emissions of a product or service system – has been a problem in some applications of life cycle thinking and LCA methodology. A different means of expressing a life cycle system has been used in education at KTH, The Royal Institute of Technology, Stockholm. This way of discussing a life cycle defines three principal stages in the life cycle with a special emphasis on the so-called core system (cf. Eriksson and Frostell 2000). Depending on who is the principal stakeholder – the stakeholder interested in the inventory (and assessment)

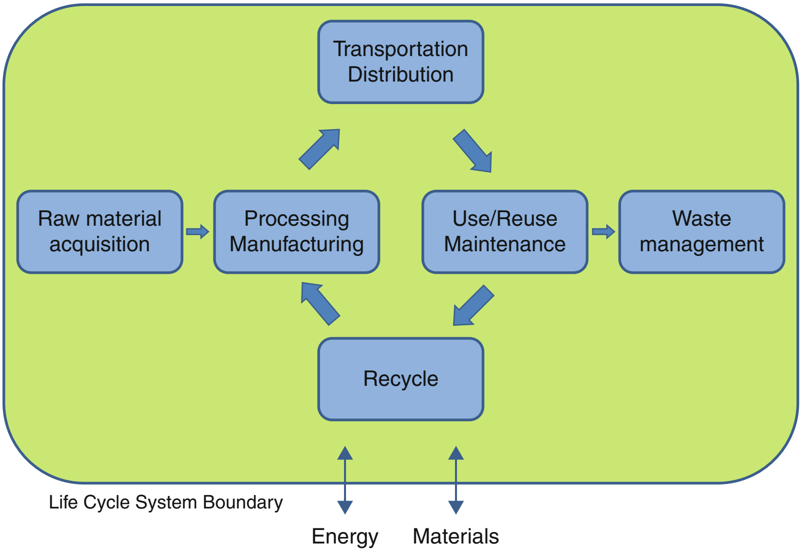

Fig. 46.4 The principal life cycle of a product (rearranged and developed from SETAC 1991)

of the entire life cycle system – the core system represents the part of the life cycle that belongs to this principal stakeholder. The core system therefore could be, for example, a product line in a factory in a production/consumption chain, a factory in a production/consumption chain, a service system, or a waste management system in a production/consumption chain.

5 Life Cycle Assessment

Life cycle assessment has gradually developed into a highly standardized procedure for assessment of environmental impacts of a product or a service (cf. ISO 2006a, b). Many commercial tools for routine LCA are available and the European Commission has published an evaluation of different approaches to LCA (Reimann et al. 2012). In the previously mentioned recent review of LCA, Finnveden et al. (2009) points at a few important challenges of current LCA practices. The most important of them were considered to be the following:

- The product system is extended in time and space, and the emission inventory is often aggregated in a form which restricts knowledge about the geographical location of the individual emissions.
- The LCA results are also typically unaccompanied by information about the temporal course of the emission or the resulting concentrations in the receiving environment.

- The functional unit of the LCA refers to the assessment of an often rather small unit.
- The LCA thus has to operate on mass loads representing a share (often near infinitesimal) of the full emission output from the process.

Now that LCA is more widely used, the methodology sees other and perhaps more serious problems and challenges. While doubtlessly having contributed to a revolution in systems thinking, the practical application of LCA has several shortcomings, for example, (i) the current methodology for LCA demands both categorization of material and energy flows into a number of impact categories that in practice typically are picked in a rather arbitrary way (an arbitrary selection of impact categories in practical LCAs), often based rather on the availability of data than on relevance, (ii) the necessity to pull the assessment through the impact stage requires considerable extra skills and work by the assessing industry or agent, and (iii) when gradually more complex systems are being assessed, the system boundaries become more and difficult to identify and the assessor faces the challenge to assess life cycles in different dimensions (see more below).

6 Different Footprint Approaches and Their Applications

6.1 The Ecological Footprint

The first footprinting concept that reached a broad worldwide recognition was the ecological footprint (EF). Originally developed by Wackernagel and Rees (1996), it has developed into a worldwide activity of accounting, where national footprints are estimated and summed up to a global footprint by the Global Footprint Network (GFN 2012).

The ecological footprint is a very pedagogic and illustrative indicator of ecologic sustainability. It is calculated as the land area needed to provide current social products and services in a sustainable way (with the best available technology; Wackernagel and Rees 1996). The EF calculated is compared with the available land area, and if the latter is smaller than the EF, the current situation is unsustainable. EFs may be calculated for the world, nations, regions, individuals, and other entities. Very obvious from EF calculations is that cities need a much larger area than they occupy themselves and thus are totally unsustainable if not connected to rural areas where resources for the city can be produced.

Alarmingly, according to the EF indicator, the world grand EF is larger than the available productive land area on Earth (app. 30% larger). If all people on Earth lived as in the west, we would currently need four to five earths according to the EF method. Besides footprints as discussed above, the EF network calculates, publishes, and discusses the so-called EF overshoot day. The EF overshoot day is that calendar day of the year when the EF of that actual year is larger than the available land area to serve the global population under current living conditions. Calculated according to the EF methodology, the world overshoot day comes earlier and earlier each year, indicating that from an ecological point of view, we are still departing from a more sustainable development despite more than 20 years of intense debate and many years of political commitments to work for a more sustainable development.

The EF methodology has been criticized as being nonscientific and thus not a reliable indicator (cf. Van den Bergh and Verbruggen 1999; Ayres 2000). Fiala (2008) criticizes it as (i) assuming zero greenhouse gas emissions in the technologies used, (ii) using national and regional boundaries for footprint calculations that do not account for the flexibility of the current global economy, and (iii) not considering productivity increases in agriculture and thus not allowing showing the possibilities of intense agriculture. He proposes to use methods that account more directly for physical phenomena such as emissions of carbon dioxide and degradation of land. Nevertheless the EF has reached a widespread application globally, thanks to its very pedagogic name and indicator (a physical area).

6.2 Energy Footprint

An interesting way to assess ecological sustainability is in terms of energy and mass balances over different system scales, for example, industrial products and product systems, industrial processes, or for geographical areas. For energy, this may be done in the form of different so-called energy footprints, mapping of energy turnover in larger systems in a more holistic way.

Probably due to the broad recognition of the ecological footprint concept, the energy footprint concept has been much associated with the EF methodology. Here, the energy footprint is a measure of land required to absorb the CO_2 emissions from a certain human activity, for example, producing a product, running a product system, running a region or a nation. Important in connection with this type of energy footprint is the fact that it is not the actual energy need that is estimated but the area required to absorb the emissions. This may give rise to ambiguities in the discussion of the actual energy used in the process. An advantage of the approach is that a system with renewable energy supply would result in a smaller footprint than the same system operated with “dirty” energy.

An alternative use of the term “energy footprint” was in a project at the University of Southampton. The aim here was to look at the energy footprint for waste management. The project brought together data on waste quantities, material flows and made mass balance studies for a range of materials including glass, paper, plastics, metals, and organics. These data were combined with information on the energy use for different types of collection and processing systems for reuse, recycling, recovery, and disposal of waste. Also considering energy recovery from any of these options, the information was used to produce an energy and materials balance, and the results showed an “energy footprint” and materials output of the current waste management practices in Southampton (Dacombe et al. 2004). This use of the term thus was connected to the actual energy turnover in different parts of the studied system.

The energy footprint is probably the least spread footprint method. A method for energy footprinting has been developed and marketed by the US consultant

Energetics. Their method is based on energy flow studies in different industries and on development of energy balances. One study focused on the chemical industry energy footprint (Energetics 2012) and was much recognized. Triantou (2009) used LCI cradle to gate system boundaries to calculate energy, carbon, and water footprints for three AkzoNobel plants producing chemicals for the pulp and paper industry.

6.3 Carbon Footprint

The Greenhouse Gas Protocol (GFN 2012) is an accounting tool for governments and business leaders to understand, quantify, and manage greenhouse gas emissions. For more than a decade, the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD) have cooperated with different stakeholders to develop the idea and use it together with businesses, governments, and environmental groups for combating climate change.

The GHG protocol is supplemented by a number of electronic calculation tools, freely available on the *GHG Protocol website* (www.ghgprotocol.org/). Guidance on calculating GHG emissions from specific sources (e.g., stationary and mobile combustion, process emissions) and industry sectors (e.g., cement, pulp and paper aluminum, iron and steel and office-based organizations) is also provided. It covers the accounting and reporting of the six greenhouse gases covered by the United Nations Framework Convention on Climate Change.

The carbon footprint is a measure of the total releases of climate impact gases caused by a business activity or for a product. It may be regarded as a simplified LCI (life cycle inventory) of carbon (or carbon dioxide equivalents) for the activity or product. As such, in practice, it may be calculated in different ways. A first attempt to create a standard for carbon footprinting was presented in a first edition of *The Greenhouse Gas Protocol: A Corporate Accounting and Reporting Standard*, published in 2001 and revised in 2004 (GGPI 2012).

The standard is based on reporting three types of direct and indirect emissions and covering six greenhouse gases (CO_2, CH_4, N_2O, SF_6, HFCs, and PFCs). For each of the emissions considered in the carbon footprint, the contribution from the above-mentioned six compounds is calculated in the form of CO_2 equivalents and added up to the footprint.

Scope 1: Direct GHG emissions (Mandatory to report)
- Generation of electricity, heat, or steam.
- Physical or chemical processing.
- Transportation of materials, products, waste, and employees.
- Fugitive emissions. These emissions result from intentional or unintentional releases, for example, equipment leaks from joints, seals, packing, and gaskets.

Scope 2: Specific indirect emissions (Mandatory to report)
- District heating and purchased electricity

Scope 3: Other indirect GHG emissions (Voluntary to report)

- Employer's flights and work travel
- Purchased transportation services
- Suppliers share of emissions

In Fig. 46.6, the carbon footprint methodology according to GHG protocol has been compared to a principal LCI, dividing the entire life cycle of a product, a process, or a service into the three stages core system, upstream system, and downstream system. Here it is clear that the carbon footprint methodology to an important part covers an LCI of climate gases (climate impact LCI), but also that potentially important flows are non-mandatory or not considered. Of flows considered are, for example, carbon emissions to water and in waste, that later could be transformed to CO_2 in biological and chemical processes and cause secondary impact. It would therefore be tempting to have a more stringent definition of the carbon footprint, preferably in line with a strict life cycle inventory of carbon.

6.4 Water Footprint

The water footprint (WF) analysis may serve as an indicator of overall water use for a certain product or service chain, but may also be used to indicate water consequences of global trade and its links to water resources management. Hoekstra and Hung (2005) showed that over the period 1995–1999, at least 13% of the water used for crop production was not used for domestic consumption but was exported to other countries in virtual form. An important outcome of this finding was the argument that virtual water trade between nations and even continents could improve global water efficiency and enhance water security in water-scarce regions; instead of producing water-intense products, water-scarce countries could adopt a strategy to import them.

Industry has been increasingly interested in understanding, applying, and adapting WF methodologies in order to manage production and supply-chain water issues. By definition, the WF of a product or a product supply chain is the total volume of freshwater used in all parts of the product or supply chain – generally expressed per year or per ton of product. WF thus reflects a life cycle perspective, providing an overall estimate of a product's water requirements. Besides being used for industrial water management, calculation of WF is also feasible for different groups of consumers (individual, family, municipality, nation etc.).

Besides for products and community groups, a WF can also be calculated for different business operations, giving a picture of both a company's freshwater requirements and water use at the product or service scale, offering a business sustainability indicator (Chapagain and Orr 2009). A corporate or business WF here corresponds to the total volume of freshwater used directly or indirectly to operate and support the business; it comprises two components: the operational or direct WF and the supply-chain or indirect WF (cf. Gerbens-Leenes et al. 2009).

The WF analysis is a geographically connected indicator system; the volumes of water used and polluted are shown both in quantities and locations. Attempting to track all relevant water uses of a product or service chain is analogous to life cycle studies (LCI studies), although following a novel accounting. The methodology of WF calculation theoretically comprises three components: the green water use (green WF), the blue water use (blue WF), and the use of water to assimilate pollution (gray WF). These three components have different characteristics, and so it is proposed that their values, weighed equally in calculating the total WF, are presented explicitly along with the total WF (Hoekstra 2008).

Green water is rainwater stored in soil, and blue water consists of surface and ground water resources. The difference is obvious if one considers that the green water can only be used in a productive way for crop production and by the ecosystem itself. On the other hand, blue water can be withdrawn to irrigate crops, but can also have other industrial and domestic end-uses. It is emphasized that water use as calculated with the WF methodology, especially for the blue component, has a different meaning than in life cycle assessment (LCA); thus, consumptive and degrading use that intervenes with the local hydrological cycle and stands in conflict with other uses, including the ecosystem, is in focus. This is in contrast to the traditional withdrawal or consumption accounting in LCA.

The so-called gray water should – according to the methodology developers – be calculated as the water volume needed to dilute pollutants to the extent that water quality standards are met. This means that the gray water is a fictive water quantity, normally much larger than the actual volume discharged to the environment. This has raised an intense debate among members of the rapidly expanding WF community and will be further discussed below; a plant with extensive wastewater treatment and following the national and local laws and regulations, for instance, could very well have to add a considerable part of its water footprint from gray water with the suggested definition.

In many ways, this new method appears to be very well suited when it comes to understanding and addressing water-related resource management issues and risks. Several companies, primarily from the agro-industrial and the food sector, are working hard to put it into practice as a management indicator. Methodological challenges, impact assessment and gray water calculation to name two, are still not resolved in a satisfactory way, but with more effort and more actors involved, a common standardized WF methodology will most probably be settled. Additionally, the interest in finding a common approach to LCA and WF – perhaps in a common tool – is growing (Koehler 2008; Pfister et al. 2009; Canals et al. 2009).

7 Discussion

Life cycle thinking is a broader means of thinking than ordinary management thinking. More and more, it may be argued that it is a necessary intellectual basis to reach a more sustainable development in a globalized world. In its broadest sense, it involves many different dimensions of human life, human activities, and their embedment in the globe system. The practical application of life cycle thinking is still in its infancy and involves many, many different activities, practices, methods, and tools. Emanating from the physical resource side, most of the discussion hitherto has focused on the ecological aspects of life cycle thinking. Important starting points in this discussion have been the industrial metabolism concept (cf. Ayres 1994) and life cycle assessments as discussed above. The European Union Joint Research Centre defines life cycle thinking in the following way: *Life Cycle Thinking (LCT) seeks to identify possible improvements to goods and services in the form of lower environmental impacts and reduced use of resources across all life cycle stages* (European Commission 2012a). UNEP takes a somewhat broader approach and says that life cycle thinking *. . . is about going beyond the traditional focus on production sites and manufacturing processes so that the environmental, social, and economic impact of a product over its entire life cycle, including the consumption and end of use phase, is taken into account* (UNEP 2012; cf. UNEP 2004). An important point in this chapter is that life cycle thinking needs to develop in all areas of human activity, now that we live in a globalized economy.

7.1 Emanating Life Cycle Thinking in Regulation

To some extent, life cycle thinking may still be regarded as somewhat irrational in ordinary business activities, since no economic laws, business operations, environmental permits, or other regulations require it. An important first step, however, toward a more mandatory life cycle thinking may be found in the so-called extended producer responsibility (EPR) concept that has gradually been introduced in the environmental laws in different countries. OECD defines EPR as *an environmental policy approach in which a producer's responsibility, physical and/or financial, is extended to the post-consumer part of the product's life cycle* (OECD 2001). In Sweden, that has been a forerunner in this area, EPR has been introduced in regulation of the following six product groups (cf. SEPA 2005):

- Packages
- Batteries
- Cars
- Electronics
- Drugs
- Radioactive products and noncontrolled radiation sources

In Sweden, the EPR involves a mandatory requirement for producers to collect and handle used products in an environmentally responsible way. It is an instrument to reach the national environmental goals and the aim is to motivate producers to develop products that are less resource demanding, easier to recycle, and do not contain hazardous compounds.

From a principal point of view, it is interesting to note that the ERP initiative only extends the responsibility from the core system to the downstream system in the principal life cycle system depicted in Fig. 46.5. Nothing is stated about the upstream system and thus the life cycle thinking in ERP is only partial.

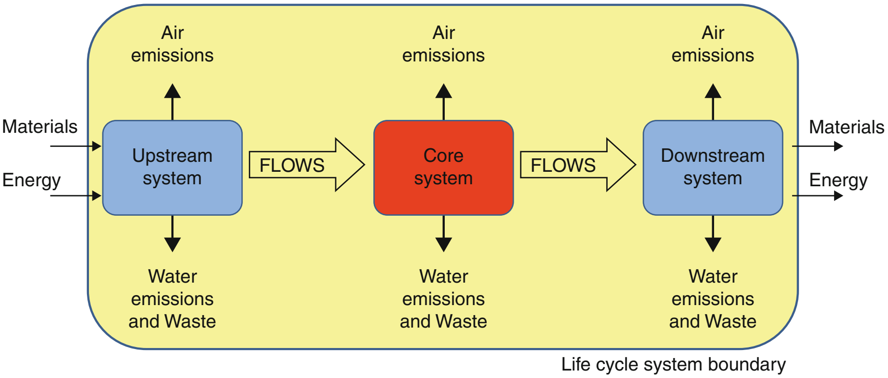

Fig. 46.5 An illustration of physical resource life cycle thinking (PR life cycle thinking) emphasizing the core system complemented by an upstream and a downstream system and thus allowing a geographical connection of life cycle thinking. The core system is always subject to mandatory environmental impact assessment (EIA), legal permits, and legal reporting practices

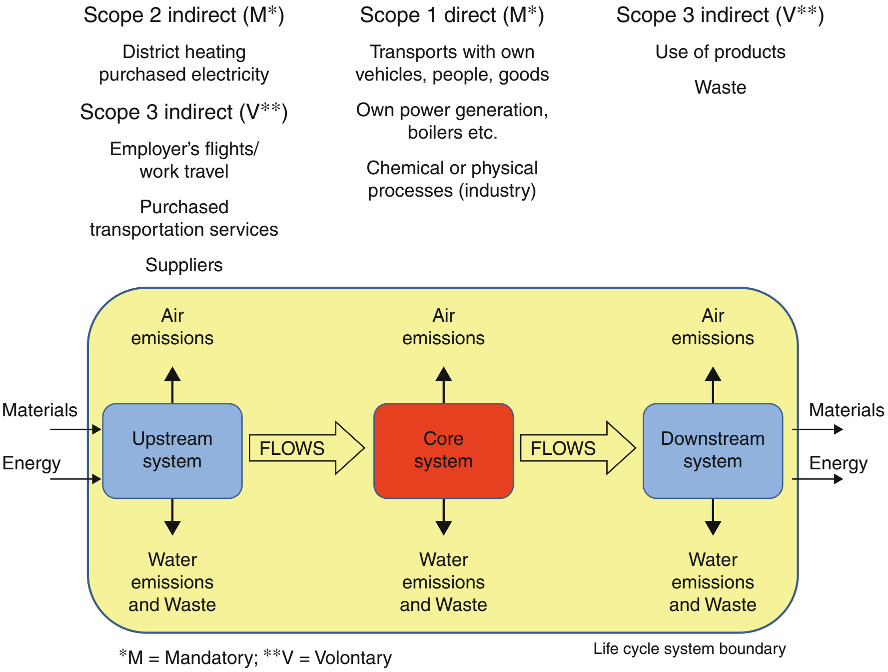

Fig. 46.6 Comparison between the GHG Network definition of carbon footprint ingredients and a division of the life cycle of products, processes, and services in an upstream, a core and a downstream system, permitting also a geographical allocation of metabolism

7.2 System Boundaries, LCA, and Life Cycle Thinking

System boundary discussions represent an important aspect of LCA and life cycle thinking. The system boundaries define what is included in an appraisal or assessment and what is excluded. When a studied system is small and easily understood, the system boundaries are rather easy to identify and communicate. With LCA – that in itself by definition represents a system broadening – system boundaries increasingly cause discussion and problems. Guinée et al. (2002) identified three major types of system boundaries in the LCI phase of LCA:

- Between the technical system and the environment
- Between significant and insignificant processes
- Between the technological system under study and other technological systems

Finnveden et al. (2009) have a broad discussion of these three types of system boundaries. They also mention time and geographical limits as potential boundaries, but regard them as special cases of boundaries toward the environment or other technological systems.

In application of LCA, the goal and scope definition phase in practice also involves a system boundary definition and that implies selection of impact categories. An inherent practical problem for all LCA applications is the difficulty to include all impact categories in the study, most typically because of difficulties with data availability. Thus, in a typical LCA study, only four to five impact categories are included, despite at least ten would have a relevance for the outcome of the study. Which are the main influencing factors in this delimitation of LCAs – and thus definition of system boundaries – that always take place? Which impact do they have on the final result and on the conclusions to be drawn?

Further broadening the discussion to general life cycle thinking, the identification, decision, and implementation of system boundaries into practices form a formidable task. This is since from a principal point of view, at least the following system boundaries will have to be considered in life cycle thinking:

- What principal pillars of sustainability shall be included in the study (the procedure) – economical, ecological, social?
- In what ways will the economical, ecological, and social pillars be characterized? Impact categories, flows and stocks calculations, qualitative characterizations of different aspects, by other means?
- How many different impact categories (flows and stocks; aspects) shall be used for each pillar of sustainability? Which impact categories (flows and stocks; aspects) should be selected?
- How shall the retrieved information be processed and communicated? Per functional unit (LCI/LCA), per decision/responsibility unit (accounting approach, per geographical unit, others?
- How shall the cutoff issues be handled (decisions on where to stop data retrieval, how to allocate between different products/functions, how to handle compensatory functions included to make a comparative study more appropriate)?

Looking at the system boundary challenges described above, it becomes clear that LCA and its discussion cover only a part of life cycle thinking. This makes the selection and use of methods and tools for life cycle thinking even more difficult and delicate than LCA application. Thus, it will be very important to find broadly accepted approaches to practical application of life cycle thinking.

7.3 Data Availability, LCA, and Life Cycle Thinking

Data availability has for long been a problem in practical application of LCA and generally for systems oriented quantitative analyses based on life cycle thinking. This situation is rapidly improving for LCA with a number of initiatives at national (Australia, Japan, Korea, Singapore, Taiwan, Denmark, Sweden, Switzerland, Canada, and USA; cf. Curran and Notten 2006) and business raw material level (aluminum, copper, iron, and steel, plastics, paper, and board; cf. Finnveden et al. 2009). Curran and Notten (2006) prepared a summary of global life cycle inventory data resources on behalf of SETAC/UNEP. It is a thorough compilation of ongoing activities in the world until 2006.

The European Reference Life Cycle Database (ELCD core database) has been compiled and improved into a version II by the EU Joint Research Centre's Institute for Environmental and Sustainability (IES), a work that was presented in early 2009 (European Commission 2012b). The database contains life cycle inventory (LCI) data from different EU-level business associations and other sources. Data are provided for key materials, such as energy carriers, transport, and waste management and a special focus is on data quality, consistency, and applicability.

The EU LCA Tools, Services and Data homepage (European Commission 2012c) is an ambitious resource with extensive information on available methods, tools, and databases for LCA practitioners.

Besides these governmental and industrial branch initiatives, there have been a great number of different LCA tools developed, sometimes offered for free and sometimes for a license fee. Often, commercial suppliers of LCA software have their own databases, access to which forms an important part of the licensing idea. Two important commercial tools are Simapro (PRé Consultants 2012) and Gabi software (Gabi 2012). It is very interesting to note that Gabi software at the moment offers software for a number of different life cycle thinking–related calculation tools according to the following list (Gabi 2012):

- Life cycle assessment according to ISO 14040/14044
- Product carbon footprint
- Design for environment and ecodesign
- Environmental product declarations
- Resource and energy efficiency
- Water footprint

Table 46.1 Potential uses of life cycle thinking and LCA by different stakeholder groups (inspired by Wentzel et al. 1997)

Stakeholder group	Application	Examples
Central and local governments	Policy formulation	Resource accounting policies Product policies
	Community action plans	Incineration versus recycling
	Environmentally conscious Public Purchases	Cars, office supplies
	Consumer information	Ecolabels and Standards
Business	Monitoring of progress in a broader perspective than currently practiced	Footprints of different kinds, e.g., energy, carbon, and water Monitoring of social aspects of the business
	Raise environmental awareness	Identify areas for improvement
	Broadening of management	Product-oriented environmental policies Environmental management
	Design choices	Concept selection, Component selection, Material selection, Process selection
	Environmental documentation	ISO certification, Ecolabels
Academia	Research on products, services, and sociotechnical systems	Knowledge formation Method development
	Education	LCA courses
NGOs and the public	Consensus development	Own assessments in preparation of public hearings
	Education	Reports and results dissemination

7.4 Current and Potential Future Applications of Life Cycle Thinking

With the broad definition of life cycle thinking used here, the number of potential applications is very high. Hardly any research, development, or practical work area will do without it. It should become at the center of all future resource management discussions, be they physical or social resources in line with Figs. 46.1 and 46.2. A compilation of potential uses of life cycle thinking is presented in Table 46.1.

8 Summary

From ecologically oriented research, there is now overwhelming evidence that current actions and plans of the global community threaten the survival of civilization in its present form. The world is caught up in a growth paradigm – based on a rapid extraction and use of natural resources, mainly fossil energy and mineral resources, combined with excessive emissions to air, water, and soil of rest materials. This cannot be sustained in the long run without a radical shift in functioning of the system (cf. Ayres 1998). Current economic theory and practices have failed to address this challenge in a satisfactory way, and new theories and practices for improved overall resource management need to be invented and implemented. A promising new conceptual approach to improved resource management is life cycle thinking – the understanding that actions in one place may cause resource use and emissions in many other places on earth. This new conceptual approach has led to the development of LCA, a method to assess the overall environmental impacts of products and services. While increasingly supporting the development of more resource-efficient product and service systems, LCA has failed to support many other areas where an improved resource management is important, for example, organizations and infrastructure systems. For this, there is an urgent need to arrive at improved information collection, accounting, and reporting practices. A recent more popular concept is to discuss different footprints of human action. Several different approaches to so-called footprint analyses have been discussed and promoted, such as ecological footprints, water footprints, carbon footprints, and energy footprints. The scientific stringency of these new approaches – as discussed within different scientific disciplines – is, however, from an overarching industrial ecology point of view many times doubtful. It is therefore necessary to develop scientifically more stringent and quantitative metrics for footprints of different kinds, be they, for example, energy footprints, carbon footprints, water footprints, nitrogen footprints, phosphorus footprints, and others. These footprints could from a scientific point of view very well be based on the principles for LCI (life cycle inventory) of material and energy flows and stocks. Three primary candidates for increased footprinting work should perhaps be energy, carbon, and water footprints.

References

R.U. Ayres, Industrial metabolism: theory and policy, in *Industrial Metabolism: Restructuring for Sustainable Development*, ed. by R.U. Ayres, U.K. Simonis (United Nations University Press, Tokyo, 1994), p. 3

R.U. Ayres, Toward a zero-emissions economy, *Environmental Science & Technology/News*, 1 Aug 1998, p. 366

R.U. Ayres, Commentary on the utility of the ecological footprint concept. Ecol. Econ. **3**, 347 (2000)

H. Baumann, A.-M. Tillman, *The Hitch Hiker's Guide to LCA, An Orientation in Life Cycle Assessment Methodology and Application* (Studentlitteratur, Lund, 2004)

I. Boustead, LCA – how it came about, the beginning in the UK. Int. J. Life Cycle Assess. **1**(3), 147 (1996)

I.L.M. Canals, J. Chenoweth, A. Chapagain, S. Orr, A. Antón, R. Clift, Assessing freshwater use impacts in LCA: part I – inventory modelling and characterisation factors for the main impact pathways. Int. J. Life Cycle Assess. **14**(1), 28–42 (2009)

A.K. Chapagain, S. Orr, An improved water footprint methodology linking global consumption to local water resources: a case of Spanish tomatoes. J. Environ. Manage. **90**(2), (2009)

R. Clift, Engineering for the environment: the new model engineer and her role. Trans. IChemE **76B**, 151 (1998)

M.A. Curran, P. Notten, Summary of global life cycle inventory data resources, report for SETAC/UNEP life cycle initiative, task force 1: database registry (2006), www.epa.gov/NRMRL/lcaccess/pdfs/summary_of_global_lci_data_resources.pdf

P. Dacombe, V. Krivtsov, C. Banks, S. Heaven, in *An Energy and Materials Flow Model for Evaluation of Alternatives for Processing Domestic and Commercial Waste – A Case Study of Southampton*, School of Civil Engineering & the Environment, University of Southampton, Southampton, 2004, 171p

J. Elkington, Enter the triple bottom line, in *The Triple Bottom Line: Does It all Add Up*, ed. by A. Henriques, J. Richardson (EarthScan, London, 2004)

Energetics (2012), Manufacturing Energy and Carbon Footprint, www.energetics.com/resourcecenter/products/misc/Documents/chemicals_footprint.pdf

O. Eriksson, B. Frostell, An approach to sustainability assessment of energy systems, in *Chapter 14 in Building Sustainable Energy Systems – Swedish Experiences*, ed. by S. Silveria (Swedish National Energy Administration, Stockholm, 2000)

European Commission, European Platform on Life Cycle Assessment (2012a), http://lca.jrc.ec.europa.eu/

European Commission, ELCD core database version II (2012b), http://lca.jrc.ec.europa.eu/lcainfohub/datasetArea.vm

European Commission, LCA Resources Directory (2012c), http://lca.europa.eu/lcainfohub/directory.vmnormally

N. Fiala, Measuring sustainability: why the ecological footprint is bad economics and bad environmental science. Ecol. Econ. **67**, 519 (2008)

G. Finnveden, M.Z. Hauschild, T. Ekvall, J. Guinée, R. Heijungs, S. Hellweg, A. Koehler, D. Pennington, S. Suh, Recent developments in Life Cycle Assessment. J. Environ. Manage. **91**, 1 (2009)

Gabi (2012), http://www.gabi-software.com

P.W. Gerbens-Leenes, A.Y. Hoekstra, Th. Van der Meer, The water footprint of energy from biomass: A quantitative assessment and consequences of an increasing share of bio-energy in energy supply, Ecol. Econ. 68, 1052 (2009)

GFN, Global Footprint Network (2012), www.footprintnetwork.org/en/index.php/GFN/

GGPI, The Greenhouse Gas Protocol Initiative (2012), www.ghgprotocol.org/

B. Giddings, B. Hopwood, G. O'Brian, Environment, economy and society: fitting them together into sustainable development. Sustain. Dev. **10**(4), 187 (2002)

J.B. Guinée, M. Gorrée, R. Heijungs, G. Huppes, R. Kleijn, A. de Koning, L. van Oers, A. Wegener Sleeswijk, S. Suh, H.A. Udo de Haes, J.A. de Bruijn, R. van Duin, M.A.J. Huijbregts, *Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards*. Series: Eco-efficiency in Industry and Science (Kluwer Academic Publishers, Dordrecht, 2002)

A.Y. Hoekstra, Water neutral: reducing and offsetting the impacts of water footprints, Value of Water Research Report Series No. 28, UNESCO-IHE (2008)

A.Y. Hoekstra, P.Q. Hung, Globalization of water resources: international virtual water flows in relation to crop trade. Global Environ. Change **15**, 45 (2005)

ISO, ISO 14040 International standard, in *Environmental Management – Life Cycle Assessment – Principles and Framework*, International Organisation for Standardisation, 2006a

ISO, ISO 14044 International standard, in *Environmental Management – Life Cycle Assessment – Requirements and Guidelines*, International Organisation for Standardisation, 2006b

A. Koehler, Water use in LCA: managing the planet's. Int. J. Life Cycle Assess. **13**, 451 (2008)

J. Lubchenko, Entering the century of the environment: a new social contract for science. Science **279**, 491 (1998)

OECD, *Extended Producer Responsibility – A Guidance Manual for Governments* (OECD, Paris, 2001)

S. Pfister, A. Koehler, S. Hellweg, Assessing the environmental impacts of freshwater consumption in LCA. Environ. Sci. Technol. **43**, 4098 (2009)

PRé Consultants, SimaPro LCA software (2012), www.pre.nl/default.htm

K. Reimann, M. Finkbeiner, A. Horvath, Y. Matsuno, Evaluation of environmental life cycle approaches for policy and decision making support in micro and macro level applications, editors and project supervisors: U. Pretato, D. Pennington, R. Pant, European Commission Joint Research Centre, Institute for Environment and Sustainability (2012), http://lct.jrc.ec.europa.eu/

SEPA, *A Strategy for Sustainable Waste Management – Sweden's Waste Plan*, Swedish Environmental Protection Agency (2005), http://www.naturvardsverket.se/Documents/publikationer/620-1249-5.pdf

SETAC, *A Technical Framework for Life Cycle Assessments* (Society for Environmental Toxicology and Chemistry, Washington DC, 1991)

Stern Review, The Economics of Climate Change, executive summary (full) (2006), www.hmtreasury.gov.uk/stern_review_report.htm

L. Strandberg, B. Frostell, Sustainable development – a multitude of concepts, tools and metrics for good or bad? in *Science for Sustainable Development – Starting Points and Critical Reflections, Proceedings 1st VHU Conference*, Västerås, 2006

A. Triantou, Carbon, Energy and water footprint of three AkzoNobel internal sizing chemicals: a Cradle to Gate LCA related study, M.Sc. Thesis in Industrial Ecology, Royal Institute of Technology, Stockholm, 2009

UN, United Nations General Assembly resolution on World Summit on Sustainable Development, resolution No. A/C.257/L.83, adopted 10 Dec 2002

UNEP, *Why take a Life Cycle Approach* (UNEP, Paris, 2004)

UNEP, United Nations Environment Programme (2012), www.unep.org/Documents

J.C.J.M. Van den Bergh, H. Verbruggen, Spatial sustainability, trade and indicators: an evaluation of the 'ecological footprint'. Ecol. Econ. **29**, 61 (1999)

P.M. Vitousek, H.A. Mooney, J. Lubchenco, J.M. Melillo, Human domination of earth's ecosystems. Science **277**, 494 (1997)

M. Wackernagel, W. Rees, *Our Ecological Footprint – Reducing Human Impact on the Earth* (New Society Publishers, Gabriola Island, 1996)

WBCSD, World Business Council for Sustainable Development (2012), www.wbcsd.org/home.aspx

WCED (World Commission on Environment and Development), *Our Common Future* (Oxford, Oxford University Press, 1987)

H. Wentzel, M. Hauschild, L. Alting, *Vol. 1: Methodology, Tools and Case Studies in Product Development*. Environmental assessment of products (Chapman & Hall, London, 1997)

World Bank, Gross domestic product 2009, Gross domestic product ranking table based on Purchasing Power Parities (2012), http://data.worldbank.org/data-catalog#Tables