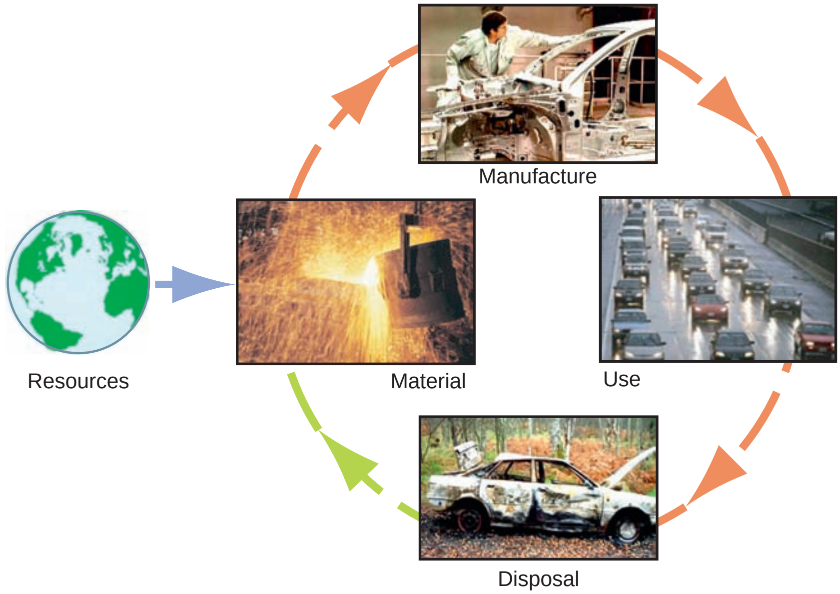
CHAPTER 3

The material life cycle



CONTENTS

3.1 Introduction and synopsis

The materials of engineering have a life cycle. Materials are created from ores and feedstock. These are manufactured into products that are distributed and used. Products, like us, have finite life, at the end of which they become scrap. The materials they contain, however, are still there; some, unlike us, can be resurrected and enter a second life as recycled content in a new product.

Life-cycle assessment (LCA) traces this progression, documenting the resources consumed and the emissions excreted during each phase of life. The output is a sort of biography, documenting where the materials have been, what they have done, and the consequences of this for their surroundings. It can take more than one form. It can be a full LCA that scrutinizes every aspect of life (arduous and expensive in time and money); or it can be a brief character-sketch painting, an approximate (but still useful) portrait; or it can be something in between.

Image of casting courtesy of Skillspace; image of car making courtesy of US Department of Energy EERE program, image of cars courtesy of Reuters.com)

Materials and the Environment.

Responsible design, today, aims to provide safe, affordable services while minimizing the drain on resources and the release of unwanted emissions. To do this, the designer needs an ongoing eco-audit of the design (or redesign) as it progresses. To be useful the eco-audit must be fast, allowing quick "what if?" exploration of the consequences of alternative choices of material, use pattern, and end-of-life scenarios. A full LCA is not well adapted for this task—it is slow and expensive. *Streamlined LCA* and the *eco-audit methods* have evolved to fill the gap. They are approximate but still have sufficient resolution to guide decision making.

This chapter is about the life cycle of materials and its assessment: how an LCA works, its precision (or lack of it), the difficulties of implementing it, and ways these difficulties can be bypassed to guide material choice in product design. The chapter starts with a brief introduction to the design process itself—we need that to see how the assessment and auditing methods mesh with design. It ends by introducing a strategy that is developed in the chapters that follow. There is also an appendix describing currently available LCA software.

3.2 The design process

The starting point of a design is a *market need* or a *new idea*; the end point is the full *specification* of a product that fills the need or embodies the idea. It is essential to define the market need precisely, that is, to formulate a *need statement*, often in the form: "a device is required to perform task X," expressed as a set of *design*

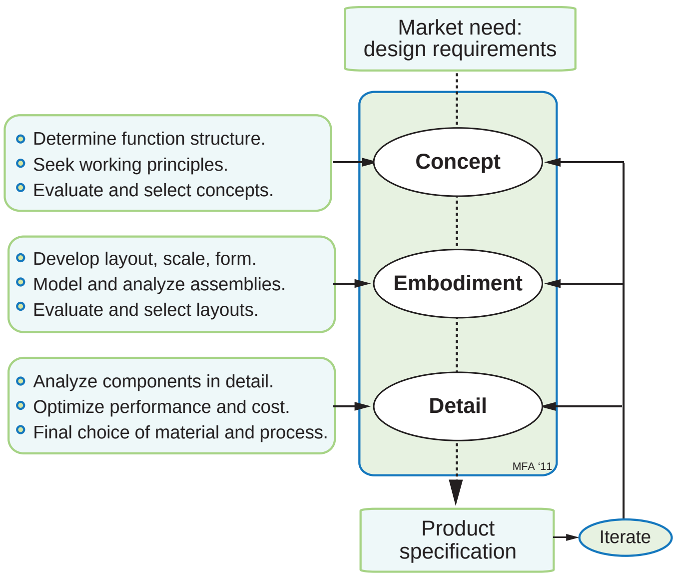


FIGURE 3.1 *The design process: requirements, concept, embodiment, detail, production*

requirements. Between the need statement and the product specification lie the set of stages shown in Figure 3.1: the stages of *concept*, *embodiment*, and *detailed design*.

The design proceeds by developing concepts to perform the functions in the design requirements, each based on a *working principle*. At the concept stage of design all options are open: the designer considers alternative concepts and the ways in which these might be separated or combined. The next stage, embodiment, takes the promising concepts and seeks to analyze their operation at an approximate level. This involves sizing the components and selecting materials that will perform properly in the ranges of stress, temperature, and environment suggested by the design requirements, examining the implications for performance and cost. The embodiment stage ends with a feasible layout, which is then passed to the detailed design stage. Here specifications for each component are drawn up. Critical components may be subjected to precise mechanical or thermal analysis. Optimization methods are applied to components and groups of components to maximize performance. A final choice of geometry and materials is made and the methods of production are analyzed and priced. The output of the detailed stage is a detailed production specification.

The environmental impact that a product has over its subsequent life is largely determined by decisions taken during the design process. The concept, the embodiment, the detail, and the choice of materials and manufacturing process all play a role. A complete assessment of this impact requires a scrutiny of the entire life cycle.

3.3 The materials life cycle

The idea of a *life cycle* has its roots in the biological sciences. Living organisms are born; they develop, mature, grow old and, ultimately, die. The progression is built-in—all organisms follow broadly the same path—but the way they develop on the way, and their behavior, lifespan, and influence depend on their interaction with their *environment*—the surroundings in which they live. Life sciences track the development of organisms and the ways in which they interact with their environment.

The life cycle idea has since been adapted and applied in other fields. In the social sciences it is the study of the interaction of individuals with their social environment. In the management of technology it is the study of the birth, maturity, and decline of an innovation in the business environment. In product design it is the interaction of products with the natural, social, and business environments. Concern about resource depletion (the Club of Rome report, already described), the oil crisis of the early 1970s, followed by the first evidence of carbon-induced global warming, focused attention on yet another field: the life cycle of manufactured products and their interaction, above all, with the natural environment. Products are made of materials—materials are their flesh and bones, so to speak—and these are central to the interaction. The study of a product and its associated material life cycle involves assessing the environmental impacts associated with its life, from the extraction of raw materials to their return to the ecosphere as "waste"—from birth to death, or (if you prefer) cradle to grave. That means tracking materials through life. So let us explore that.

Figure 3.2 is a sketch of the materials life cycle. Ore, feedstock, and energy are drawn from the planet's natural resources and processed to produce materials. These are further processed to create the materials that are subsequently manufactured into products, which are distributed, sold, and used. Products have a useful life at the end of which they are discarded; a fraction of the materials they contain might enter a recycling loop, the rest is committed to incineration or landfill.

Energy and materials are consumed at each point in the life cycle of Figure 3.2, depleting natural resources. There is an associated penalty of carbon dioxide, CO_2, oxides of sulfur, SO_x, and of nitrogen, NO_x, and other emissions in the form of gaseous, liquid, and solid waste and low-grade heat. In low concentrations most of these are harmless, but as their concentrations build, they become damaging. The problem, simply put, is that the sum of these unwanted by-products now often exceeds the capacity of the environment to absorb them. For some, the damage is local and the originator of the emissions accepts the responsibility and cost of containing and fixing it (the environmental cost is said to be *internalized*). For others the damage is global and the creator of the emissions is not held directly

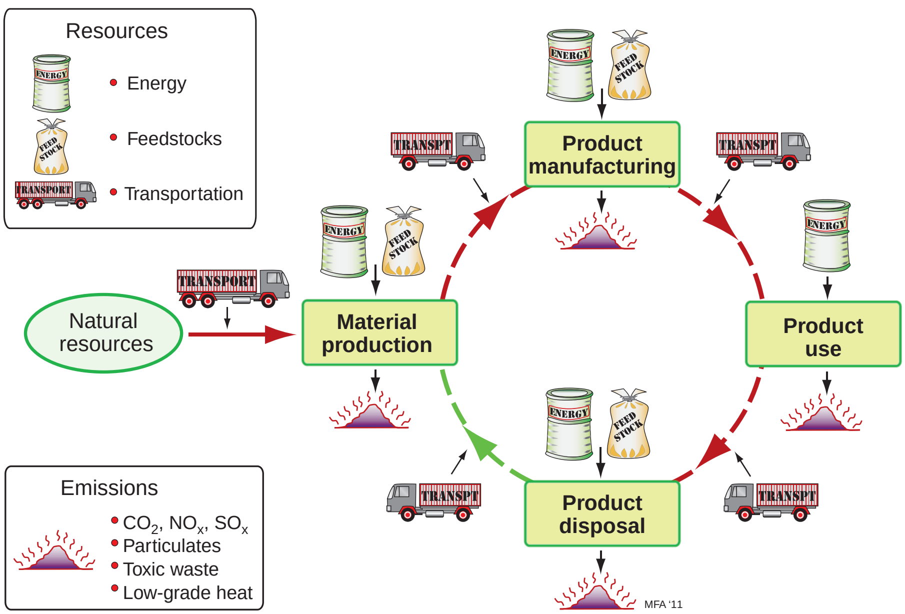


FIGURE 3.2 *The material life cycle. Ore and feedstock are mined and processed to yield a material. This is manufactured into a product that is used and, at the end of its life, discarded, recycled, or, less commonly, refurbished and reused. Energy and materials are consumed in each phase, generating waste heat and solid, liquid, and gaseous emissions.*

responsible, so the environmental cost becomes a burden on society as a whole (it is *externalized*). The study of resource consumption, emissions, and their impacts is called *life-cycle assessment* (LCA).

News-clip: Externalized costs

Nitrogen pollution.
A study evaluates the cost of nitrogen run-off as 150–740 euros per year per EU inhabitant.

***Le Monde*, April 14, 2011**

Nitrates increase the productivity of land and help meet the increasing demand for food that accompanies population growth. The damage caused by nitrate run-off to the ecology of rivers and coastal waters has long been known, but its cost has not been factored into the economics of agriculture. We know the gain in agricultural output that nitrates provide, but up until now, no figure has been placed on the damage they cause. This study sets a very broad range on this figure and allows a first estimate of the net gain or loss associated with the use of nitrates. But until this cost is attached to the price of agricultural produce from nitrated soil, it remains externalized, a hidden cost falling on all EU inhabitants.

3.4 Life-cycle assessment: details and difficulties

Formal methods for life-cycle assessment first emerged in a series of meetings organized by the Society for Environmental Toxicology and Chemistry (SETAC) of which the most significant were held in 1991 and 1993. This led, from 1997 on, to a set of standards for conducting an LCA, issued by the International Standards Organization (ISO 14040 and its subsections 14041, 14042, and 14043). These prescribe procedures for (and here I quote)

> *defining goal and scope of the assessment, compiling an inventory of relevant inputs and outputs of a product system; evaluating the potential impacts associated with those inputs and outputs; interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study.*

The study must (according to the ISO standards) examine energy and material flows in raw material acquisition, processing and manufacturing, distribution and storage (transport, refrigeration, and so forth), use, maintenance and repair, recycling options, and waste management.

There is a lot here and there is more to come. A summary in plainer English might help.

- *Goals and scope:* Why do the assessment? What is the subject and which bit(s) of its life are assessed?

- *Inventory compilation:* What resources are consumed? What emissions are excreted?
- *Impact assessment:* What do the resource consumption and emissions do to the environment—particularly, what bad things?
- *Interpretation:* What do the results mean? If they are bad, what can be done about it?

We look now at what each involves.

Goals and scope. Why do the study? Here are some possible answers.

- To guide the design of more environmentally friendly products
- To demonstrate that you are an environmentally responsible manufacturer
- To allow the public to form their own judgment about your products
- To demonstrate that your products are greener than those of your competitor
- To be able to claim conformity to standards such as ISO 14040 and PAS 2050 (described later)
- Because the enterprise to which you are a supplier or subcontractor requires that you do so so that they can claim conformity to standards.

There is a wide spread of motives here—it would be surprising if one assessment method fit the needs of all.

And there is the question of scope: where should the LCA start and finish? Figure 3.3 shows the four phases of life, each seen as a self-contained unit, with notional “gates” through which inputs pass and outputs emerge. If you were the manager of the manufacturing unit, for example, your purpose might be to assess your plant, ignoring the other three phases of life because everything outside your gates is beyond your control. This is known as a “gate-to-gate” study; its scope is limited to the activity inside the box labelled System Boundary A. There is a tendency for the individual life phases to seek to minimize energy use, material waste, and internalized emission costs spontaneously because it saves money to do so. But this action by one phase may have the result of raising resource consumption and emissions of the others. An example: if minimizing the manufacturing energy and material costs for a car results in a heavier vehicle and one harder to disassemble at end of life, then the gains made in one phase have caused losses in two of the others. Put briefly: the individual life phases tend to be self-optimizing; the system as a whole does not. We return to this in Chapters 9 and 10 where the necessary trade-off methods are developed.

If the broader goal is to assess the resource consumption and emissions of the product over its entire life, the boundary must enclose all four phases (System Boundary B). The scope becomes that of product birth to product death, including, at birth, the ores and feedstock and, at death, the consequences of disposal.

Some LCA proponents see a still more ambitious goal and grander scope (System Boundary C). If ores and feedstock are included (as they are within System Boundary B), why not the energy and material flows required to make the

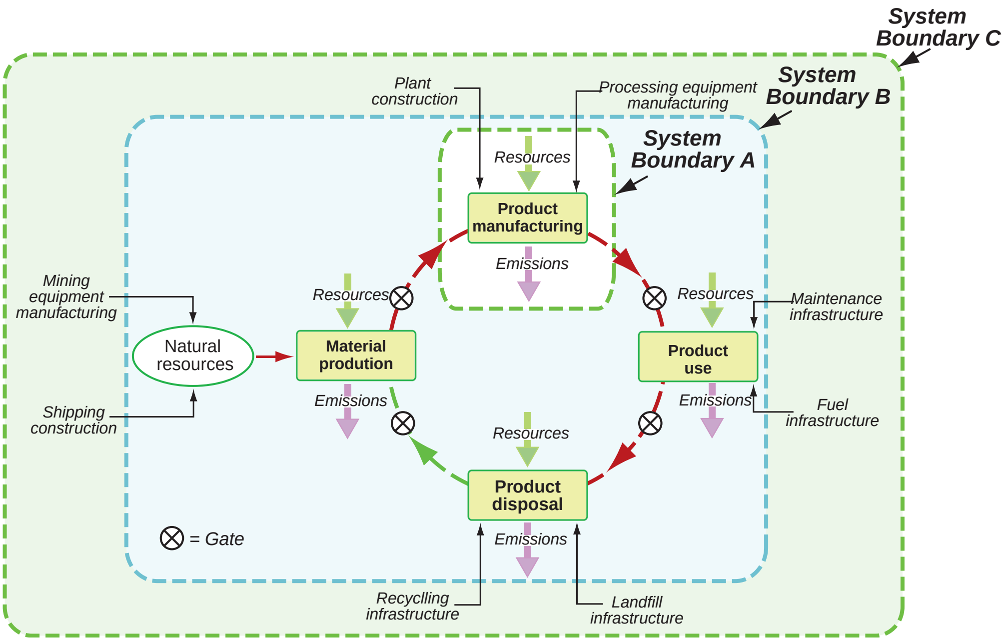


FIGURE 3.3 *LCA system boundaries with the flows of resources and emissions across them. System Boundary A encloses a single phase of the lifecycle. System Boundary B encloses the direct inputs and emissions of the entire life. It does not make sense to place the system boundary at C, which has no well-defined edge.*

equipment used to mine them? And what about the resource and emission flows to make the equipment that made *them*? It is the "infinite recession" problem. Here an injection of common sense is needed. Setting the boundaries at infinity gets us nowhere. Equipment-making facilities make equipment for other purposes, too, and this produces a dilution effect: the remoter they are, the smaller the fraction of their resources and emissions that is directly linked to the product being assessed. The standards are vague on how to deal with this point, merely instructing that the system boundary "shall be determined," leaving the scope of the assessment as a subjective decision. Input-output analysis gives a formal structure for dealing with these more remote contributions, but we shall leave that for later. For now, the practical way forward is to include only the primary flows directly required for the materials, manufacturing, use, and disposal of the product, excluding the secondary ones needed to make the primary ones possible.

Inventory compilation. Setting the boundaries is the first step. The second is data collection: amassing an inventory of the resource flows passing into the system and the emissions passing out. But how should it be measured? Per kilogram (kg) of final product? Yes, if the product is sold and used by weight. Per cubic meter (m^3)

of final product? Yes, if it is sold by volume. But few products are sold and used in this way. More usually it is neither of these but per *unit of function*, a point we will return to in later chapters. The function of a container for a soft drink (a Coke bottle, a plastic water bottle, a beer can) is to contain fluid. The bottle maker might measure resource flows per bottle, but if the idea is to compare containers of different size and material, then the logical measure is the resources consumed *per unit volume of fluid contained*. Refrigerators provide a cooled environment and maintain it over time. The maker might measure resource flows per fridge, but the logical measure from a life-cycle standpoint is the resource consumption *per unit of cooled volume per unit time* (cold space/m^3/year).

We will find that the functional units of resources entering one phase are not the same as those leaving it. There is nothing subtle about this, it's just to make accounting easier. Thus the flow of materials leaving Phase 1 of life and entering Phase 2 *is* traded by weight, so the functional unit here is "per unit weight": the embodied energy of copper, for instance, is listed as 68–74 MJ/kg. The output of Phase 2 is a product; here "per product" might be used. In the use phase, the function performed by the product is of central importance and here the logical measure is "per unit of function."

The inventory analysis, then, assesses resource consumption and emissions per functional unit. It is also necessary to decide on the level of detail—the granularity—of the assessment. It doesn't make sense to include every nut, bolt, and rivet. But where should the cut-off come? One proposal is to include the components that make up 95% of the weight of the product, but this is risky: electronics, for instance, don't weigh much, but the resources and emissions associated with their manufacture can be large, a point we return to in Chapter 6.

Figure 3.4 is a schematic of the start of an inventory analysis—the identification of the main resources and emissions for a washing machine. Most of the parts are made of steel, copper, plastics, and rubber. Both materials production and product manufacturing require carbon-based energy with associated emissions of CO_2, NO_x, SO_x, and low-grade heat. The use phase consumes water as well as energy, with contaminated water as an emission. Disposal of the washing machine creates burdens typical of any large appliance.

Impact assessment. The inventory, once assembled, lists resource consumption and emissions but they are not all equally malignant—some are of more concern than others. Impact categories include *resource depletion, global warming potential, ozone depletion, acidification, eutrophication,*[1] *human toxicity*, and more. Each impact is calculated by multiplying the quantity of each inventory item by an *impact assessment factor*[2]—a measure of how profoundly a given inventory type

[1]The over-enrichment of a body of water with nutrients—phosphates, nitrates—resulting in excessive growth of organisms and depletion of oxygen concentration.

[2]Normalization and impact assessment factors can be found in PAS 2050 (2008) or Saling et al. (2002).

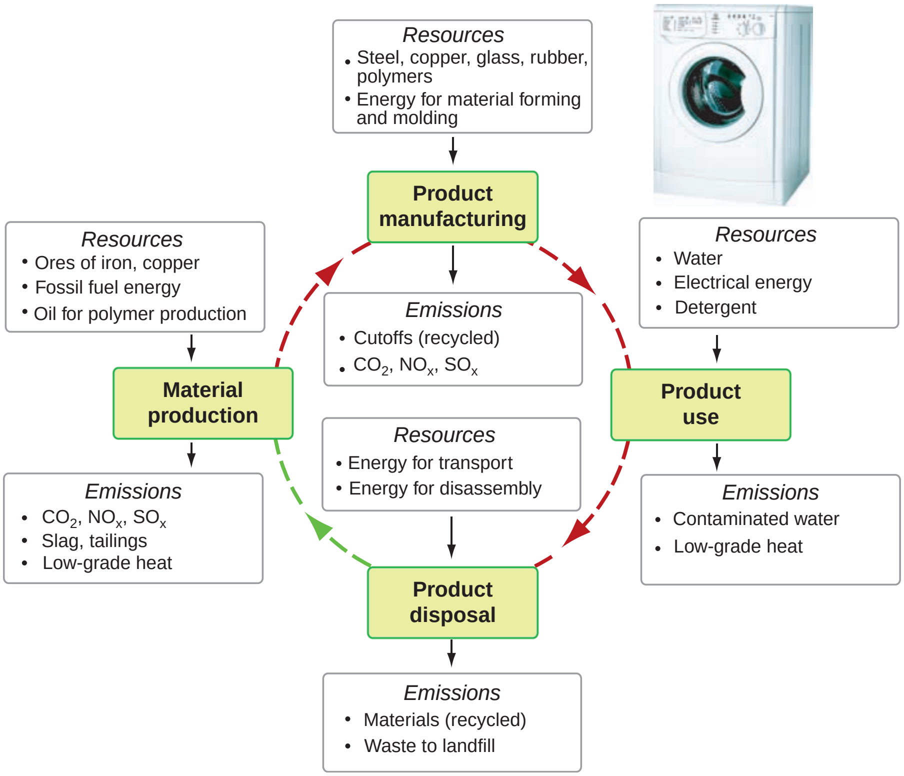


FIGURE 3.4 *The principal resource emissions associated with the lifecycle of a washing machine*

Table 3.1 Example of global warming potential impact assessment factors

Gas	Impact assessment factor
Carbon dioxide, CO_2	1
Carbon monoxide, CO	1.6
Methane, CH_4	21
Di-nitrous monoxide, N_2O	256

contributes to each impact category. Table 3.1 lists some examples of that for assessing global warming potential. The overall impact contribution of a product to each category is found by multiplying the quantity of each emission by the appropriate impact assessment factor, and summing the contributions of all the components of the product for all four phases of life.

Interpretation. What do these inventory and impact values mean? What should be done to reduce their damaging qualities? The ISO standard requires answers to these questions but gives little guidance about how to reach them beyond suggesting that it is a matter for specialists.

All this makes a full LCA a time-consuming matter requiring experts. Expert time is expensive. A full LCA is not something to embark on lightly. And while it is very detailed, it is not necessarily very precise.

The output and its precision. Figure 3.5 is part of the output of an LCA—one for the production of aluminum cans (it stops at the exit gate of the manufacturing plant, so this is a "cradle to gate" and not a "cradle to grave" study). The functional unit is "per 1,000 cans." There are three blocks of data: the first is an inventory of resources of ores, feedstock, and energy; the second is a catalog of emissions of gases and particulates; the third is an assessment of impacts—only some of them are shown in the figure.

Despite the formalism that attaches to LCA methods, the results are subject to considerable uncertainty. *Resource* and *energy* inputs can be monitored in a straightforward and reasonably precise way. The *emissions* rely more heavily on sophisticated monitoring equipment—few are known to better than ±10%. Assessments of *impacts* depend on values for the marginal effect of each emission on each impact category; many of these have much greater uncertainties.

And there are two further difficulties, both troublesome. First, what is a designer supposed to do with these numbers? The designer, seeking to cope with the many interdependent decisions that any design involves inevitably finds it hard to know how best to use data like those of Figure 3.5. How are energy, or CO_2 and SO_x, emissions to be balanced against resource depletion, energy consumption,

	Aluminum cans, per 1000 units		
Resource consumption	• Bauxite	59	kg
	• Oil fuels	148	MJ
	• Electricity	1572	MJ
	• Energy in feedstocks	512	MJ
	• Water use	1149	kg
Emissions inventory	• Emissions: CO_2	211	kg
	• Emissions: CO	0.2	kg
	• Emissions: NO_x	1.1	kg
	• Emissions: SO_x	1.8	kg
	• Particulates	2.47	kg
Impact assessment	• Ozone depletion potential	0.2×10^{-9}	
	• Global warming potential	1.1×10^{-9}	
	• Acidification potential	0.8×10^{-9}	
	• Human toxicity potential	0.3×10^{-9}	

FIGURE 3.5 *Typical LCA output showing three categories: resource consumption, emission inventory, and impact assessment (data in part from Boustead, 2007)*

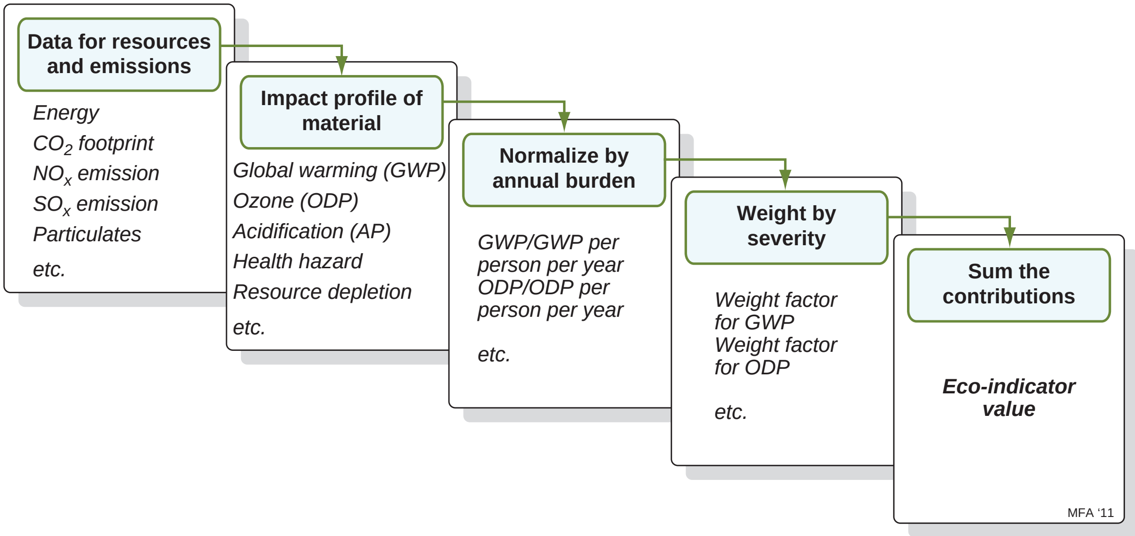


FIGURE 3.6 *The steps in calculating an eco-indicator. Difficulties arise in steps 3 and 4: there is no agreement on how to choose the weight factors.*

global warming potential, or human toxicity? They are not measured in the same units and they differ, in the example of Figure 3.5, by six orders of magnitude. And second, how is the assessment to be paid for? A full LCA takes days or weeks. Does the result justify this considerable expense? LCA has value as a *product assessment tool*, but it is not a *design tool*.

Aggregated measures: eco-indicators. The first of these difficulties has led to efforts to condense the LCA output into a single measure called an *eco-indicator*. To do this, four steps are necessary, shown in Figure 3.6. The first is that of *classification* of the data listed in Figure 3.5 according to the impact each causes (global warming, ozone depletion, acidification, etc.). The second step is that of *normalization* to remove the units and reduce the data to a common scale (0–100, for instance). The third step is that of *weighting* to reflect the perceived seriousness of each impact. Thus global warming might be seen as more serious than resource depletion, and therefore, it is given a larger weight. In the final step, the weighted, normalized measures are *summed* to give the indicator.[3] Eco-indicators are most used in condensing eco-information for the first phase of life, that of material production. Values for materials, when available, are included in the data sheets of Chapter 15.

The use of eco-indicators is criticized by some. The grounds for criticism are that there is no agreement on normalization or weighting factors, that the method is

[3]Details can be found in EPS (1993), Idemat (1997), EDIP (1998), and Wenzel et al. (1997).

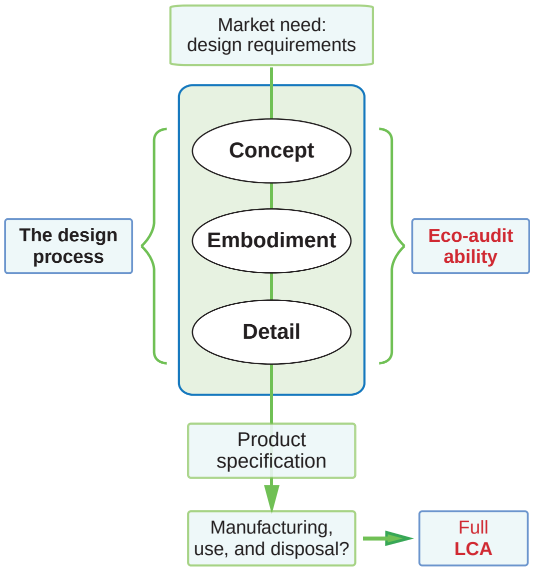


FIGURE 3.7 *An LCA is an end-of-life assessment tool. A streamlined LCA and an eco-audit are design tools.*

opaque since the indicator value has no simple physical significance, and that defending design decisions based on a measurable quantity like *energy consumption* or *carbon release to atmosphere* carries more conviction than doing so with an indicator.

In summary, a full LCA offers the most complete and exhaustive analysis of the environmental impact of products, but it is an expensive, time-consuming tool that requires great detail, much of it unavailable until the product has been manufactured and used. To guide design decisions, particularly the choice of materials, we need tools of a different sort, ideally with the ability to carry out rapid "what if?" audits that allow the designer to explore alternative options (Figure 3.7).

3.5 Streamlined LCA and eco-auditing

Emerging legislation imposes ever increasing demands on manufacturers for eco-accountability. The EU Directive 2005/32/EC on energy-using products (EuPs), for example, requires that manufacturers of EuPs must demonstrate "that they have considered the use of energy in their products as it relates to materials, manufacture, packaging, transport, use and end of life." This sounds horribly like it requires that the manufacturers conduct a full LCA on each one of their products. Many manufacturers make hundreds of different products. The expense both in money and time would be prohibitive.

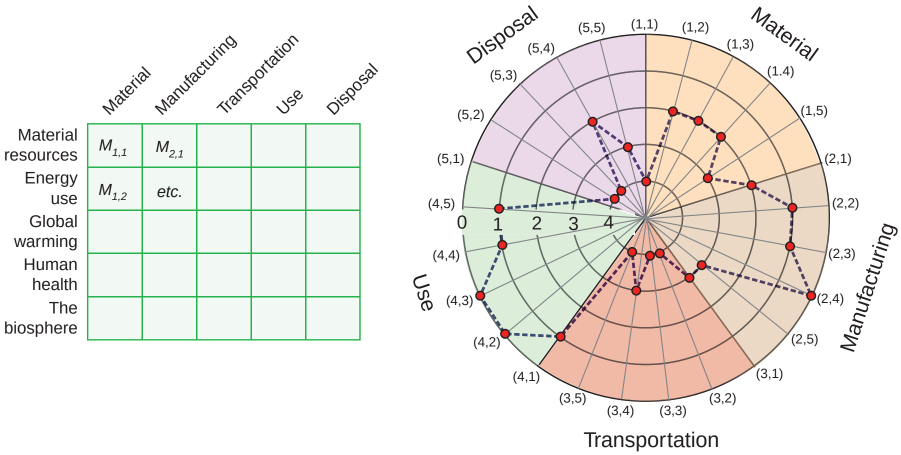


FIGURE 3.8 *An example of a streamlined LCA matrix and a target plot displaying the rankings in each element of the matrix. In this example the use phase gets poor ratings.*

As already explained, the complexity of a full LCA makes it unworkable as a design tool. This perception has stimulated two lines of development: simplified or "streamlined" methods of assessment that focus on the most significant inputs, neglecting those perceived to be secondary; and software-based tools that ease the task of a conducting an LCA. Software solutions are documented in the appendix to this chapter. Let's turn now to streamlining.

The matrix method. The detail required for a full LCA precludes its use as a design tool; by the time the necessary detail is known, the design is too far advanced to allow radical change. *Streamlined LCA* attempts to overcome this by basing the study on a reduced inventory of resources, accepting a degree of approximation. One approach is to simplify while still attempting a *quantitative* analysis—one using numbers—described in Chapters 7 and 8 of this book. The other—one developed by Graedel[4] and others, and used in various forms by a number of industries—is *qualitative*. The matrix on the left of Figure 3.8 shows the idea. The life phases appear as the column headers; the impacts as the row headers. An integer between 0 (highest impact) and 4 (least impact) is assigned to each matrix element M_{ij}, based on experience guided by checklists, surveys, or protocols.[5] The overall *Environmentally Responsible Product Rating*, R_{erp}, is the sum of the matrix elements.

$$R_{erp} = \sum_i \sum_j M_{ij} \tag{3.1}$$

[4]Graedel (1998); Todd and Curran (1999)—see Further reading at the end of the chapter.

[5]Graedel (1998) provides an extensive protocol.

Alternative designs are ranked by this rating.

The information in the matrix is displayed in a more visual way as a target plot, shown on the right of Figure 3.8. It has five concentric circles corresponding to the ranking 0 (highest impact) to 4 (least impact); the elements of the matrix are plotted as dots on radial lines, one line for each element. For an "ideal" product, all the dots lie on the innermost ring, scoring a "bull's-eye." A product with its dots near the outermost circle has much room for improvement.

An eco-comparison of 1950s and 1990s cars[6]

Example: *The task.* Table 3.2 is a low-resolution bill of materials and fuel consumption for typical cars of the 1950s and the 1990s. The 1950s car is heavier, made of relatively few materials, none of them of recycled origin, has poor fuel efficiency, and was dumped at end of life. The more modern car is lighter, made of a more complex

Table 3.2 Estimated material content of generic automobiles*

Material	1950s auto (kg)	1990s auto (kg)
Iron	220	207
Steel	1290	793
Aluminum	0	68
Copper	25	22
Lead	23	15
Zinc	25	10
Plastics	0	101
Rubber	85	61
Glass	54	38
Platinum	0	0.001
Fluids	96	81
Other	83	38
Total weight (kg)	**1901**	**1434**
Fuel consumption	**15 mpg**	**27 mpg**

**From Graedel (1998)*

[6]Data and basic methods from Graedel (1998).

mix of materials, some derived from recycling, has better fuel efficiency, and will be 80% recycled at end of life. Compare the eco-profiles of the two vehicles.

Answer: The assessor chooses energy efficiency, carbon efficiency, and material efficiency as three eco-criteria to use in the assessment ("efficient" means that the function, private transport, is provided with the minimum use of material and energy resources and of carbon emissions). The assessment is to be cover life. Using this background information and considerable experience, the assessor assigns the rankings of 0 to 4 to each element of the matrices shown in the upper part of Figure 3.9. The 1950s car scores an R_{erp} value of 18. The 1990s car scores 39. The lower part of the figure shows the corresponding target plots. Unsurprisingly, the eco-character of the 1990s car in this example is rather better than that of the 1950s, particularly in its use and disposal phases. All very instructive, but how did the assessor arrive at the rankings? The answer is buried in the store of experience the assessor brings to bear on the task. And do the absolute values of the numbers have any significance? Clearly not. The energy used to propel a car over its life greatly exceeds that required to manufacture it or to create the materials of which it is made. The matrix and target plot capture the issues, but not their relative importance. For that, we need numbers.

1950s automobile

	Material	Manufacturing	Transportation	Use	Disposal
Material efficiency	*0*	*0*	*3*	*2*	*0*
Energy efficiency	*2*	*1*	*3*	*0*	*2*
Carbon efficiency	*2*	*0*	*2*	*0*	*1*

$R_{erp} = 18$

1990s automobile

	Material	Manufacturing	Transportation	Use	Disposal
Material efficiency	*4*	*2*	*1*	*3*	*3*
Energy efficiency	*3*	*3*	*2*	*2*	*3*
Carbon efficiency	*3*	*2*	*2*	*2*	*4*

$R_{erp} = 39$

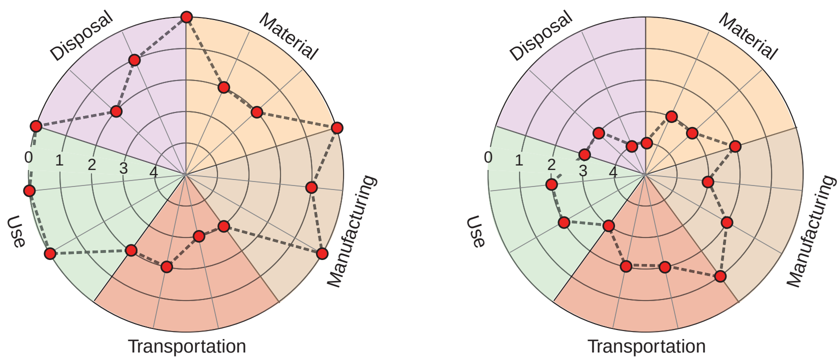


FIGURE 3.9 *The assessment matrices and the target plots for cars of the 1950s and of 1990s. The more modern car has a higher value of* R_{etp} *and a smaller enclosed area on the target plot.*

FIGURE 3.10 *It is now standard practice to report official fuel economy figures for cars (e.g., Combined: 42–46 mpg [5.9–6.4 liter/100 km]),* CO_2 *emissions: 143–154 g/km) and energy ratings for appliances (e.g., 330 kWh/year, efficiency rating: A).*

There are many variants of the matrix approach, differing in the impact categories of the rows and the life (or other) categories of the columns. The method's benefits include that it is flexible, easily adapted to a variety of products, carries a low overhead in time and effort, and—in the hands of practitioners of great experience—can take the subtleties of emissions and their impacts into account. It has the drawback that it relies heavily on experience and judgment. It is not a tool to put in the hands of a novice. Is there an alternative?

One resource, one emission. There is, as yet, no consensus on a metric for the eco-impact of product life that is both workable and able to guide design. On one point, however, there is a degree of international agreement[7]: a commitment to a progressive reduction in carbon emissions, generally interpreted as meaning carbon dioxide (CO_2) or carbon dioxide equivalent ($CO_{2,eq}$), a value corrected for the global warming potential of the other gaseous emissions. At the national level the focus is more on reducing energy consumption, but since this and CO_2 production are closely related, reducing one generally reduces the other. Thus there is a certain logic in basing design decisions on one resource—energy—and one emission—CO_2. They carry more conviction than the use of a more obscure indicator, as evidenced by the now-standard reporting of both energy efficiency and the CO_2 emissions of cars, and the energy rating and efficiency ranking of appliances (Figure 3.10) dealing with the use-phase of life. To justify this further, we digress briefly to glance at the IPCC report of 2007.

The 2007 IPCC report. The Intergovernmental Panel on Climate Change (IPCC)—an international study set up by the World Meteorological Organization and the

[7]The Kyoto Protocol of 1997 and subsequent Treaties and Protocols, detailed in Chapter 5.

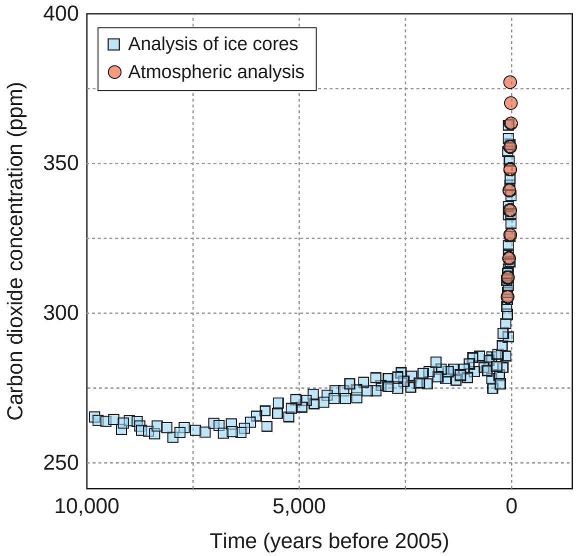


FIGURE 3.11 *Atmospheric concentration of CO_2 over the past 10,000 years measured from ice cores and atmospheric samples. Redrawn from the IPCC report of 2007.*

United Nations Environmental Panel—publishes a series of reports on the effect of industrial activity on the biosphere and the human environment. The most recent of these (IPCC, 2007) is of such significance that familiarity with it is a prerequisite for thinking about sustainability and the environment. Briefly, the conclusions it reaches are these:

- The average air, ocean, and land surface temperatures of the planet are rising. The increase is causing widespread melting of snow and ice cover, rising sea levels, and changes of climate.
- Climate change, measured, for instance, by the annual averages of the air, ocean, and land temperatures, affects natural ecosystems, agriculture, animal husbandry, and human environments. An increase in average global temperature of just 1°C can have a significant effect on all of them. A rise of 5° would create great difficulties.
- The global atmospheric concentration[8] of CO_2 has increased at an accelerating rate since the start of the industrial revolution (around 1750) and is now at its highest level for the past 600,000 years. Most of the increase has been between 1950 and the present day (Figure 3.11).

[8]Throughout this book carbon release to the atmosphere is measured in kg of CO_2. One kg of elemental carbon is equivalent to 3.6 kg of CO_2. For a wide range of materials the value of $CO_{2,eq}$ can be equated to $1.06 \times CO_2$, both measured in kg/kg.

- Increasingly accurate geophysical measurements allow the history of temperature and atmospheric carbon to be tracked, and increasingly precise meteorological models allow scenario exploration and prediction of future trends in both. Both suggest that climate-temperature rise is caused by greenhouse gases, and that anthropomorphic (man-made) CO_2 is the probable cause.

The point is that, of the many emissions associated with industrial activity, it is CO_2 that is of greatest current concern. It is global in its impact, causing harm both to the nations that generate most of it and those that do not. It is closely related to the consumption of fossil fuels, themselves a diminishing resource and one that is a source of international tension. If the IPCC report is to be taken seriously, the urgency to cut carbon emissions is great. At this stage in structuring our thinking about materials and the environment, taking energy consumption and the release of atmospheric CO_2 (or $CO_{2,eq}$) as metrics is a logical simplification.

3.6 The strategy

The need is for an assessment strategy that addresses current concerns and combines acceptable cost burden with sufficient precision to guide decision making. It should be flexible enough to accommodate future refinement and simple enough to allow rapid "what if?" exploration of alternatives. To achieve this, it is necessary to strip off much of the detail, multiple targeting, and complexity that make standard LCA methods so cumbersome.

The approach developed here has three components:

1. ***Adopt simple metrics of environmental stress.*** As already discussed, energy consumption and CO_2 emissions are logical choices as simple metrics for environmental stress. The two are related and are understood by the public at large. Energy has the merit that it is the easiest to monitor, can be measured with relative precision, and, with appropriate precautions, can if necessary be used as a proxy for CO_2.
2. ***Distinguish the phases of life.*** Figure 3.12 suggests the breakdown—assigning a fraction of the total life-energy demands of a product to material creation, product manufacturing, transport, product use, and disposal. Product disposal can take many forms, some carrying an energy penalty, some allowing energy recycling or recovery. Because of this ambiguity, disposal has a chapter (Chapter 4) to itself.
   When this distinction is made, it is frequently found that one of the phases of life dominates the picture. Figure 3.13 presents the evidence. The upper row shows an approximate energy breakdown for three classes of energy-using products: a civil aircraft, a family car, and an appliance. For all three the use-phase consumes more energy than the sum of all the others.

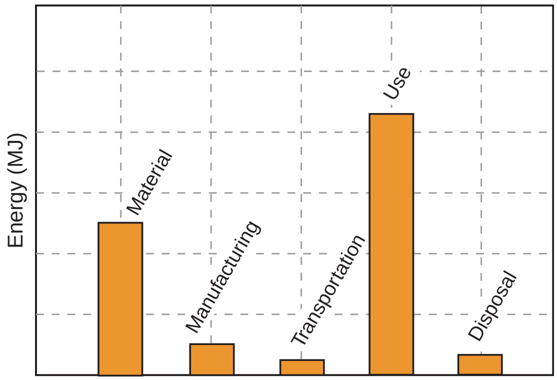


FIGURE 3.12 *Breakdown of energy into that associated with each life phase*

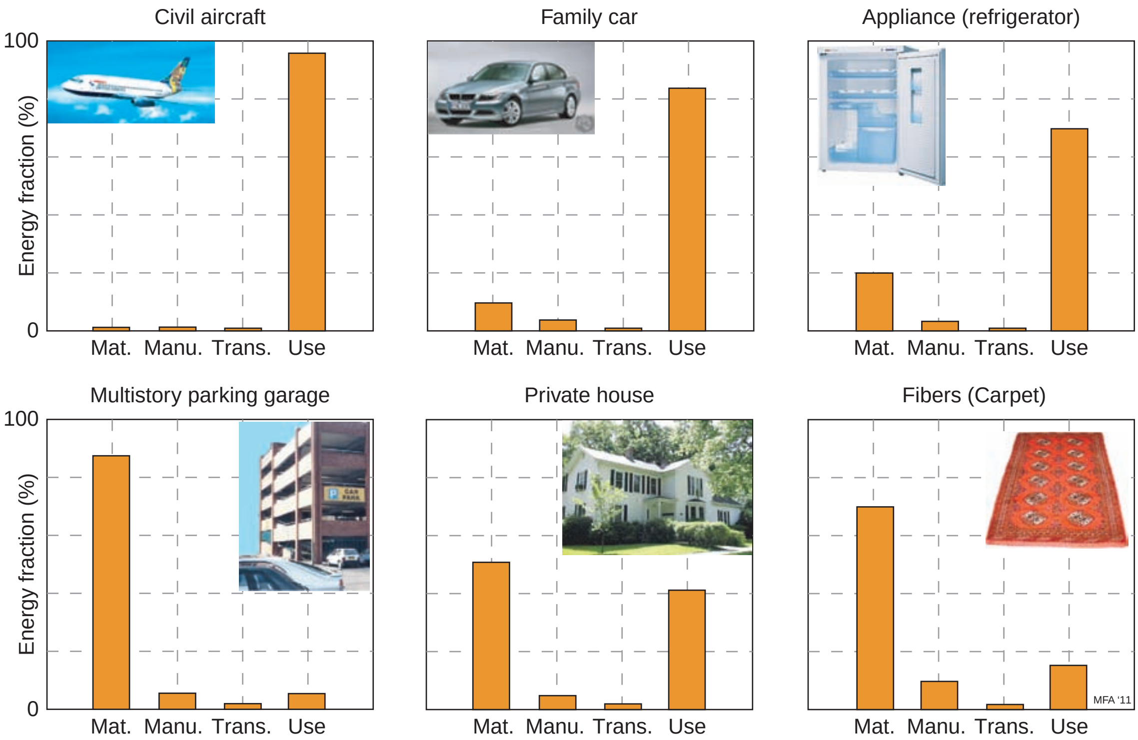


FIGURE 3.13 *Approximate values for the energy consumed at each phase of Figure 3.2 for a range of products. The disposal phase is not shown because there are many alternatives for each product.*

The lower row shows products that still require energy during the use-phase of life, but not as much as those of the upper row. For these, the embodied energies of the materials of which they are made are frequently the largest contribution.

Two conclusions can be drawn. The first: when one phase of life dominates, it is this dominant phase that becomes the first target for redesign since it is here that a given fractional reduction makes the biggest contribution. The second: when differences are as great as those in Figure 3.13, great precision is not essential because it is the ranking that matters. Modest changes to the input data leave the ranking unchanged. It is the nature of people who measure things to wish to do so with precision, and precision must be the ultimate goal. But it is possible to move forward without it: precise judgments can be drawn from imprecise data.

3. ***Base the subsequent action on the energy or carbon breakdown.*** Figure 3.14 suggests how the strategy can be implemented. If material production is the dominant phase, then the logical way forward is to choose materials with low embodied energy and to minimize the amount of it that is used. If manufacturing is an important energy-using phase of life, reducing processing energies becomes the prime target. If transportation

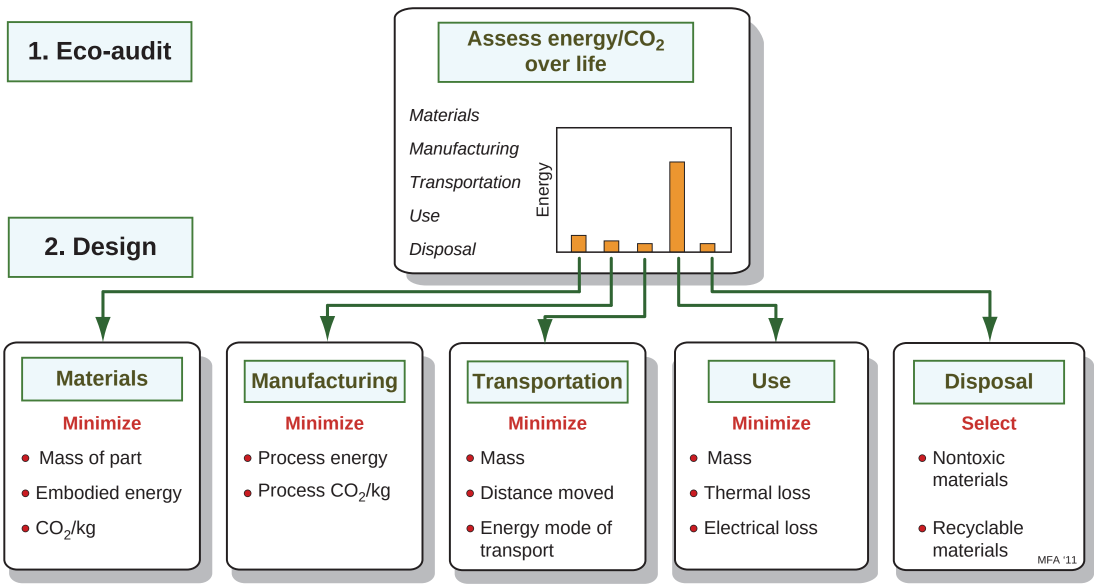


FIGURE 3.14 *Rational approaches to the ecodesign of products start with an analysis of the phase of life to be targeted. Its results guide redesign and materials selection to minimize environmental impact. The disposal phase, shown here as part of the overall strategy, is not included in the current version of the tool.*

makes a large contribution, then seeking a more efficient transportation mode or reducing transportation distance becomes the first priority. When the use-phase dominates, the strategy is that of

- minimizing mass and rolling resistance if the product is part of a system that moves,
- increasing thermal efficiency if the product is a thermal or thermo-mechanical system, or
- reducing electrical losses if the product is an electromechanical system.

In general, the best material choice to minimize one phase will not be the one that minimizes the others, requiring trade-off methods (Chapter 9) to reach an appropriate compromise.

Implementation requires tools. Two tools are needed, one to perform the eco-audit sketched in the upper part of Figure 3.14, the other to enable the analysis and selection of the lower part. The first, the eco-audit tool, is described in Chapter 7 and 8. The second, that of optimized selection, is the subject of Chapters 9 and 10. Tools require data. Data sheets for materials, documenting their engineering and eco-properties,[9] appear in Chapter 15.

3.7 Summary and conclusions

Products, like organisms, have a life, during the course of which they interact with their environment. Their environment is also ours; if the interaction is a damaging one, it diminishes the quality of life of all who share it.

Life-cycle assessment (LCA) is the study and analysis of this interaction, quantifying the resources consumed and the waste emitted. It is holistic, spanning the entire life from the creation of the materials, through the manufacture of the product, its use, and its subsequent disposal. Although standards (the ISO 14040 series) now prescribe procedures for conducting an LCA, they remain vague, allowing a degree of subjectivity. Implementing them requires skill and access to much detail, making a full LCA expensive in both money and time, and one that delivers outputs that are not well adapted to the needs of designers.

No surprise. The technique of LCA is relatively new and is still evolving. The way forward is to adopt a less rigorous but much simpler approach, streamlining the assessment by restricting it to the key eco-aspects of most immediate concern. The matrix method, of which there are many variants, assigns a ranking for each impact category in each phase of life, summing the rankings to get an Environmentally Responsible Product Rating. Another approach, better adapted to guiding material choice, is to limit the impact categories to one resource—energy—and one emission—CO_2—auditing designs or products for their demands on both.

[9]The data sheets are a subset of those contained in the CES (2011) software, which also implements both the tools described here.

Providing that the resolution of the audit is sufficient to draw meaningful conclusions, the results can guide design decisions without imposing an unacceptable burden of analysis.

3.8 Further reading

Aggregain (2007), The Waste and Resources Action Program (WRAP), www.wrap.org.UK. ISBN 1-84405-268-0. *(Data and an Excel-based tool to calculate energy and the carbon footprint of recycled road-bed materials)*

Allwood, J.M., Laursen, S.E., de Rodriguez, C.M., and Bocken, N.M.P. (2006), *Well dressed? The present and future sustainability of clothing and textiles in the United Kingdom*, University of Cambridge, Cambridge, UK. ISBN 1-902546-52-0. *(An analysis of the energy and environmental impact associated with the clothing industry)*

"Boustead Model 5" (2007), Boustead Consulting, West Sussex, UK, www.boustead-consulting.co.uk. Accessed December 2011. *(An established life-cycle assessment tool)*

"Eco-indicator "(1999), PRé Consultants, Amersfoort, Netherlands, www.pre.nl/eco-indicator99/eco-indicator_99.htm. Accessed December 2011. (An explanation of the Eco-indicator method.)

EPS (1992), "The EPS enviro-accounting method: an application of environmental accounting principles for evaluation and valuation in product design," *Report B1080*, IVL Swedish Environmental Research Institute, by Steen, B., and Ryding, S.O. Gothenburg, Sweden. (The EPS method is an alternative to the Eco-indicator approach.)

EU Directive on Energy Using Products (2005), "Directive 2005/32/EC of the European Parliament and of the Council of 6 July 2005 establishing a framework for the setting of ecodesign requirements for energy-using products and amending Council Directive 92/42/EEC and Directives 96/57/EC and 2000/55/EC of the European Parliament and of the Council." Strasburg, France *(One of several EU Directives relating to the role of materials in product design)*

GaBi (2008), PE International, Leinfelden-Echterdingen, Germany. www.gabi-software.com/. Accessed December 2011. *(GaBi is a software tool for product assessment to comply with European legislation.)*

Goedkoop, M., Effting, S., and Collignon, M. (2000), "The Eco-indicator 99: A damage oriented method for Life-cycle Impact Assessment, Manual for Designers," www.pre.nl. Accessed December 2011. *(An introduction to eco-indicators, a technique for rolling all the damaging aspects of material production into a single number)*

Graedel, T.E., and Allenby, B.R. (2003), *Industrial ecology,* 2nd edition, Prentice Hall, NJ, USA. ISBN 978-0131252387. *(An established treatise on industrial ecology)*

Graedel, T.E. (1998), *Streamlined Life-cycle Assessment*, Prentice Hall, NJ, USA. ISBN 0-13-607425-1. *(Graedel is the father of streamlined LCA methods. The first half of this book introduces LCA methods and their difficulties. The second half develops his streamlined method with case studies and exercises. The appendix details protocols for informing assessment decision matrices.)*

GREET (2007), Argonne National Laboratory and the US Department of Transportation, www.transportation.anl.gov/. Accessed December 2011. *(Software for analyzing vehicle energy use and emissions)*

Guidice, F. La Rosa, G., and Risitano, A. (2006), *Product design for the environment,* CRC/Taylor and Francis, London, UK. ISBN 0-8493-2722-9. (*A well-balanced review of current thinking on ecodesign*)

Heijungs, R. (editor) (1992), "Environmental life-cycle assessment of products: background and guide," Netherlands Agency for Energy and Environment, Amsterdam, the Netherlands.

"Idemat Software" version 1.0.1 (1998), Faculty of Industrial Design Engineering, Delft University of Technology, Delft, The Netherlands. *(An LCA tool developed by the University of Delft)*

ISO 14040 (1998), Environmental management—Life-cycle assessment—Principles and framework.

ISO 14041 (1998), Goal and scope definition and inventory analysis.

ISO 14042 (2000), Life-cycle impact assessment.

ISO 14043 (2000), Life-cycle interpretation, International Organization for Standardization, Geneva, Switzerland. *(The set of standards defining procedures for life-cycle assessment and its interpretation)*

Kyoto Protocol (1997), United Nations, Framework Convention on Climate Change. Document FCCC/CP1997/7/ADD.1, http://unfccc.int/resource/docs/convkp/kpeng.pdf. Accessed December 2011. *(An international treaty to reduce the emissions of gases that, through the greenhouse effect, cause climate change)*

MEEUP Methodology Report, final (2005), VHK, Delft, Netherlands, www.pre.nl/EUP/. Accessed December 2011. *(A report by the Dutch consultancy VHK commissioned by the European Union, detailing their implementation of an LCA tool designed to meet the EU Energy-using Products directive)*

MIPS (2008), The Wuppertal Institute for Climate, Environment and Energy, www.wupperinst.org/en/projects/topics_online/mips/index.html. Accessed December 2011. *(MIPS software uses an elementary measure to estimate the environmental impacts caused by a product or service.)*

National Academy of Engineering and National Academy of Sciences (1997), *The Industrial Green Game: Implications for Environmental Design and Management*, National Academy Press, Washington, DC, USA. ISBN 978-0309-0529-48. *(A monograph describing best practices that are being used by a variety of industries in several countries to integrate environmental considerations in decision making)*

PAS 2050 (2008), *Specification for the assignment of the life-cycle greenhouse gas emissions of goods and services*, ICS code 13.020.40, British Standards Institution, London, UK. ISBN 978-0-580-50978-0. *(A proposed European Publicly Available Specification (PAS) for assessing the carbon footprint of products)*

Saling, P, Kicherer, A., Dittrich, B.Wittlinger, R., Zombik, W., Schmidt, I., Schrott, W., and Schmidt, S. (2002), "Eco-efficiency analysis by BASF: the method," *Int. J. Life-cycle Assess*, 7, pp 203–218. (A description of the eco-efficiency metric devised for use by BASF.)

SETAC (1991), "A technical framework for life-cycle assessment," Fava, J.A., Denison, R., Jones, B., Curran, M.A., Vignon, B., Selke, S., and Barnum, J., (Eds.), Society of Environmental Toxicology and Chemistry, Washington, DC, USA. *(The meeting at which the term Life-cycle Assessment was first coined)*

SETAC (1993), "Guidelines for life-cycle assessment—a code of practice," Consoli, F., Fava J.A., Denison, R., Dickson, K., Kohin, T., and Vigon, B. (Eds.), Society of Environmental Toxicology and Chemistry, Washington, DC, USA. *(The first formal definition of procedures for conducting an LCA)*

Todd, J.A., and Curran, M.A. (1999), "Streamlined life-cycle assessment: a final report from the SETAC North America streamlined LCA workshop," Society of Environmental Toxicology and Chemistry, Washington, DC, USA. *(One of the early moves toward streamlined LCA)*

3.9 Appendix: software for LCA

The most common uses of life-cycle assessment are for product improvement ("how can I make my products greener?"), support of strategic choices ("is this or that the greener development path?"), benchmarking ("how do our products compare?"), and for communication ("our products are the greenest."). Most of the software tools designed to help with this use ISO 14040 to 14043 as a prescription. In doing so, they commit themselves to a process of considerable complexity.[10] There is no compulsion to follow this route and some do not. Some of these are aimed at specific product sectors (vehicle design, building materials, paper making). Others are aimed at the early stages of product design and these, of necessity, are simpler in their structure. Two, at least, have education as its target. So there is quite a spectrum, 11 of which are listed in Table 3.3. Some of these tools are free, some can be bought, and others are available only through the services of a consultant—an understandable precaution, given their complexity.

SimaPro (2008). SimaPro 7.1 is a widely used tool to collect, analyze, and monitor the environmental performance of products and services developed by Pré Consultants in the Netherlands. Life cycles can be analyzed in a systematic way, following the ISO 14040 series recommendations. There is an educational version. A free demo is available from the Pré web site.

Boustead Model 5 (2007). The Boustead Model is a tool for life-cycle inventory calculations broadly following the ISO 14040 series recommendations. Ian Boustead, the author of the software, has many years of experience in cycle assessment working with European polymer suppliers.

TEAM (2008). TEAM is Ecobilan's Life-cycle Assessment software. It allows the user to build and use a large database and to model systems associated with products and processes following the ISO 14040 series of standards.

[10]Pré Consultants estimate that the time needed to perform a "screening" LCA is about 8 days, that for a full LCA is about 22 days.

Table 3.3 LCA and LCA-related software

Tool name	Provider
SimaPro	Pré Consultants (www.pre.nl)
Boustead model 5	Boustead Consultants (www.boustead-consulting.co.uk)
TEAM (EcoBilan)	PricewaterhouseCoopers (www.ecobalance.com/)
GaBi	PE International (www.gabi-software.com/)
MEEUP method	VHK, Delft, Netherlands (www.pre.nl/EUP/)
GREET	US Department of Transport (www.transportation.anl.gov/)
MIPS	Wuppertal Institute (www.wupperinst.org/)
CES Eco '12	Granta Design, Cambridge, UK (www.grantadesign.com)
Aggregain	WRAP (www.aggregain.org.uk/)
KCL-ECO 3.0	KCL Finland (www.kcl.fi)
Eiloca	Carnegie Mellon Green Design Institute, USA (www.eiolca.net/)
Okala Ecodesign guide	Industrial Design Society of America (www.idsa.org/okala-ecodesign-guide)
LCA Calculator	IDC, London, UK(www.lcacalculator.com/)

GaBi (2008). GaBi 4, developed by PE International, is a sophisticated tool for product assessment to comply with European legislation. It has facilities for analyzing cost, environment, social, and technical criteria and optimization of processes. A demo is available.

MEEUP method (2005). The Dutch Methodology for Ecodesign of Energy-using Products (MEEUP) is a response to the EU directive on energy-using products (the EuP directive) described in Chapter 5. It is a tool for the analysis of products—mostly appliances—that use energy, following the ISO 14040 series of guidelines.

GREET (2007). The Greenhouse Gasses, Regulated Emissions and Energy Use in Transportation Model (GREET) is a free spreadsheet running in Microsoft Excel developed by Argonne National Laboratory for the US Department of Transportation. There are two versions, one for fuel-cycle analysis and one for vehicle-cycle analysis. They deal with specific emissions, not with impacts and weighted combinations. For a given vehicle and fuel system, the model calculates energy consumption, emissions of CO_2-equivalent greenhouse gases—primarily carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O)—and six criteria pollutants: volatile organic compounds (VOCs), carbon monoxide (CO), nitrogen oxide (NO_x), particulate matter with size smaller than 10 micron (PM10), particulate matter with size smaller than 2.5 micron (PM2.5), and sulfur oxides (SO_x).

MIPS (2008). MIPS stands for Material Input per Service Unit. MIPS is an elementary measure to estimate the environmental impacts caused by a product or service. The full life cycle from cradle to grave (extraction, production, use, waste/recycling) is considered. It allows the environmental implications of products, processes, and services to be assessed and compared. It enables material intensity analysis both at the micro-level (focusing on specific products and services) and at the macro-level (focusing on national economies).

CES Edu (2012). Granta Design specializes in materials information-management software. One of their products, CES Edu, is a widely used tool for teaching the selection and use of materials and processes. It includes modules that implement the eco-audit methods described in Chapter 7 and the eco-selection procedures of Chapter 9.

Aggregain (2008). Aggregain, developed and distributed by WRAP, is a free analysis tool that runs in Microsoft Excel and is used for promoting the supply and use of recycled and secondary aggregates (including recycled concrete from construction, demolition waste material, and railway ballast) for the construction and road-building industries.

KCL-ECO 3.0. KCL represents the paper-making industry. KCL-Eco is an LCA tool designed specifically for this industry.

Eio-lca (2008). Economic input-output LCA (Eio-lca) of Carnegie Mellon University calculates sector emissions based on input-output data for the sectors of the North American Industry Classification Scheme (NAICS). It is not designed for the assessment of products. Demo available.

Okala Ecodesign Guide (2010). Okala provides an introduction to ecological and sustainable design for practicing and beginning designers; it was developed with the support from Eastman Chemical, Whirlpool, and the Industrial Design Society of America (ISDA).

LCA Calculator (2011). This is a quick and intuitive way for designers and engineers to understand, analyze, and compare environmental impacts of products and particular design decisions.

3.10 Exercises

E3.1. (a) Which phase of life would you expect to be the most energy intensive (in the sense of consuming fossil fuel) for the following products?

- A toaster
- A two-car garage
- A bicycle
- A motorcycle

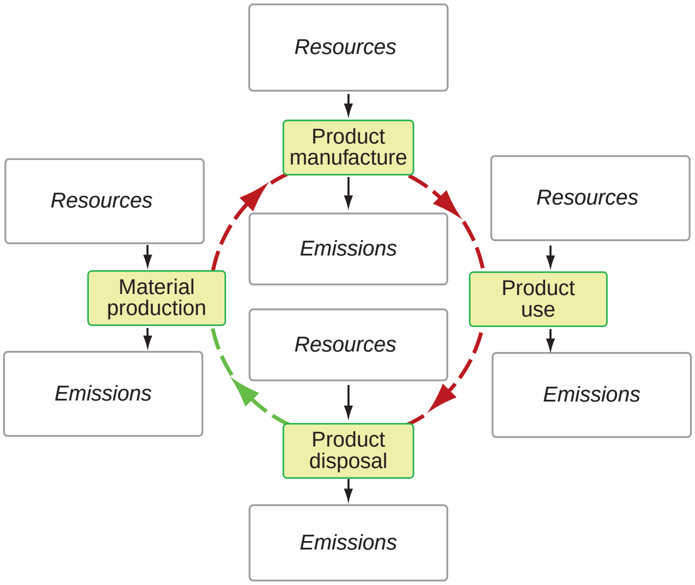


FIGURE 3.15 *A template for listing the principal resources and emissions associated with the life of a product*

- A refrigerator
- A coffee maker
- An LPG-fired patio heater

(b) Pick one of these and list the resources and emissions associated with each phase of its life along the lines of Figure 3.4 (template provided in Figure 3.15).

E3.2. Functional units. Think of the basic need filled by the products listed here. List what you would choose as the functional unit for an LCA.

- Washing machines
- Refrigerators
- Home heating systems
- Air conditioners
- Lighting
- Home coffee maker
- Public transport
- Hand-held hair dryers

E3.3. (a) What is meant by "externalized" costs and costs that are "internalized" in an environmental context?

(b) Now a moment of introspection. List three externalized costs associated with your lifestyle. If your life is so pure that you have less than three, then list some of other people you know.

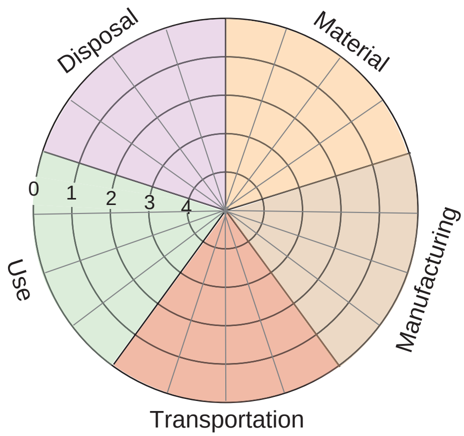
E3.4. What, in the context of life-cycle assessment, is meant by "system boundaries"? How are they set?

E3.5. Describe briefly the steps prescribed by the ISO to guide life-cycle assessment of products.

E3.6. What are the difficulties with a full LCA? Why would a simpler, if approximate, technique be helpful?

E3.7. Pick two of the products listed in Exercise E.3.1 and, using your judgment, attempt to fill out the simplified streamlined LCA matrix in Figure 3.16 to give an Environmentally Responsible Product Rating, R_{epr}.

	Material	Manufacturing	Transportation	Use	Disposal
Material resources *(high use = 0, none = 4)*					
Energy use *(high use = 0, none = 4)*					
Global warming *(much CO_2 = 0, no CO_2 = 4)*					
Human health *(Toxic emissions or waste?)*					
Column totals					
			R_{erp} = Sum across column totals		



EXAMPLE

	Material	Manufacturing	Transportation	Use	Disposal
Material resources *(high use = 0, none = 4)*	2	2	2	3	2
Energy use *(high use = 0, none = 4)*	2	1	3	3	1
Global warming *(much CO_2 = 0, no CO_2 = 4)*	2	1	2	3	1
Human health *(Toxic emissions or waste?)*	1	1	2	0	0
Column totals	7	5	9	9	4
			R_{erp} = Sum across column totals		34

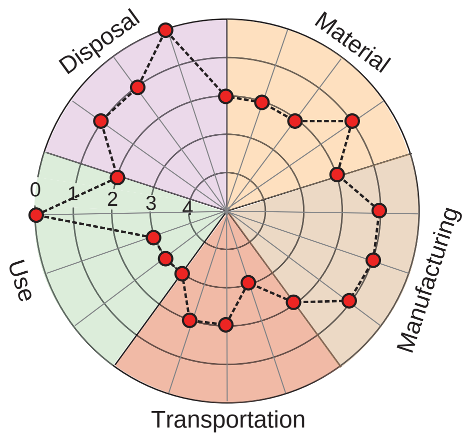


FIGURE 3.16 *A blank target and an example of a filled target.*

Make your own assumptions (and report them) about where the product was made, how far it has been transported thus far, and whether it will be recycled. Assign an integer between 0 (highest impact) and 4 (least impact) to each box and then add them to give an environmental rating, providing a comparison. Try the following protocol:

- Material: Is it energy-intensive? Does it create excessive emissions? Is it difficult or impossible to recycle? Is the material toxic? If the answer to these questions is *yes*, score 4. If *no*, score 0. Use the intermediate integers for other combinations.
- Manufacturing: Is the process one that uses much energy? Is it wasteful (meaning cut-offs and rejects are high)? Does it produce toxic or hazardous waste? Does make use of volatile organic solvents? If yes, score 4. If no, score 0, etc.
- Transportation: Is the product manufactured far from its ultimate market? Is it shipped by air freight? If yes to both, score 4. If no to both, score 0.
- Use: Does the product use energy during its life? Is the energy derived from fossil fuels? Are any emissions toxic? Is it possible to provide the use-function in a less energy-intensive way? Scoring as above.
- Disposal: Will the product be sent to a landfill at end of life? Does disposal involve toxic or long-lived residues? Scoring as above.

What difficulties did you have? Do you feel confident that the results are meaningful?