Chapter 2
Integration of Design for Environmental Concepts in Product Life Cycle

Several enterprises in various geographic regions recognized that good environmental performance is an important factor for their future success and does a lot to reduce environmental impacts by treatment actions, implementation of cleaner technologies, and by product modifications. Thus, significant environmental improvements can very often be achieved by integrating environmental properties as an optimization parameter during the product development together with parameters such as function, production costs, aesthetics, ergonomics etc.

In some markets such as the car industry, environmental considerations have had a fundamental impact on product development processes with the quest for energy-efficient, low/zero-emission vehicles (Thornton 1999). In particular markets, a large proportion of new product introductions involve products marketed at least partly on the basis of their environmental performance. In the USA, the proportion of green products among new product introductions rose from 1.1% in 1986 to a high of 13.4% in 1991 (Ottman 1998). Tighter regulations and consumer skepticism have since led to a reduction in such introductions, but in markets such as paper towels, dishwasher liquids, and diapers, steady market growth for green brands has continued (Speer 1997). In 1997, green products accounted for 10% of all new US product introductions, with the highest proportion in the ‘‘household products’’ category, accounting for 30% of product introductions (Fuller 1999). This phenomenon is also not limited to manufacturers and the design of physical products. Eco-tourism products and green and ethical investment products address fast-growing segments of the tourism and financial services markets.

Some of the most important decisions with respect to environmental properties of a new product are taken during the product development.

The growing interest in ‘sustainable development’ has led many companies to examine the ways in which they deal with environmental issues (Glazebrook 2000). To achieve sustainable industry, environmentally conscious design (eco-design) or design for environment (DfE) is becoming an increasingly important topic (Brezet and Van Hemel 1997). The introduction of Design for Environment (DfE) methodologies in manufacturing firms allows attention to be

M. Bevilacqua et al., *Design for Environment as a Tool for the Development of a Sustainable Supply Chain*, DOI: 10.1007/978-1-4471-2461-0_2,

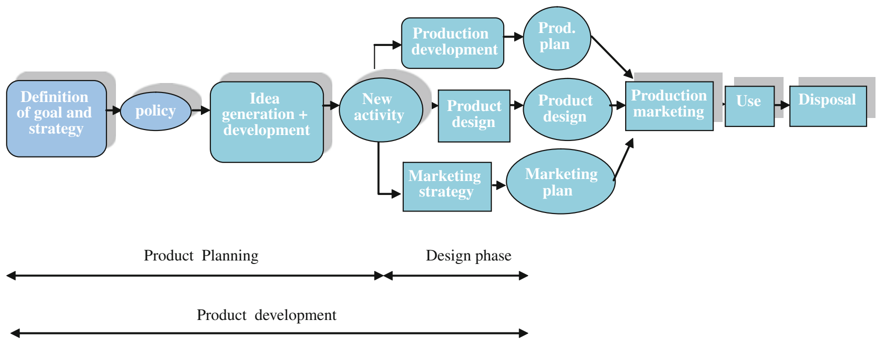

Fig. 2.1 Product development process in a company

paid to environmental aspects right from the start of the design stage leading to a reduction in the materials used and the waste products, avoiding any future weaknesses and inefficiencies.

DfE bears in mind the potential environmental impact throughout the life cycle of the product: emission of harmful substances, excessive use of energy or non-renewable energy sources. It also considers the life cycle of the materials from extraction to disposal. In this way the designers do not create just a product but a whole life cycle.

The use of DfE is also proof of a sense of responsibility toward the consumer and may improve the market position of the firm. Many firms have decided to develop DfE for different core products for several reasons, the main one being that customers are increasingly asking for information concerning the environmental performance of products. This is due to growing environmental awareness and the desire to compare products of different types and from different companies in an environmental context. The development and presentation of Environmental Product Declarations (EPDs) based on the International Standard ISO TR 14025—Environmental labels and declaration: Type III environmental declarations—are a logical way of achieving this (Fraser of Allander Institute 2001). The information incorporated in each EPD is based on life cycle assessments (LCAs), according to the international ISO 14040 standard—Environmental management, Life cycle assessment: principles and framework. The resulting EPDs can also serve as good sales arguments for environmentally friendly products.

2.1 Environmental Aspects in Product Life Cycle

Before speaking of environmental aspects involved in product design processes it is necessary to analyse some general concepts of this company's process.

Figure 2.1 shows the main phases of product development as outlined by several authors. During each phase, aspects such as technical properties,

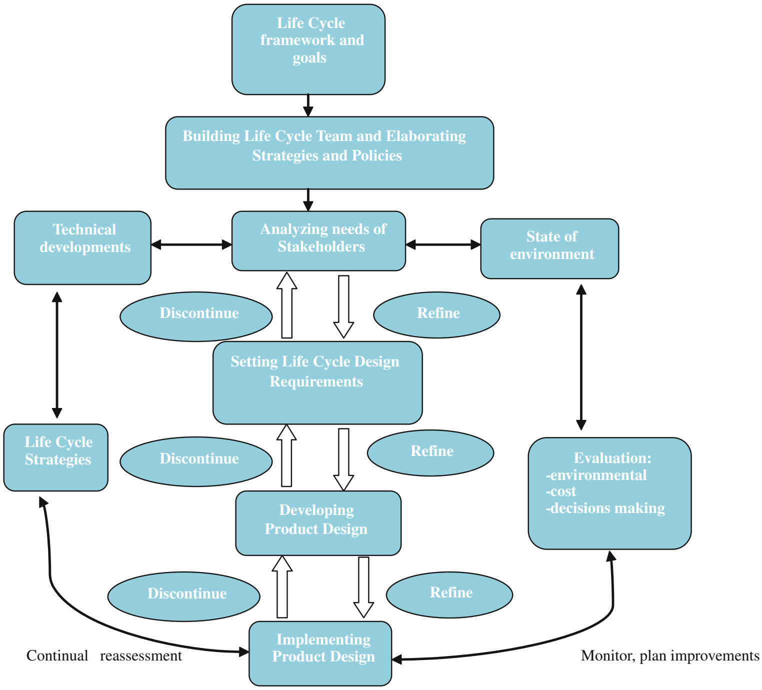

Fig. 2.2 Flow chart: life cycle design process. (Source: Keoleian and Mezerey 1993)

ergonomic properties, economic properties, health properties, and environmental properties of the product are taken more or less into account and the final product usually comes out as a compromise between the different priorities.

After building an interdisciplinary multi-stakeholder life cycle team, understanding, and integration of life cycle thinking, and development of life cycle design goals and principles, life cycle design process should be elaborated. Keoleian and Menerey (1995) have elaborated and offered a useful plan to build Life Cycle Design Process (see Fig. 2.2) that consists of six main steps: (1) Developing of Life Cycle Framework and Goals, (2) Building Life Cycle Team and Elaborating Strategies and Policies (Integration of Life Cycle Thinking idea), (3) Analyzing needs of Stakeholders (Stakeholders Management), (4) Setting Life Cycle Design Requirements, (5) Developing Product Design, and (6) Implementing Product Design.

As Fig. 2.2 shows, product development is a complex system. In the diagram, life cycle goals are very important, therefore they are located at the top. Management influences all the stages of life cycle design process. Concurrent design and life cycle quality provide models for life cycle design. Moreover, measures of success, life cycle team coordination, and policy, strategy are needed in order to support all life cycle design process with design projects.

According to Keoleian and Menerey (1995), a typical design project begins with a needs analysis that identifies customers' needs and ideas of a company. Here I also add that not only customers' needs and interests should be analyzed but also other stakeholders' needs and interests (suppliers, government, competitors, consumer, and environmental organizations). After identification and analysis of the needs, the project team formulates the requirements. Requirements can be set with a use of Requirements Matrix that allows project team to study the interactions between life cycle requirements. Matrices are effective for organizing data and evaluating it later. After development of requirements, project team evaluates conceptual, preliminary, and detailed design. Before implementation, a detailed design is compared to benchmark products. All the weaknesses, minor problems, and unclearness can still be corrected. After formal approval of a detailed design, it can be implemented. Implementation includes production, distribution, marketing, and labeling.

However, there are several barriers that can limit life cycle design process:

- Lack of data for determining life cycle impacts.
- Lack of motivation within a company.
- Decrement in total impacts may increase local impacts (Keoleian and Menerey 1993).

In order to succeed the implementation of Life Cycle Design, involvement of different stakeholders is essential. According to Behrendt et al. (1997), stakeholders, who are involved in life cycle design, can be divided into three levels according to the importance of their involvement (see Fig. 2.3).

The most important stakeholders of life cycle design are in a Design Team. Design Team elaborates and facilitates Life Cycle Design process. Usually it consists of designers, constructors, product managers, sales and marketing managers, and environmental and safety experts. The successful introduction of LCD depends on the commitment of product managers (Keoleian and Menerey 1993). They should control that product projects are applied in the environmental requirements. Marketing managers define market and environmental characteristics of a product by analyzing environmental performance, price levels, and customer profiles.

In the second level, the stakeholders of the whole product chain (production, operation, distribution, supply, packaging, etc.) are involved. Especially good cooperation with suppliers in environmental programs is important because it enables a company to have environmentally certified materials, and components. In the third level, customers, government, stockholders, environmental organizations can play a role of a driving force toward implementation of life cycle design.

However, in my opinion, there can not be the same common picture of stakeholders for Life Cycle Design for all companies. Each company should identify, prioritize, and involve stakeholders in Life Cycle Design process individually and according to the company's Life Cycle Design goals. For example, I can argue that a group of big customers and suppliers should be named not as

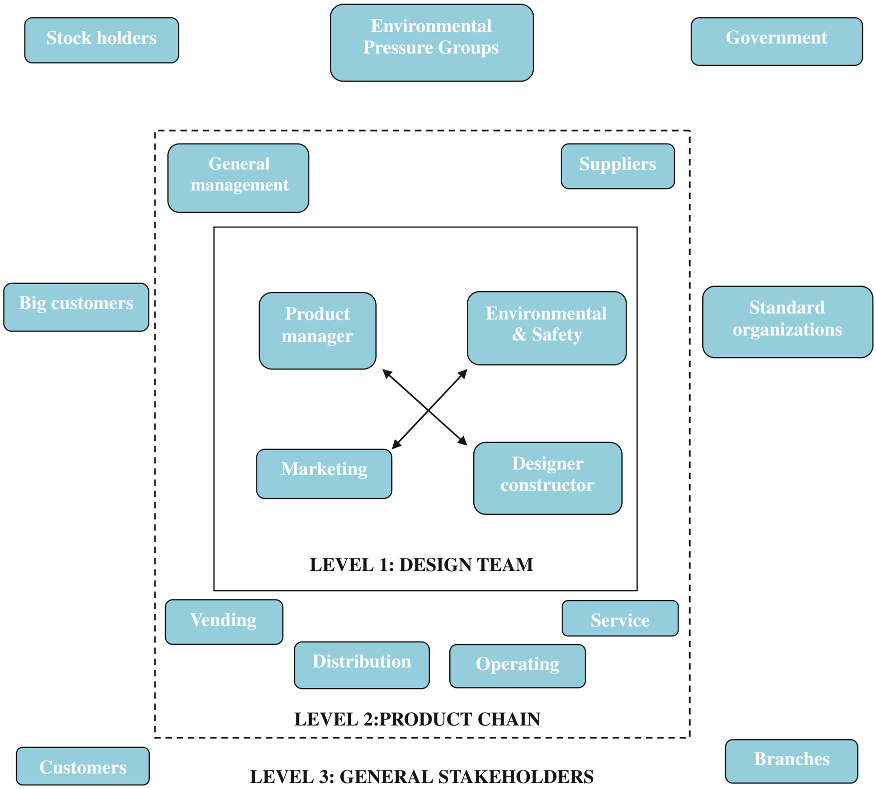

Fig. 2.3 Stakeholders for life cycle design, (modified by Behrendt et al. 1997)

external stakeholders but as a part of a Design Team. Big customers and suppliers should be involved in Life Cycle Design decision-making process (Johansson 2001). According to McAloone (1998), the supplier network can provide important information in choosing environmental alternatives of materials, components, and process. The customers are the one that can contribute in identification and determination of environmental criteria and profile of a product.

Existing studies have analyzed economic and environmental effects of selected policies, usually in partial equilibrium models, but comparison across policies is made difficult by differences in the design of those studies (Fullerton and Wu 1998).

The U.S. Office of Technology Assessment (1992) defines green design as a "process in which environmental attributes are treated as design objectives." The purpose is to reduce pollution at its source, that is, to "avoid the generation of waste in the first place". It also finds that "better product design offers new opportunities to address environmental problems, but that current governmental regulations and market practices are not sufficient to fully exploit these opportunities".

A variety of reforms have been proposed to deal with these perceived problems, both at state and federal levels. Packaging could be subjected to standards, taxes, deposit-refund systems, or recycling requirements. Other proposals would tax toxic substances, require a minimum percentage of recycled content in certain products such as newspapers, require manufacturers to "take back" certain products such as batteries, provide tax credits for machinery used in recycling, require local governments to collect household recycling at the curb, and require households to pay a price per unit of garbage. Table 2.1 lists 34 such policy interventions.

Table 2.1 shows how proposed policies target different stages of this life cycle, and our model shows how the stages are connected. Policies to affect product design will also affect product disposal, and vice versa. Another policy directed at consumers may similarly affect market prices and firm behavior.

2.1.1 LCA and Product Development

As environmental awareness increases, industries and businesses are assessing how their activities affect the environment. Society has become concerned about the issues of natural resource depletion and environmental degradation. Many businesses have responded to this awareness by providing "greener" products and using "greener" processes. The environmental performance of products and processes has become a key issue, which is why some companies are investigating ways to minimize their effects on the environment. Many companies have found it advantageous to explore ways of moving *beyond* compliance using pollution prevention strategies and environmental management systems to improve their environmental performance. One such tool is Life Cycle Assessment (LCA). This concept considers the entire life cycle of a product (Curran 1996).

According to Khan et al. (2002) LCA is one of the most important techniques for the successful implementation of a process or product development in the context of environmental sustainability. As Allen (1996) indicated, one of the most common uses of LCA is identifying critical areas in which the environmental performance of the product can be improved.

Life cycle assessment technique is unique because it encompasses all processes and environmental releases beginning with the extraction of raw materials and the production of energy used to create the product through the use and final disposition of the product. When deciding between two or more alternatives, LCA can help decision-makers compare all major environmental impacts caused by products, processes, or services.

Life cycle assessment is a "cradle-to-grave" approach for assessing industrial systems. "Cradle-to-grave" begins with the gathering of raw materials from the earth to create the product and ends at the point when all materials are returned to the earth. LCA evaluates all stages of a product's life from the perspective that they are interdependent, meaning that one operation leads to the next. LCA

Table 2.1 Policy options that could affect materials flows (source: U.S. Office of Technology Assessment 1992)

Life cycle stage	Regulatory instruments	Economic instruments
Raw material extraction and processing	(1) Regulate mining, oil and gas non-hazardous solid wastes under the Resource Conservation and Recovery Act (RCRA) (2) Establish depletion quotas on extraction and import of virgin materials	(1) Eliminate special tax treatment for extraction of virgin materials, and subsidies for agriculture (2) Tax the production of virgin materials
Manufacturing	(1) Tighten regulations under Clean Air Act, Clean Water Act, under RCRA (2) Regulate non-hazardous industrial waste under RCRA (3) Mandate disclosure of toxic materials use (4) Raise corporate average fuel Economy Standards for automobiles (5) Mandate recycled content in product (6) Mandate manufacturer take-back and recycling of products (7) Regulate product composition, e.g. volatile organic compounds or heavy metal (8) Establish requirements for product reuse, recyclability or biodegradability (9) Ban or phase out hazardous chemicals (10) Mandate toxic use reduction	(1) Tax industrials emissions, effluents, and hazardous wastes (2) Establish tractable emissions permits (3) Tax the carbon content of fuels (4) Establish tractable recycling credits (5) Tax the use of virgin toxic materials (6) Create tax credits for use of recycled materials (7) Establish a grant fund for clean technology research
Purchase, use, and disposal	(1) Mandate consumer separation of materials for recycling	(1) Establish weight/volume-based waste disposal fees (2) Tax hazardous or hard-to-dispose products (3) Establish deposit-refund system for packaging, hazardous products (4) Establish a fee/rebate system based on product energy efficiency (5) Tax gasoline
Waste management	(1) Tighten regulation of waste management facilities under RCRA (2) Ban disposal of hazardous products in landfills and incinerators (3) Mandate recycling diversion rates for various materials (4) Exempt recyclers of hazardous wastes from RCRA Subtitle C (5) Establish a moratorium on construction of new landfills and incinerators	(1) Tax emissions or effluents from waste management facilities (2) Establish surcharges on wastes delivered to landfills or incinerators

enables the estimation of the cumulative environmental impacts resulting from all stages in the product life cycle, often including impacts not considered in more traditional analyses (e.g., raw material extraction, material transportation, ultimate product disposal, etc.). By including the impacts throughout the product life cycle, LCA provides a comprehensive view of the environmental aspects of the product or process and a more accurate picture of the true environmental trade-offs in product and process selection.

An LCA allows a decision maker to study an entire product system hence avoiding the sub-optimization that could result if only a single process were the focus of the study. For example, when selecting between two rival products, it may appear that Option 1 is better for the environment because it generates less solid waste than Option 2. However, after performing an LCA it might be determined that the first option actually creates larger cradle-to-grave environmental impacts when measured across all three media (air, water, land) (e.g., it may cause more chemical emissions during the manufacturing stage). Therefore, the second product (that produces solid waste) may be viewed as producing less cradle-to-grave environmental harm or impact than the first technology because of its lower chemical emissions.

This ability to track and document shifts in environmental impacts can help decision-makers and managers fully characterize the environmental trade-offs associated with product or process alternatives. By performing an LCA, analysts can:

- Develop a systematic evaluation of the environmental consequences associated with a given product.
- Analyze the environmental trade-offs associated with one or more specific products/processes to help gain stakeholder (state, community, etc.) acceptance for a planned action.
- Quantify environmental releases to air, water, and land in relation to each life cycle stage and/or major contributing process.
- Assist in identifying significant shifts in environmental impacts between life cycle stages and environmental media.
- Assess the human and ecological effects of material consumption and environmental releases to the local community, region, and world.
- Compare the health and ecological impacts between two or more rival products/processes or identify the impacts of a specific product or process.
- Identify impacts to one or more specific environmental areas of concern.

An extensive explanation of LCA techniques has been carried out in Chap. 3.

The product development team should have an indication of the relative importance of the environmental impact in the product planning; otherwise it cannot balance environmental aspects against other aspects (Table 2.2). It is very important to understand the following mechanism in an eco-design process:

1. At the beginning of the process the most important decision are made; an important part of the environmental impact is defined at this stage. For example

Table 2.2 LCA use in different stages of the product development

	Activity	Information needed	Information generated
Product Planning	The company management sets the target for the design process. It is usually described as a market/technology combination	General information: policy consumer behavior	Primary goals and directions
Analysis phase	The design problem is analyzed, and the requirements are defined. LCAs of reference products, short what-if? Analysis	General data	Provisional rules of thumb that apply for this product definition of priorities
Idea-generation	Different creativity techniques are defined in order to generate as many new solution as possible short what-if? analysis	Eco-indicators	An indication of the type of product that seems to be desirable
Concept-development phase	The best ideas are elaborated further into a limited number of concepts short provisional LCAs	Eco-indicators	Information on the most important contributions to the environmental impact for the chosen concept
Detailed design phase	The best concept is reworked into detailed drawings. Answering very specific question on the contents of materials etc.	Very specific information	Verification of the goals

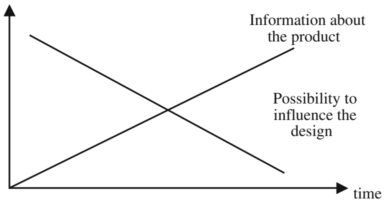

Fig. 2.4 Interaction between the possibilities to influence a design in relation to time

a manufacturer decides to make electric or diesel cars. At this stage there is no product definition. Therefore an LCA cannot be carried out.
2. At the end of the design process the product is defined to a large extent. It is possible to carry out an LCA, but it is hardly possible to influence the design. It is simply too late.

Figure 2.4 shows how during process more will become known about the product and better LCAs are possible. At the same time, however, the possibility of influencing its environmental impacts is reduced.

To overcome this dilemma the type of analysis that can be used should be carefully considered. There are several problems when applying LCAs in the design process:

1. There is not enough time to carry out an LCA for each decision.
2. Even if there was enough time it would be very difficult to produce LCAs. Product ideas are not yet products. In many case the ideas only refer to an operational principle. The idea has not been fleshed out: the material composition, weight, and dimensions are not fully known and, of course, even less is known about consumer behavior and disposal.

This does not imply that LCAs cannot be used. On the contrary, they are essential. It means the LCAs should be used differently at different product development stages. Once the product planning process has set the goals for the design process, it is important to understand the impacts of this type of product in general. LCAs of reference products are essential in this phase. These are existing products that perform a similar function to the desired product. Since many product development processes can be considered as redesign processes it is usually the current product that can serve as a reference product.

2.2 Design for Environmental Concepts

Design for environment (DFE) is defined as systematic consideration of design performance with respect to environmental, health, and safety objectives over the full product and process life cycle (Ray and Guzzo 1993).

This concept was created in 1992 by a number of electronic firms that were attempting to build environmental awareness in product development. The

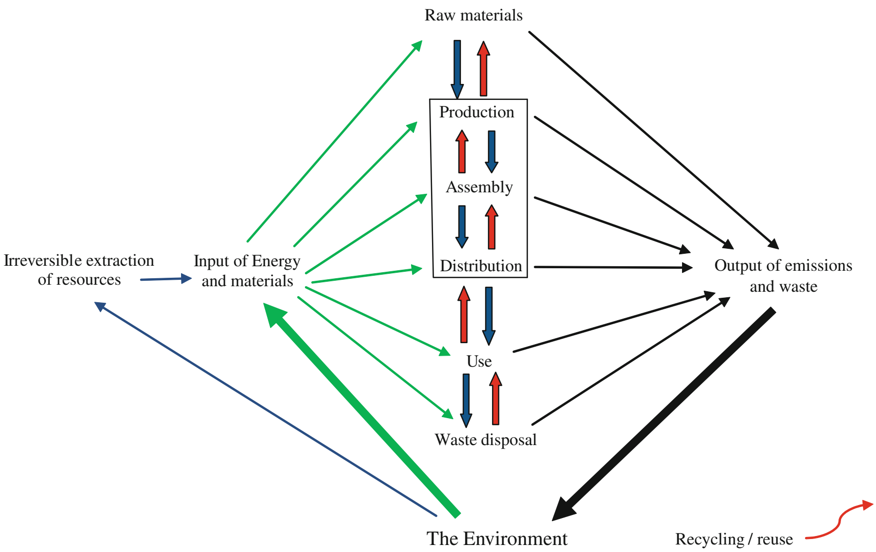

Fig. 2.5 Flow chart of materials: Adapted Life Cycle Concept (modified by Bakker 1995)

American Electronics Association was a first initiator of DFE (AEA 1992). After that, this concept started to be used widely by many industries that wanted to integrate environmental awareness into product design.

In the end, it should lead to sustainable production and consumption that can be achieved together with a number of other measures that are very important, for example, legislation. Life Cycle Design integrates environmental issues into product development by considering all product life cycle stages: raw material acquisition, manufacturing, use, distribution, and disposal (Keoleian et al. 1995).

There are many terms that relate to the life cycle design: eco-design, design for the environment, life cycle design, and environmentally conscious design and production (Brezet and Van Hemel 1997). The product life cycle is a model that contains and describes all the processes that are necessary for the extraction and processing of raw materials, production, distribution, consumption and disposal of the product (Fig. 2.5). Environmental impact is the material influence on the environment. Environmental criteria are product- and production process- oriented solution strategies that lead to less environment damaging products (Bakker 1995).

Environmental impact is any change to the environment which can be adverse or beneficial. This change comes from activities, products, or services of the company. It is important to notice that environmental impact can be positive. For example, production of heating (for district heating purposes) harms the environment, but the overall impact is less than if all households have their own boiler (Brorson and Larsson 1999).

Gertsakis et al. (1997) defined 15 strategies of "design for environment" (eco-design or Life cycle design as synonyms) concept: design for resource conservation, design for environmentally preferred materials, design for cleaner production, design for efficient distribution, design for energy efficiency, design for water conservation, design for minimal consumption, design for low-impact use, design for durability, design for re-manufacture, design for re-use, design for disassembly, design for recycling, design for degradability, design for safe disposal.

Moreover, Simon (2000) provides a concept of DFX, where X can be any environmental criteria. It depends on a company and designers to choose these criteria. It should be noted that the concept of design for environment covers whole life cycle of a product. Therefore, different "design for environment" strategies and tools apply to different life cycle phases.

Bakker (1995) describes a method of "design for environmental efficiency". In the Dutch manual for environment oriented product development it is called as "product analysis". The purpose of this method is to improve efficiency and effectiveness of product's functions, and reduce the environmental impact of the product. This method is based on existing design approaches, like for example value analysis (or value engineering), which objective is to increase the value of the product for the purchaser and reduce the costs for its producer. Recently Fiksel (2009) has developed a comprehensive guide that provides a powerful case for integration of environmental principles and into product development.

Some Design for Environmental guidelines with respect to life cycle strategies were followed (Table 2.3).

Design guidelines are among the most basic tools in design and the introduction of appropriate design guidelines is one of the easiest ways in introducing environmental issues in design. Guidelines can be taken into consideration with checklists in which a designer marks whether he or she has considered the corresponding guideline. Combined with a short course or dedicated education session, guidelines and checklists provided an effective means for exposing designers to environmental issues and ways to reduce the environmental impact of products.

The principles in product design shown in Table 2.3 can be analysed in depth using a methodological approach proposed by Tsoulfas and Pappis (2006).

- *Design and develop recoverable products, which are technically durable, repeatedly usable, harmlessly recoverable after use, and environmentally compatible in disposal*: materials with a high recycling rate and which have the least impact on the environment, both in use and origin, should be preferred. Where possible, environmentally safer substitutes should be used and the abuse of products should be actively prevented. Digital uses the 6R approach (Recycle, Reclaim, Refurbish, Remanufacture, Resell, and Reuse) on their used products (Dorgelo 1996). Xerox offers a 3-year total satisfaction guarantee on equipment containing reprocessed parts to demonstrate its confidence in the products, the same as that given on new equipment (Maslennikova and Foley 2000). In addition, Xerox designers choose a minimal number of materials from the Xerox material environmental index to simplify the eventual segregation of materials and to avoid hazardous materials. The index specifies the relative

Table 2.3 Design for environmental guidelines

Life cycle	Guidelines
Optimization of initial life-time	Reliability and durability
	Easy maintenance and repair
	Modular product structure
	User taking care of product
Selection of low-impact materials	Non-hazardous materials
	Non-exhaustable materials
	Low energy content materials
	Recycled materials
	Recyclable materials
Reduction of material	Reduction in weight
	Reduction in (transport) volume
Optimization of production techniques	Alternative production techniques
	Fewer production processes
	Low/clean energy consumption
	Low generation of waste
	Few/clean production consumables
Reduction of the environmental impact in the user stage	Low energy consumption
	Clean energy source
	Few consumables needed during use
	Clean consumables during use
	No energy/auxiliary material use
Efficient distribution system	Less/clean packaging
	Efficient transport mode
	Efficient logistics
Optimization of end-of-life system	Reuse of product
	Remanufacturing/refurbishing
	Recycling of materials
	Clean incineration

nature of various materials' impact on the environment and helps designers choose non-toxic materials that resist equipment to assert that products should wear during normal use and lend themselves well to reuse and recycling. IBM also develops design specifications for its new products to improve product's end-of-life material recovery (Germans 1996). Billatos and Nevrekar (1994) underline the Mercedes Benz design efforts, which include the selection of environmentally compatible and recyclable materials for components, the reduction of the variety and the volume of plastics used and the avoidance of using composite materials as much as possible. Hundal (1994) reports that another automotive company, BMW, has been trying to introduce more recyclable components in the original design so that it can produce cars out of 100% recycled parts. Finally, Rosenbach and Lindsay (2002) have reported many cases of the application of this principle in various companies.

- *Produce using minimum energy and materials*: the wasting of materials and energy either due to inappropriate design, or due to excessive number of defects should be avoided. Intel has worked in increasing the number of transistors in a single chip, which will result in fewer chips to build and fewer chips to dispose (Gungor and Gupta 1999).
- *Secondary raw materials should be given priority in usage*: primary raw materials should be used only in cases where there would be no stock of secondary ones. Furthermore, in many cases this policy is also moneysaving. Such a case is reported by Tsoulfas et al. (2002) and by Daniel et al. (2003), where lead is recovered and recycled from lead-acid batteries and then it is used for the production of new ones. In addition, Recopol Furniture report that they make furniture which incorporates up to 75% recycled resins and plastics that come from used appliances such as computers, vacuum cleaners, telephones, televisions, washing machines, and refrigerators, which would otherwise go to the landfill (http://www.wharington.com.au).
- *Use eco-friendly energy production, reduce water usage and keep control of pollution sources*: Using less energy is obviously good for the environment. It is also self-evidently good for business because it cuts companies' costs, and eventually avoids potential environmental liabilities. It is, therefore, a prerequisite to the long-term sustainability of business. To replace nonrenewable and polluting technologies, it is crucial to support the use of renewable energy resources, as well as to reduce energy consumption. The identification of where great amounts of energy are used could subsequently lead to redesign of the product or its use in order to make significant energy reductions. Major improvements in energy efficiency can often be achieved at little or no cost, even with net savings, through the use of targeted programs. Installed water-saving techniques and the use of closed re-circulating systems can lead to reduction of water use. In addition, the elimination of the stochastic factors, which affect pollution, may lead to greener production.
- *Use standardized parts*: such a policy ensures that these parts could be reused not only by the original producer, but also by a larger group of producers. For example, automotive companies use standardized screws, speedometers, etc. In most cases this policy is also money-saving. Pappis et al. (2005) report the case of containers that are standardized and can be used by different companies. Standardization is of major importance in Xerox and focus is paid standardizing components as much as possible between product families, thus simplifying and optimizing the opportunities for reuse (Maslennikova and Foley 2000).
- *Provide for easy disassembly of the product*: this would lead to cost, time, and energy savings. The opposite case would make the disaggregation of the product unpractical and costly. It has been reported that Chrysler, Ford, and GM researchers are trying to improve disassemblability features whilst improving the assembly ones (Gungor and Gupta 1999). BMW has been using a color coding scheme for differing plastic materials for the past 30 years, which allows the development of efficient dismantling and disassembly techniques (Hundal 1994).

- *Reduce by-products and get the best out of them:* during manufacture by-products are also produced. Some of them can and should be reduced and/or reused. The rest must be eliminated and disposed properly.
- *Packaging*: packaging design is important for attaining a company's environmental objectives. Though it serves certain needs related mainly to the distribution of the product (e.g. safe transportation), it is not part of the actual service offered by the product. In any case, it affects environment in many aspects. This is the reason why regulations concerning packaging constitute an essential part of governmental policies for environmental protection. The following principles may apply concerning packaging.
- *Limit packaging to the necessary size*: The opposite case not only is contrary to environment protection, but it also affects transportation negatively. Furthermore, environmentally safe packaging can be used as a marketing argument.
- *Design packaging for refilling or recycling and use standardized packaging when applicable*: there are examples of standardized bottles, crates, boxes, pallets, and containers, which may be used by different companies. In reorganizing the packaging policy, Xerox changed its packaging and established packaging-reuse centers in the UK, the Netherlands, and the US. In addition, it reduced the amount of internal packaging to minimize waste (Maslennikova and Foley 2000).
- *Collection and transportation*: despite the obvious environmental gain from used products' recovery, collection, and transportation of recovered products have an environmental cost. Minimizing such a cost is important in order to increase the total environmental gain from recovery. Principles applicable in this phase of the reverse supply chain are the following.
- *Formulate a policy for the recovery of used products*: such a policy favors the maximum utilization of used products. Companies may decide either to undertake the recovery of used products on their own, or to establish cooperation via local or more extended networks for the collection and recycling of similar products. United efforts may be more effective and provide higher recycling rates. Also, recovered products often suit more than one manufacturer. Leasing is a policy that has received much attention lately regarding its environmental dimension. Indeed, companies that lease their products instead of selling them have better chances in the management of their used products. Such cases are reported in detail in Fishbein et al. (2000).
- *Consider using existing forward supply chain facilities and transportation system as much as possible for the reverse supply chain*: transportation and the consequent environmental effects can be significantly limited if the recovery of used products can occur at the same time or in combination with the distribution of new products. The theoretical minimal average transportation distances can be determined using a tool for allocation and route planning. An application of this principle is reported by Vergitsi (2000), where the case of used beverage bottles of Hellenic bottling company (3E) is examined. The tracks that carry the beverages do not return empty to the warehouses of 3E,

since they carry the empty bottles from the consumer spots, in order to be reprocessed. Krikke et al. (2002) conclude that in the case of Printed Wiring Assemblies of Honeywell the forward supply chain is used in order to facilitate the returns of spent products.

- *Classify used products as early in the recovery chain as possible*: this eases the planning of storage of used products and redundant processes are avoided. Daniel et al. (2003) mention that using lead-acid batteries are classified in the electricians' shops, where they are bought by customers.
- *Treat hazardous materials safely*: it is necessary to ensure that the generation of hazardous wastes is reduced and also that adequate disposal facilities are available, for the environmentally sound management of hazardous wastes. In Ohio Manufacturer's Association Case Studies in Team Excellence (Ohio Manufacturer's Association 1992) the initiative of a Chrysler team from the Jeep plant in Toledo is reported, which was formed to respond to state legislation prohibiting the disposal of certain biodegradable and recyclable materials in landfills. The establishment of collection points and of a network of recyclers for such materials together with setting up returnable packaging systems with suppliers led to significant savings in an annual basis.
- *Recycling and disposal*: after its useful life, a used product may be either disposed or recycled (generally recovered). As in the phase of collection and transportation, recycling and disposal may significantly contribute to the total environmental gain and the attainment of the environmental goals of a company. Ideally, companies should borrow from natural cycles to design their systems as part of a larger natural cycle, where materials are borrowed from and returned to nature, without negatively affecting its overall balance. The following principles may be applied regarding recycling and disposal.
- *Close the supply loop by recycling effectively and efficiently*: the biological designs of nature provide a role model for sustainability. The goal is to work continuously toward closed-loop production systems and zero-waste factories, wherein every output is returned to natural systems as a nutrient or becomes an input for manufacturing another product (Executive Committee 2002). Designing for recyclability is essential but recycling becomes unproductive when the energy, materials and pollution used in collecting and processing used products exceed those used to produce the goods in the first place. Closing the loop by extending responsibility throughout the life cycle chain ensures total product and service stewardship. Mercedes Benz started taking scrap cars back in 1991 and has been performing the material recovery process as part of their environmentally friendly production program (Billatos and Nevrekar 1994).
- *Reduce the volume and amount of materials going to landfill and consider alternative uses of used products or wastes*: using appropriate techniques one can compact the scrap. In addition, smaller landfills can be used. Alternative uses of used products extend their life cycle. For example, used tires can be used as a protective in seaports, speedways, etc.

2.2.1 *Integration of LCA Technique and Design for Environmental Methods*

Many authors developed procedures and software in order to integrate LCA technique and DfE methods. Hideki Kobayashi (2005) presented a methodology and a software tool to establish an eco-design concept of a product and its life cycle by assigning appropriate life cycle options to the components of the product. He made a design support tool for efficiently planning product life cycles by using quality function deployment (QFD) and life cycle assessment (LCA) data. Bovea and Wang (2003) introduced a novel approach for identifying environmental improvement options by taking into account customer preferences. The LCA methodology is applied to evaluate the environmental profile of a product while a fuzzy approach based on the House of Quality in the QFD methodology provides a more quantitative method for evaluating the imprecision of the customer preferences.

In order to evaluate or select a solution idea or a design concept, other weighted rating methods are utilized (Pahl and Beitz 1988). In these methods, weighting of the evaluation criteria greatly affects the evaluation result. Total evaluations of eco-products have been reported in Williams et al. (1996) and in Zhang et al. (1998). In these evaluations, the weighting factors of the evaluation criteria were calculated using the analytic hierarchy process (AHP) (Satty 1980). Huang et al. (2004) combined three methods to evaluate the impact of packaging materials: (1) life cycle assessment (LCA), a quantitative method, to assess environmental loading, (2) analytic hierarchy process (AHP), a qualitative method, to obtain opinions from experts, and (3) cluster analysis to integrate the results of the former two methods. The authors developed this method to provide integrated information and avoid a bias toward either a qualitative or a quantitative approach.

The methodology proposed in this book, illustrated in Fig. 2.6, involves the integration of DfE and LCA techniques into those processes which are normally carried out when developing a new product: "Project definition", "Concept Development", "Prototype Assembly Testing" and "Field Test", and "Commercial Launch". Figure 2.6 shows the main phases of product development as outlined by several authors (Pahl and Beitz 1991; Olesen et al. 1996; Nielsen and Wenzel 2002). During each phase, aspects such as technical properties, ergonomic properties, economic properties, health properties, and environmental properties of the product are taken more or less into account and the final product usually comes out as a compromise between the different priorities.

The importance of eco-design in earlier phases has been emphasized, because decisions made in these phases greatly affect the environmental impact throughout the product life cycle (Frei and Züst 1997). The solution space, i.e. the degree of freedom to choose solutions (Jensen et al. 1998) and hence the potential for environmental improvements is large in the beginning of product development when ideas and conceptual solutions are open. However, it decreases gradually as the general product features are established and more and more details are

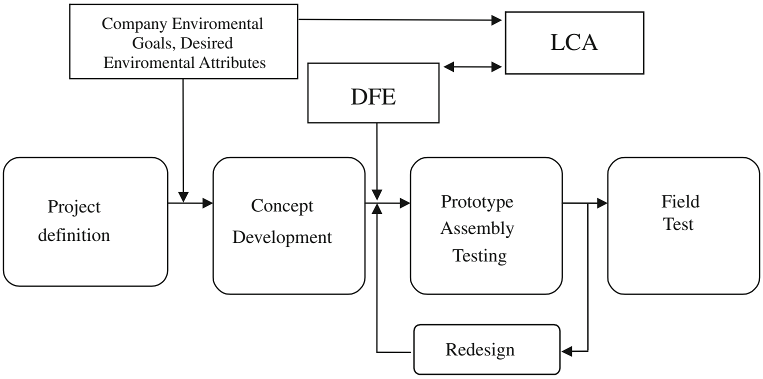

Fig. 2.6 Class product design

determined. The environmental improvement options are limited to production processes, logistics, recycling etc. when the production has been set up and the product is ready for the market.

The activities in the environmental part of the product development procedure shall be considered as a supplement to the traditional values (technical performance, economic performance etc.), and as a contribution to the overall competitiveness of the product.

First of all a manufacturer must examine the context in which the DfE is to be developed. He must identify the important and possible environmental goals within the process and fix the market objective that he wants to reach, whether it is local, national, or international. For example, prior to the introduction of legislation he may consider using this technique to arrive at the standards of eco-management contained in ISO 14000. He must assign responsibilities within the firm and must ensure that the process is controllable and traceable. He must involve all the firms, in particular the managerial staff, indicating DfE as a factor for improvement and market achievement. At the same time he must create awareness (for example by organizing seminars) in all the parties involved in the production process.

The methodology proposed in this study is a closed feedback cycle which is able to improve itself: this is based on a scheduled report system which indicates to the environmental management the need to change some characteristics of the product or the production processes or to address their study toward new products.

The means by which this concept can be integrated into the company is through its Design for Environment (DfE) program. The Design for Environment (DfE) tool considered in this book, is a methodological framework based on Life Cycle Assessment (LCA) thinking, which allows the integration of environmental parameters directly into the design of products and processes. DfE serves therefore as an environmental decision-making support for designers. In the design phase of a product the different problems and solutions should be assessed from a technical, economic, and ecological point of view at the same time.

LCA can be used in any phase of product development showed in Fig. 2.6, but the major potential exists in the project definition phase and the concept development phase and this paper.

- In the *project definition* step it is necessary to define a reference product, which can serve as a representative for the new product. Since new products are usually based on existing technologies in new compositions, it is in most cases possible to compose a useful reference product by putting existing units and technologies together. The environmental performance of a product or a service is determined as a sum of all impacts throughout the product's life cycle. Thus, from the beginning of the product development procedure the entire life cycle of the product system must be taken into account in order to achieve the best environmental performance of the new product (Nielsen and Wenzel 2002). Although much input can be obtained from the company's suppliers, LCA experts, public organisations and from public databases and literature, this procedure can be quite resource demanding for complex products. However, materials and processes, which from an initial judgement are found unimportant from an environmental point of view can be left out of considerations to keep the work in appropriate proportion. In this step it is necessary to make an LCA computer model of the product. The model must be constructed in a manner that allows the existing solutions in the reference product to be removed and replaced easily with others. Although the LCA is quite rough at this stage, special attention shall always be paid to possible emissions of toxic substances, which can occur in small but significant amounts in any stage of the product's life cycle. In this step the most important sources of environmental impact in the reference product's life cycle (environmental 'hot spots') are pointed out in order to identify potential focus areas for the further product development.
- In the *Concept development* step the designers have to determine whether some of the environmental 'hot spots' can be moderated or removed by modifying or replacing certain conceptual solutions in the reference product. In this step, all aspects such as economy, design, technical feasibility etc. must of course be taken into account to ensure that the new product becomes attractive in the market. At this stage existing and new conceptual solutions are compared with each other from an environmental point of view. Before any physical modifications of the product have been made, simulations in the LCA computer tool are used to test new conceptual ideas against each other. The purpose of this activity is to reveal how different conceptual solutions interact with the environment and hereby provide a basis for selection of optimal solutions. It is necessary to verify if environmental improvements are associated with increased production costs. Frequently decisions including both: environmental, technical, and economical aspects may very often lead to solutions with the same or even lower costs due to resource and tax saving (e.g. waste deposition duty). Costly environmental improvements can eventually be motivated by an anticipation of increased profits due to more goodwill toward the product and the company in general.

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http://www.springer.com/978-1-4471-2460-3

Design for Environment as a Tool for the Development
of a Sustainable Supply Chain
Bevilacqua, M.; Ciarapica, F.E.; Giacchetta, G.
2012, X, 374 p., Hardcover
ISBN: 978-1-4471-2460-3