高等学校规划教材·化学

PROGRAMMING TEXTBOOKS FOR HIGHER EDUCATION

高分子材料的环境影响评价和可持续发展

THE ENVIRONMENTAL IMPACT EVALUATION FOR POLYMERS AND SUSTAINABLE DEVELOPMENT

陈立新　顾军渭　孔杰　陈芳　编

Edited by Chen Lixin，Gu Junwei，Kong Jie and Chen Fang

西北工業大學出版社

高等学校规划教材·化学

The Environmental Impact Evaluation for Polymers and Sustainable Development

高分子材料的环境影响评价和可持续发展

Edited by Chen Lixin, Gu Junwei, Kong Jie and Chen Fang

陈立新　顾军渭　孔　杰　陈　芳　编

西北工业大学出版社

图书在版编目(CIP)数据

高分子材料的环境影响评价和可持续发展/陈立新等编.—西安:西北工业大学出版社,2013.9

ISBN 978-7-5612-3840-0

Ⅰ.①高… Ⅱ.①陈… Ⅲ.①高分子材料—环境影响—评价 ②高分子材料—可持续性发展 Ⅳ.①TB324

中国版本图书馆 CIP 数据核字(2013)第 233626 号

出版发行:西北工业大学出版社
通信地址:西安市友谊西路 127 号　　**邮编**:710072
电　　话:(029)88493844　88491757
网　　址:www.nwpup.com
印 刷 者:兴平市博闻印务有限公司
开　　本:787 mm×1 092 mm　　1/16
印　　张:15
字　　数:365 千字
版　　次:2013 年 9 月第 1 版　　2013 年 9 月第 1 次印刷
定　　价:32.00 元

前　　言

目前高分子材料已普遍应用于生产、生活、科技等各个领域，人们日常生活中的衣、食、住、行都离不开它，尤其是塑料、橡胶和纤维这三大高分子材料，在我们身边随处可见。同时其在航空、航天、交通运输和生物医学等方面也有突出贡献，已成为本世纪最活跃的支柱材料。但高分子材料的使用期限却使其产品在废弃后产生固体废弃物，对环境产生巨大的影响。

本书针对日常生活中随处可见的高分子材料和产品，运用生命周期方法，将高分子材料和产品划分为七个阶段——生产、使用、废物的产生、消费后废物的回收、再利用、回收和填埋，从环境可持续发展的角度概述了高分子材料在原料合成、产品生产、产品使用和最终废弃中对环境产生的重大影响，确定了减少资源的使用、减少废弃物的产生以及使用后废弃物的回收等优化高分子材料生产和使用过程方面的措施，以保证环境的可持续发展。

本书力图优化高分子材料的生产和使用，使资源消耗最小化，减少废弃物的产生和解决废弃物的回收问题；设计新型高效的方法将回收材料用于新材料的合成及制备中，以便找出高分子材料生产、使用和废弃物管理最佳的适合可持续发展的方法。

本书各章主要内容和编写分工如下：第一章主要介绍可持续发展的概念及生命周期评价方法，由陈立新和顾军渭共同编写；第二章介绍高分子材料的种类、特性、应用以及全世界消费概况，由陈立新和顾军渭共同编写；第三章为高分子基础理论和高分子材料生产中消耗的资源，由孔杰编写；第四章为高分子材料废弃物回收采取的方法，由顾军渭编写；第五章为高分子材料再循环的动力与阻力，由孔杰编写；第六章为再循环对环境造成的影响，由顾军渭和陈芳编写；第七章重点介绍高分子材料可持续发展采取的新技术，由陈立新编写。

本书主要适用于高分子材料与工程、化学工程与工艺和环境科学的本科生，也适用于对高分子材料、高分子材料对环境的影响以及可持续发展等感兴趣的工程技术人员。

在本书的编写过程中，参考了国内外大量图书和文献资料，在此对原作者表示感谢；并对西北工业大学教务处、西北工业大学出版社和西北工业大学理学院在本书出版过程中给予的支持和帮助一并表示感谢。

鉴于水平有限，书中难免存在不足之处，恳请读者批评指正。

编　者

2013 年 2 月

目　录

Chapter 1 Polymers, the Environment and Sustainable Development

1.1 Introduction to Sustainable Development

The idea of *sustainable development* was firstly used in the *World Conservation Strategy* report by the International Union for the Conservation of Nature (IUCN), published in 1980[1-2]. It was followed in 1983 by the Brandt *Commission's Common Crisis* which in effect was the forerunner of, and in many ways formed the basis to, the report *Our Common Future*, published in 1987 by the World Commission on Environment and Development (WCED) led by the former Prime Minister of Norway, Gro Harlem Brundtland. This publication, also known as the Brundtland Report, set the benchmark for all future discussions of sustainable development and gave the most commonly used, working definition of sustainable development. The most frequently quoted definition is taken from the Brundtland report "Our Common Future": "sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs"[3-4]. Along the lines of this definition, sustainable development implies improving the quality of life for all of the Earth's citizens without increasing the use of natural resources beyond the capacity of the environment to supply them indefinitely.

The Brundtland report called for policies which foster economic growth but also satisfy the needs of people and improve quality of life without depleting the environment. This vision of sustainable development required a different attitude to economic development, in which the quantity of growth is replaced by the quality of growth.

The Brundtland report called on governments, local authorities, businesses and consumers to define and adopt strategies for sustainable development. One of the most notable of these activities, instigated as a direct consequence of the emergence of the concept of sustainable development, was the Earth Summit held in Rio, Brazil, 1992. The 1992 Rio Earth Summit was attended by 120 world leaders from 152 countries, and sustainability was enshrined in Agenda 21, a plan of action, and a recommendation that all countries should produce national sustainable development strategies.

In response to the Agenda, many governments and organizations started developing their own plans of action and setting out strategies for sustainable development. Countries such as Sweden, Canada, Germany and the United Kingdom (UK) have already started working towards their own sustainability targets and, more recently, the European Union

(EU) sustainable development strategy has also been adopted. A research project of the Association of Academies of Sciences in Asia (AASA) on the sustainable development in Asia has been launched. China's approach towards sustainable development can be divided into four steps: the formulation of a national strategy, the preliminary establishment of a legal system of the national strategy, the establishment of an institutional framework and the implementation of the national strategy through a national development plan[5].

1.2 Sustainable Development Issues

Sustainable development may be regarded as the progressive and balanced achievement of sustained economic development, improved social equity and environmental quality. This concept has both spatial and temporal dimensions as it must satisfy these three goals equally across the globe for both present and future generations. The field of sustainable development can be conceptually broken into three constituent parts: environmental sustainability, economic sustainability and sociopolitical sustainability. It means resolving the conflict between the various competing goals, and involves the simultaneous pursuit of economic prosperity, environmental quality and social equity famously known as three dimensions of Sustainability.

Figure 1.1 is a representation of sustainability showing how both economy and society are constrained by environmental limits[6].

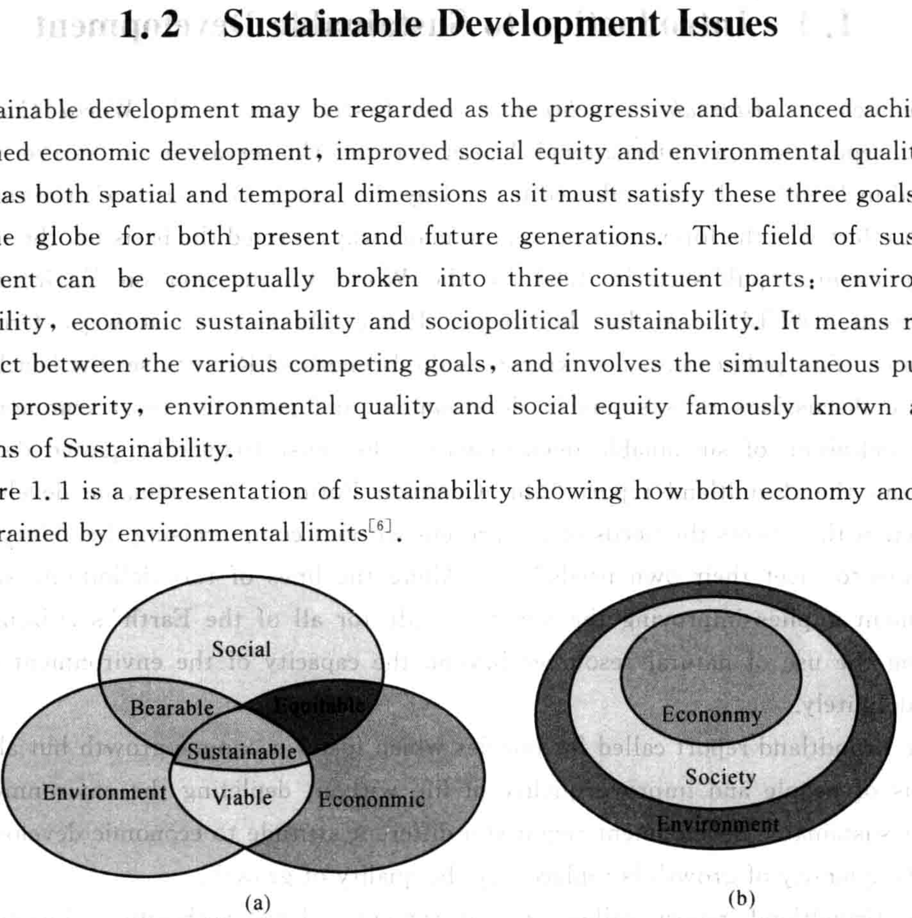

Figure 1.1 Relations on three components of sustainable development

(a) relation on an equal basis; (b) relation of subordination

More than a decade since Rio, there has been little change in poverty levels, inequality or sustainable development, as the World Development Movement describes. "Despite thousands of fine words the last decade has joined the 1980s as another "lost decade for sustainable development" with deepening poverty, global inequality and environmental destruction"[7].

As Lead and Panos highlight, "In the ten years since Rio, sustainable development hasn't been very high on international agendas" and criticizes both rich and poor nations alike: In many countries, rich and poor, this is often because of a perception that sustainability is expensive to implement and ultimately a brake on development[8].

One major issue leading to this happen is global inequality and widespread poverty: 20% of the world's population receives nearly 83% of total world income. There are significant links between poverty and the environmental quality and much of the environmental degradation we see in the developing world arises as a result of people seeking basic essentials of life: food, water, *etc*. On the other hand, environmental problems are a significant cause of poverty and generally hit the poor hardest, *e. g.* a quarter of all diseases are found in developing countries. One of the main causes of environmental degradation, however, is unsustainable development by the rich. The "big seven", *i. e.* USA, Japan, Germany, Canada, France, Italy and the UK, make up less than 12% of the world's population, but consume between 55% and 65% of world resources. If the rest of the world continued to consume the energy resources as the UK does today, we would need eight and a half planets to sustain current global consumption in 2050 (see Figure 1.2). The patterns of consumption and distribution of resources cannot be sustained if, as currently predicted, the world population grows to 10 billion by the end of the 21st century.

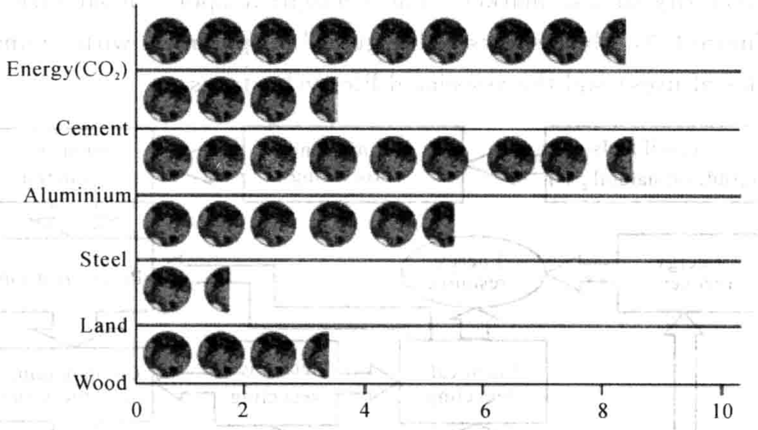

Figure 1.2 Number of planets needed to sustain current global consumption in 2050 if all countries consumed as the UK does

(Key facts for resource consumption: 12% of the world's population consume; 43% of the world's fossil fuel production; 64% of the world's paper; 55%−60% of all the aluminium, copper, lead, nickel and tin)

Coupled with other global environmental problems, such as soil erosion, acid rain, thermal pollution, greenhouse effect, stratospheric ozone depletion, global climate change and biodiversity loss (As the Global Biodiversity Outlook report summarizes, despite numerous successful conservations measures supporting biodiversity, none of the specific targets were met, and biodiversity losses continue), there are clear indications that we are now exceeding the "carrying capacity" of the environment.

This is exacerbated by local or regional issues, such as air pollution and generation of solid waste. For example, some 2.6 Gt of industrial, agricultural and domestic waste is generated each year in Europe alone. The decreasing capacity of landfills and their recognized impact on the environment give waste management a high priority at the local and regional levels. To enable the move towards sustainability on the practical level, it is first necessary to understand these causes of un-sustainability, then to identify more sustainable options and finally to determine how they may be implemented. In doing so, it is paramount that problems and solutions are analyzed by adopting more holistic, life cycle thinking. This requires a paradigm shift from the current, fractured view of the environment, with the emphasis on one stage of the life cycle (*e. g.* the production process), to a whole life cycle approach, which examines the consequences of human activities on the environment from "cradle" (extraction of resources) to "grave" (disposal of waste).

In this book, we adopt such an approach in an attempt to examine the options and contribute towards the practice of sustainable development by addressing two important areas: resource use and waste management. We concentrate on polymeric materials and products, ubiquitous in our everyday life, to try and understand what drives and limits their production, use, re-use and recycling. We will consider a wide range of polymers, but will mainly concentrate on plastic materials, *i. e.* thermoplastics and thermosets, because they constitute the majority of the market. The conceptual approach adopted in the book is illustrated in Figure 1. 3, which shows a "life guide" for polymers with a number of different lives (or cascades of uses) and the associated life cycle stages.

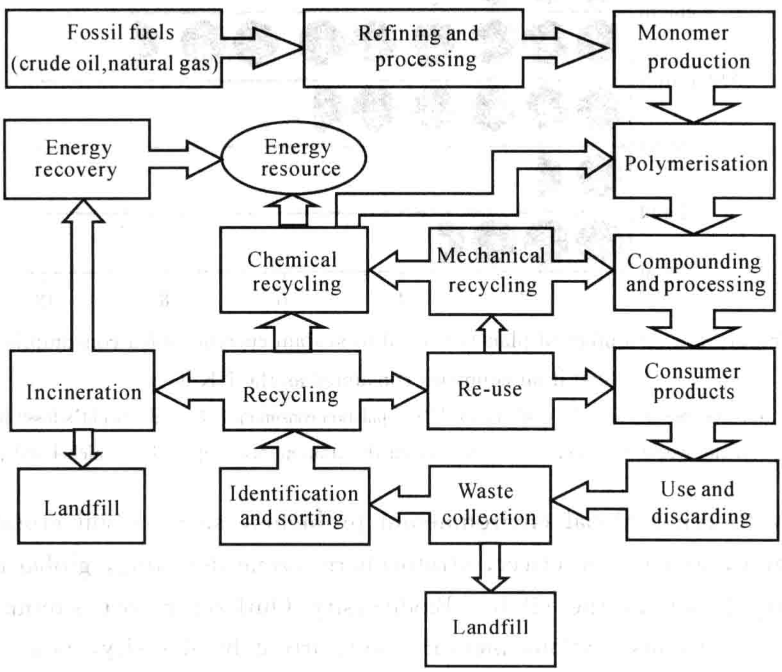

Figure 1. 3　A "life guide": following polymeric materials and products through cascades of uses from "cradle to grave"

(note that both energy and materials are consumed in every life cycle stage)

Before looking into these issues in detail in the chapters that follow, we continue here to examine why polymers may be an issue for sustainable development.

1.3 Polymers: An Issue for Sustainability

The emergence of the concept of sustainable development has once again made fossil fuels an issue, we must therefore rethink our use of such fuels and general consumption patterns into a more sustainable model.

Most synthetic polymers are derived from fossil fuels, *i. e.*, from naphtha or natural gas (see Figure 1.3), which puts them immediately into the environmental "spotlight". Because it is clear that reserves of fossil fuels will run out on time scales relevant to sustainable development, although perhaps not as soon as was predicted in the 1970s. However, scarcity of resources is not the only issue to be considered, since burning fossil fuels affects climate change and it is now widely accepted that the millions of tonnes of CO_2 produced each year by burning fossil fuels are one of the main causes of global warming.

Consumption of fossil fuels and the associated environmental damage have made polymeric materials and products a focus of much attention by various environmental and government groups (see in Figure 1.3). They have argued that polymers use material and energy resources, which are then lost when the polymers are disposed of, usually in landfill. The production process itself also results in a loss of "feedstock" and energy. For example, the production of 1 t of high density polyethylene (HPDE) loses 17.9 GJ of the 71.4 GJ of calorific value in the naphtha feedstock. Put another way, some 40% of the energy of the original crude oil is lost during processing.

However, the consumption of material and energy resources is not the only issue surrounding polymeric materials and products. Because of their widespread use and our "linear" consumption patterns (in which materials and products are used only once and then discarded), polymers also contribute to an ever-increasing amount of solid waste. Since the 1930s, the total world production and consumption of polymers have risen rapidly to reach figures in excess of 100 Mt in 1995, about a quarter of which was produced in Europe. The types of material involved include plastic products (made from both thermoplastics and thermosets), fibres (*e. g.* textiles), elastomers, coatings and adhesives. In Western Europe around 45, mainly multinational companies, produce the basic polymer, which is sold to around 30,000 small- and medium-sized companies. These, in turn, convert the polymer into products for use in many sectors, for example, packaging, automotive parts and electronic equipment. Since 40% of plastics are used for packaging, it is not surprising that this product category has attracted most attention from policy makers and environmentalists. For example, the total plastics consumption in Western Europe in 1999 was 33.5 Mt or 84 kg of plastics per person, 19 Mt of which were available for collection as waste, with the rest remaining in use. Because packaging has a much shorter life than, for instance, plastics used in the construction or automotive industry, it reaches the waste stream much more quickly, which explains the fact that 70% (or 13 Mt) of the total plastics waste that appeared in the same year was packaging.

On average, polymers account for 7%-8% by weight and 20% by volume of municipal solid waste in Europe and elsewhere. Of that, still relatively little is recycled. For example, in Western Europe only 6 Mt or 30% of the total post-consumer waste were recycled in 1999, with the rest going to landfill. Similar trends are found in other parts of the world. Not only does this practice waste valuable resources, but it also has negative impacts on the environment. Very few polymers are biodegradable, so that, once in a landfill, they will remain there occupying space for a long time, according to some estimates, up to 200 years for some polymers. However, some of the additives used to improve polymer properties can leach from a landfill to contaminate the water table; or in poorly managed landfills burning of plastic waste can generate toxic substances and cause air pollution.

Furthermore, as we all know, not all polymer waste reaches the landfill; much of the waste also remains abandoned and scattered in the streets of our cities and towns, as well as in the countryside, affecting the aesthetic aspects of life.

It is thus apparent that continuing with the same "make-use-discard" practice is unsustainable because it leads to generation of waste, loss of resources (material and economic), environmental damage and also raises social concerns. Hence, we need to identify more sustainable practices for polymeric materials and products.

1.4 The Method for Assessing the Impact of Polymer on the Environment: Life Cycle Assessment

1.4.1 The Definition of Life Cycle Assessment

Environmental problems are complex and still not fully understood. There is a need for better solutions to the environmental problems. Thus there is additional cost to the product if it is required to be produced under conditions such that detrimental environmental effects are kept to minimum, *i. e.* green product cost more than usual products. As a consequence, different attempts at developing models to describe environmental impacts have led to different results. Industrial approach to assess the environmental performance of products is termed as *Life Cycle Analysis/Assessment*(LCA)[9-10].

In other words, LCA is a method of comparison of environmental impacts of products, technologies or services with a view to their whole life cycle, so called from cradle to grave. LCA is a technique for assessing the environmental aspects and potential impacts associated with a product over its life cycle, starting at the raw materials extraction through the product manufacturing, until use and final disposal stages (ISO, 1997). Unlike other environmental management tools, such as Environmental Impact Assessment or Environmental Audit, which focus solely on the emissions and wastes generated by the plant or manufacturing site, LCA broadens system boundaries to consider environmental burdens and impacts along the whole life cycle of a product or a process. This holistic approach to environmental system management avoids shifting environmental burdens from one part of the system to another, as can often happen in a more narrow system analysis. For instance, prior to taking a life cycle approach, paper recycling had always been considered an activity that provided an overall benefit to the environment. The usual argument used was that it reduced solid waste and saved trees. However, LCA studies have shown that this is not always the case and that, for example, in Northern Europe paper incineration with energy recovery is environmentally a better option. These at first surprising findings showed something that should have been obvious long before: recycling does not come without cost; it requires energy, materials, chemicals and transportation, all of which generate additional environmental impacts. Furthermore, the argument that paper recycling is "good for the environment" because it saves trees does not apply in Northern Europe because trees are planted purposefully and forests are managed in a sustainable way. Results like these obtained by adopting life cycle thinking and using LCA as a tool, have opened up a completely new debate on how resources should be used, re-used and recycled to the benefit of the whole society and the environment.

As illustrated in Figure 1.4, the life cycle of a product starts from extraction and processing of raw materials ("cradle"), which are then transported to the manufacturing site to produce a product. The product is then transported to the user and at the end of its useful life is either recycled and returned for reprocessing, or is disposed in a landfill ("grave"). The question mark in Figure 1.4 indicates that it may be possible to further extend the "cradle to grave" concept and turn it into "cradle to cradle". This would require going back to our landfill sites and "mining" valuable resources, which were discarded in the past as waste. Although at present this may sound like unfounded optimism, it is worth noting that this is already happening in the metals sector, particularly in North America, where some of the landfills are richer in metals content than some of the primary repositories. Thus, it may be possible that in the future we will be able to close the materials loops completely and so reduce the use of primary resources. However, closing the loop in this way is not helped by the fact that we have mixed the waste prior to depositing it in the ground and that advanced separation technologies are needed if we want to reclaim them. Nevertheless, this may be a good reason to change our current waste management practices and start "storing" different type of waste materials in separate landfill sites. Whatever cannot be re-used and recycled at present, may well become a valuable resource in the future, when more advanced technologies become available to reclaim them.

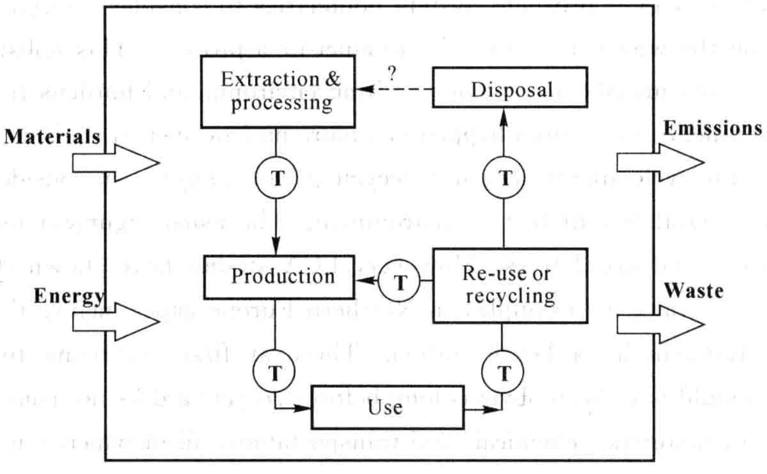

Figure 1.4 Stages in the life cycle of a product (T, transport)

1.4.2 LCA Methodology

According to ISO 14040—2006[11], "LCA is a technique for assessing the environmental aspects and potential impacts associated with a product". It assesses the aspects of the whole life cycle (*i. e.* cradle-to-grave). LCA is used for environmental improvements at various points in a life cycle of a product and for finding relevant environmental indicators. It is also used for decision-making in the industry, and by governmental and non-governmental organizations. The typical use is in product development. It is standardized in ISO 14040 — 2006 to 14043 — 2000. These are currently under revision.

The LCA method is one of the most important information tools of environmentally oriented product policy. LCA quantifies the use of materials and energy taken from the environment to generate goods and services within economic systems. It also identifies emissions and wastes that are associated with the life cycles of these goods and are eventually returned to the environment. This means that, in terms of the model of sustainable development illustrated in Figure 1.1, LCA as an environmental management tool can be positioned within the overlap between the economic and environmental components of sustainable development. This is shown in Figure 1.5. It also means that, if used correctly, LCA can help to identify more sustainable economic activities.

A correct use of LCA is indeed one of the most important issues associated with this type of analysis. Because LCA assumes a very broad view of usually complex systems (products, processes or activities) and considers a wide range of environmental impacts, it is quite possible for different LCA practitioners (or interest groups) assessing the same system to arrive at different conclusions. Some of the reasons for misinterpretation (and sometimes misuse) of LCA studies lie in the way the system boundaries are defined and in the type and quality of data used for analysis. Many LCA studies have been criticized and discredited for this reason, particularly if the results were used to gain commercial or other advantages.

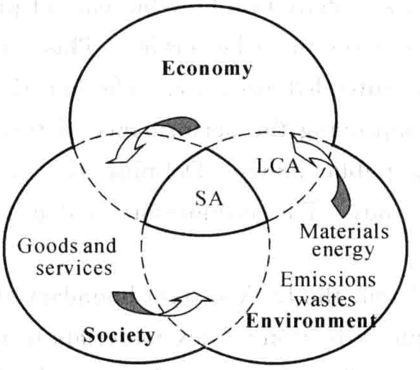

Figure 1.5 Positioning LCA as a tool for sustainable development (SA, sustainable activity)

It is expected that standardization of the LCA methodology, which has been finalized only recently, will help towards more uniform use of LCA and will contribute towards increasing its credibility as a tool. Two major international bodies have been involved in developing the methodology: Society for Environmental Toxicology and Chemistry (SETAC) and International Organization for Standardization (ISO). ISO 14040 defines four phases of LCA:

(1)Goal and Scope Definition (ISO 14041)[12]

(2)Inventory Analysis (ISO 14041)

(3)Impact Assessment (ISO 14042)[13]

(4)Interpretation (ISO 14043)[14]

Figure 1.6 shows the position and interactions of these phases within the LCA methodological framework.

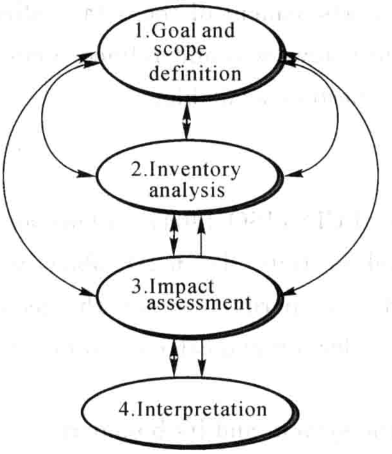

Figure 1.6 The methodological framework for LCA

Goal and Scope Definition

The first and probably most critical phase of an LCA study is the goal and scope definition. Goal and scope aims to definition how big part of product life cycle will be taken in assessment and to what will assessment be serving. This component includes defining the purpose of the study and its intended use, *i. e.* whether the study is going to be used internally by a company for improving the performance of their system or externally, *e. g.* for marketing or influencing public policy. Defining the system and system boundaries determines the scope of the study. The assumptions and limitations of the study are also identified in this phase.

It must be borne in mind that the LCA system boundary should be drawn to encompass all stages in the life cycle from extraction of raw materials to the final disposal. As already explained, this is referred to as a "cradle-to-grave" approach. However, in some cases, the scope of the study will demand a different approach, where it is not appropriate to include all stages in the life cycle. For instance, this is the case with intermediate products (*e. g.* granulated polymer), which can have a number of different uses, so that it is not possible to follow their numerous life cycles after the manufacturing stage. The scope of such studies is from "cradle to gate", and they follow a product from the extraction of raw materials to the point where they leave the factory gate.

The functional unit, one of the most important elements of an LCA study, is also defined in this phase. This is a quantitative measure of the output of products or services that the system delivers. In comparative studies it is crucial that systems are compared on the basis of equivalent function, *i. e.* functional unit. For example, comparison of different drinks packaging should be based on their equivalent function, which is to contain a certain amount of beverage. The functional unit is then defined as "the quantity of packaging necessary to contain a specified volume of beverage".

This phase also includes an assessment of the data quality. As indicated in Figure 1. 6, the goal and scope are constantly reviewed and refined while LCA is being carried out, as additional information and data become available.

Inventory Analysis

The Life Cycle Inventory (LCI) (ISO 14041—1998) analysis represents a quantitative description of the system and is thus the most objective phase in LCA. It aims at determining flows of material and energy between the technical product system and the environment. It involves data collection and calculation procedures for the technical process. Inventory Analysis includes:

(1) Further definition of the system and its boundaries

(2) Flow diagrams of the system

(3) Data collection

(4) Allocation of environmental burdens

(5) Calculation and reporting of the results

Following a general definition in the Goal and Scope Definition phase, the system is further defined and characterized in LCI to identify the data needs. A system is defined as a collection of materially and energetically connected operations (including for example manufacturing process, transport or fuel extraction process) which perform some defined function. The system is separated from its surroundings, *i.e.* the environment, by a system boundary. Thus, for these purposes the environment is defined along with the system, by exclusion. This simple definition is illustrated by Figure 1.7.

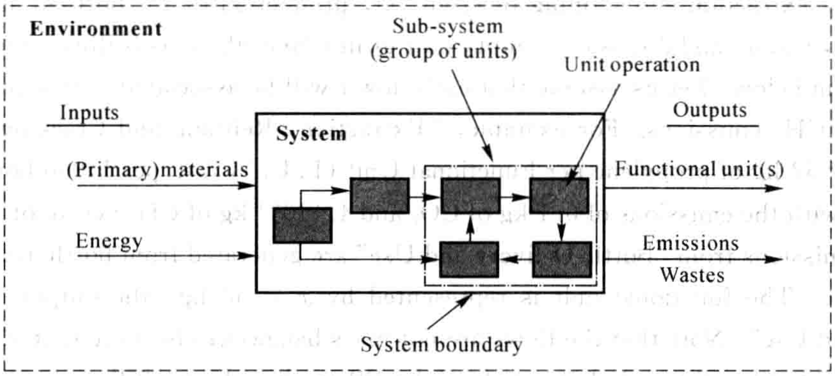

Figure 1.7 Inventory Analysis: a flow diagram showing a system and its boundaries

The system is disaggregated into a number of inter-linked subsystems and their interdependence is illustrated by flow diagrams (see Figure 1.7). Depending on the level of detail of the available data, the subsystems can represent the unit operations or a group of units. Each subsystem is described in detail by flows of materials and energy, as well as emissions to air and water and solid wastes. All inputs into, and outputs from, the subsystems are balanced in this phase and data are normalized with respect to the unit output from each subsystem. This is equivalent to carrying out mass and energy balances, an approach central to process systems analysis. On the basis of the data collected for a period statistically relevant for the study, the environmental burdens defined as resource depletion and emissions to the environment, are then calculated for the whole system. The results are listed in the inventory tables and represented graphically. Environmental burdens include, for instance, fossil fuel consumption, emissions of sulphur dioxide, emissions of metals to water and amount of solid waste, and they can be calculated as:

$$B_k = \sum_{i=1}^{I} bc_{k,i} X_i \quad k = 1, 2, \cdots, K \tag{1.1}$$

Where $bc_{k,i}$ is burden k associated with the material or energy flow x_i in a process or activity. An example would be an emission of CO_2 (burden $bc_{k,i}$) generated per tonne of natural gas (material flow x_i) used to generate electricity (process or activity). As defined by Equation (1.1), there would be in total K burdens from I flows. A simple example 1 in the follow illustrates how the burdens can be calculated.

Example 1: Calculating environmental burdens and impacts

To illustrate how the environmental burdens and impacts from a system can be