Industrial Ecology and Sustainable Engineering

T.E. Graedel • B.R. Allenby

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11.6 You are the engineer in charge of two office building designs—one in the American Southwest, where there is very little rain and hot temperatures for much of the year, and one in British Columbia, where it is frequently rainy and foggy, and winter, the longest season, is quite cold. How good is the guidance provided by the LEED green building standards in each case? How could you make this better?

11.7 Identify and review a local building project. Evaluate it from the DfES principles of Table 11.2.

11.8 Your civil engineering construction firm, which prides itself on designing and building "sustainable infrastructure," is given two projects by a local city. One involves replacing a mile of old water pipe in the center of a downtown business and residential area. The second involves building a water system for a new community that, in an effort to be more sustainable, involves construction of a town center with closely spaced town homes around it.

(a) What elements of materials selection and design constitute "sustainable" choices for each project, and how do they differ?

(b) As lead design engineer, you note that you are seriously constrained in your water pipe replacement project by the existing design and operation of the municipal water system. How might this lead you to rethink your new design?

(c) You design a very energy efficient water infrastructure for the new build community, only to be told by the city that your initial costs are too high. How do you respond, and what data would you use to support your response?

(d) From reading engineering journals, you are increasingly aware of the trend to build "intelligent" infrastructure, such as the "smart grid" for electricity. You therefore propose to the city that it construct an "intelligent water infrastructure" for the new community. What sorts of information systems and functions might such an intelligent water infrastructure include?

CHAPTER 12

An Introduction to Life Cycle Assessment

12.1 THE CONCEPT OF THE LIFE CYCLE

The environmentally related activities of the 1970s and 1980s focused on the manufacturing facility and its emissions. This was a necessary concentration of effort, but it ignored some other obvious effects of its operations—the use of resources mined and processed elsewhere, the creation of products that may have environmental impacts when used, and so forth. In the 1990s, the scope of interest was enlarged to consider the entire life cycle of products and their associated flows and impacts, as sketched in Figure 12.1.

The components of a product life cycle can be defined in various ways depending on the goals and level of detail desired, but the four numbered stages in Figure 12.1 are typical: (1) acquisition and processing of the necessary resources, (2) manufacture, (3) use, and (4) reuse/recycling/disposal. The generation of reusable discards in manufacturing stimulates a "prompt scrap" subcycle as well (upper right on the diagram). Resources, either from primary ("virgin") or secondary (recycled) sources, are required to a greater or lesser degree at a number of points in the cycle, and emissions occur at a number of points as well.

The goal of life cycle assessment (LCA) is to quantify or otherwise characterize all of these material flows, to specify their potential environmental impacts, and to consider alternative approaches that can change those impacts for the better. The product cycle itself and the LCA that studies it are complex, but LCAs have become widely practiced, and many gains have been made as a result.

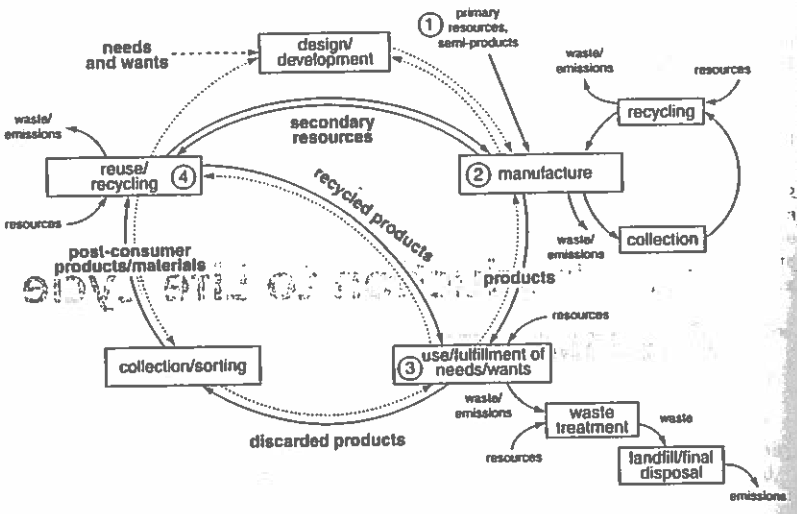


Figure 12.1

A representation of the generic life cycle of a product. Solid arrows represent energy and material flows, dashed arrows flows of information. (Adapted from G. Rebitzer, et al., Life cycle assessment Part 1: Framework, goal and scope definition, inventory analysis, and applications, *Environment International*, *30*, 701–720, 2004.)

12.2 THE LCA FRAMEWORK

The formal structure of LCA has been delineated by the International Standards Organization; in its basic form it contains three stages: *goal and scope definition*, *inventory analysis*, and *impact analysis*. The concept is pictured in Figure 12.2. First, the goal and scope of the LCA are defined. An inventory analysis and an impact analysis are then performed. The *interpretation of results* that follows these three steps guides an analysis of potential improvements (which may feed back to influence any of the stages, so that the entire process is iterative).

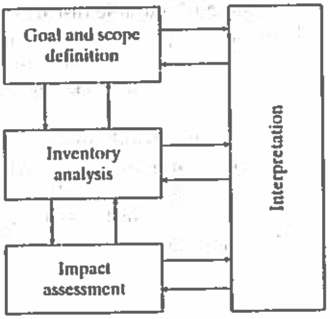


Figure 12.2

Phases in the life cycle assessment of a technological activity. The arrows indicate the basic flow of information. At each stage, results are interpreted, thus providing the possibility of revising the environmental attributes of the activity being assessed. (Adapted from International Standards Organization, *Environmental Management-Life-Cycle Assessment, Principles and Framework*, Geneva, 1997.)

There is perhaps no more critical step in beginning an LCA evaluation than to define as precisely as possible the questions to be answered (the goal) followed by choosing the evaluation's scope: what materials, processes, or products are to be considered, and how broadly will alternatives be defined? Consider, for example, the question of releases of chlorinated solvents during a typical dry-cleaning process. The purpose of the analysis is to reduce environmental impacts. The scope of the analysis, however, must be defined clearly. If it is limited, the scope might encompass only good housekeeping techniques, end-of-pipe controls, administrative procedures, and process changes. Alternative materials—in this case, solvents—might be considered as well. If, however, the scope is defined broadly, it could include alternative service options: Some data indicate that a substantial number of items are sent to dry-cleaning establishments not for cleaning per se but simply for pressing. Accordingly, offering an independent pressing service might reduce emissions considerably. One could also take a systems view of the problem: Given what we know about polymers and fibers, why are clothing materials and designs that require the use of chlorinated solvents for cleaning still being provided? Among the considerations that would influence the choice of scope in cases such as the above are: (a) who is sponsoring and who is performing the analysis, and how much control they can exercise over the implementation of options; (b) what resources are available to conduct the study; and (c) what is the most limited scope of analysis that still provides for adequate consideration of the systems aspects of the problem.

The resources that can be applied to the analysis should also be assessed. Most traditional LCA methodologies provide the potential for essentially open-ended data collection and, therefore, virtually unlimited expenditure of effort. As a general rule, the depth of analysis should be keyed to the degrees of freedom available to make meaningful choices among options, and to the importance of the environmental or technological issues leading to the evaluation. For example, an analysis of using different plastics in the body of a currently marketed portable disk player would probably not require a complex analysis, because the constraints imposed by the existing design and its market niche make the options available to a designer quite limited. On the other hand, a government regulatory organization contemplating limitations on a material used in large amounts in numerous and diverse manufacturing applications would want to conduct a fairly comprehensive analysis, because the degrees of freedom involved in finding substitutes could be quite numerous and the environmental impacts of substitutes could be significant.

The second component of LCA, inventory analysis (sometimes termed "LCI"), is by far the best developed. It uses quantitative data to establish the levels and types of energy and materials used throughout the lifetime of a product, process, or system, and the environmental releases that result. The approach is based on the idea of a family of materials budgets, in which the analyst measures the inputs and outputs of energy and resources. The assessment is done over the entire life cycle. The products of this activity are a comprehensive flow diagram of the manufacturing process (often involving suppliers and sometimes industrial customers), and a list (by mass) of resources used and of emissions to air, water, and soil, all detailed by mass flow and chemical speciation.

The third stage in LCA, the impact analysis, involves relating the outputs of the system to environmental impacts, or, at least to the stresses being placed on the environment by the outputs. Aspects of this difficult and potentially contentious topic are discussed in the next chapter.

The interpretation of results phase is where the findings from one or more of the three stages are used to draw conclusions and develop recommendations. The output from this activity is often the explication of needs and opportunities for reducing environmental impacts as a result of industrial activities being performed or contemplated. It follows ideally from the completion of stages one through three, and occurs in two forms: Design for Environment and Sustainability (the proactive activities discussed in Chapters 10 and 11) and Pollution Prevention (the "best current practice" activities discussed in Chapter 8).

12.3 GOAL SETTING AND SCOPE DETERMINATION

A common LCA goal is to derive information on how to improve environmental performance. If the exercise is conducted early in the design phase, the goal may be to compare two or three alternative designs. If the design is finalized, or the product is in manufacture, or the process is in operation, the goal can probably be no more than to achieve modest changes in environmental attributes at minimal cost and minimal disruption to existing practice.

It is possible, though not nearly so common, for an LCA target to be much more ambitious than the evaluation of a single product or process. This usually occurs with the evaluation of an organization of some sort: the operation of an entire facility or corporation, for example, or of an entire governmental entity. In such a case, it is likely that alternative operational approaches can be studied, but not alternative organizations. In addition, an organization that makes a logical entity from an LCA viewpoint may involve more than one implementer (an entire supply chain, for example), so collaborative goal setting may be required. If a goal can be quantified, such as "achieve a 20 percent decrease in overall environmental impact," it is likely to be more useful and the result more easily evaluated than with qualitative goals. Quantification of the goal requires quantification of each assessment step, however, and quantitative goals should be adopted only when one is certain that adequate data and assessment tools are available.

The scope of the assessment is perhaps best established by asking a number of questions: "Why is the study being conducted?" "How will the results be used, and who will use them?" "Do specific environmental issues need to be addressed?" "What level of detail will be needed?" It is useful to recognize that LCA is an iterative process, and that the scope may need to be revisited as the LCA proceeds.

12.4 DEFINING BOUNDARIES

The potential complexity of comprehensive LCAs is nowhere better illustrated than by the problem of defining the boundaries of the study. There are many potential issues for discussion in this regard, and no consensus on the best ways of approach. The discussion that follows explores a number of these issues and concludes with some general recommendations concerning choices of boundaries in LCA.

12.4.1 Level of Detail Boundaries

How much detail should be included in an LCA? An analyst frequently needs to decide whether effort should be expended to characterize the environmental impacts of trace constituents such as minor additives in a plastic formulation or small brass components in a large steel assembly. With some modern technological products containing hundreds of materials and thousands of parts, this is far from a trivial decision. One way it is sometimes approached is by the *5 percent rule*: If a material or component comprises less than 5 percent by weight of the product, it is neglected in the LCA. A common amendment to this rule is to include any component with particularly severe environmental impacts. For example, the lead-acid battery in an automobile weighs less than 5 percent of the vehicle, but the toxicity of lead makes the battery's inclusion reasonable. Potential items for inclusion in this way could be ozone-depleting fire suppressants or radioactive materials.

12.4.2 The Natural Ecosystem Boundary

A natural ecosystem issue that arises when choosing LCA boundaries is that of biological degradation. When industrial materials are discarded, as into a landfill, biodegradation produces such outflows as methane from paper, chlorofluorocarbons from blown foam packaging, and mobilized copper, iron, and zinc from bulk metals. LCA approaches to these complications have included incorporating these flows in the inventory, excluding landfill outflows completely, or including those flows for a specific time period only. Flows from landfills are generally difficult to estimate, so one is faced with a trade-off between comprehensiveness and tractability.

A second example of the natural/industrial boundary issue is the process of making paper from wood biomass, as shown in Figure 12.3. Here the assessor has several possible levels of inventory detail to choose from. The basic analysis is essentially a restriction of the inventory to life stage 2. The energy envelope incorporates some of the external flows related to the production of energy. The extended envelope includes all life cycle stages and flows directly connected with the industrial system. The comprehensive envelope adds the natural processes of biomass formation and the degradation of materials in a landfill. None of these options is inherently correct or incorrect, but the choice that is made could determine the amount of effort required for the LCA, as well as the results that emerge.

12.4.3 Boundaries in Space and Time

A characteristic of environmental impacts is that their effects can occur over a very wide range of spatial and temporal scales. The emission of large soot particles affects a local area, those of oxides of nitrogen generate acid rain over hundreds of kilometers, and those of carbon dioxide influence the planetary energy budget. Similarly, emissions causing photochemical smog have a temporal influence of only a day or two, the disruption of an ecosystem several decades, and the stimulation of global climate change several centuries. LCA boundaries may be placed at short times and small distances, long times and planetary distances, or somewhere in between. The choice of any of these boundary options in space and time may be appropriate depending on the scope of the LCA.

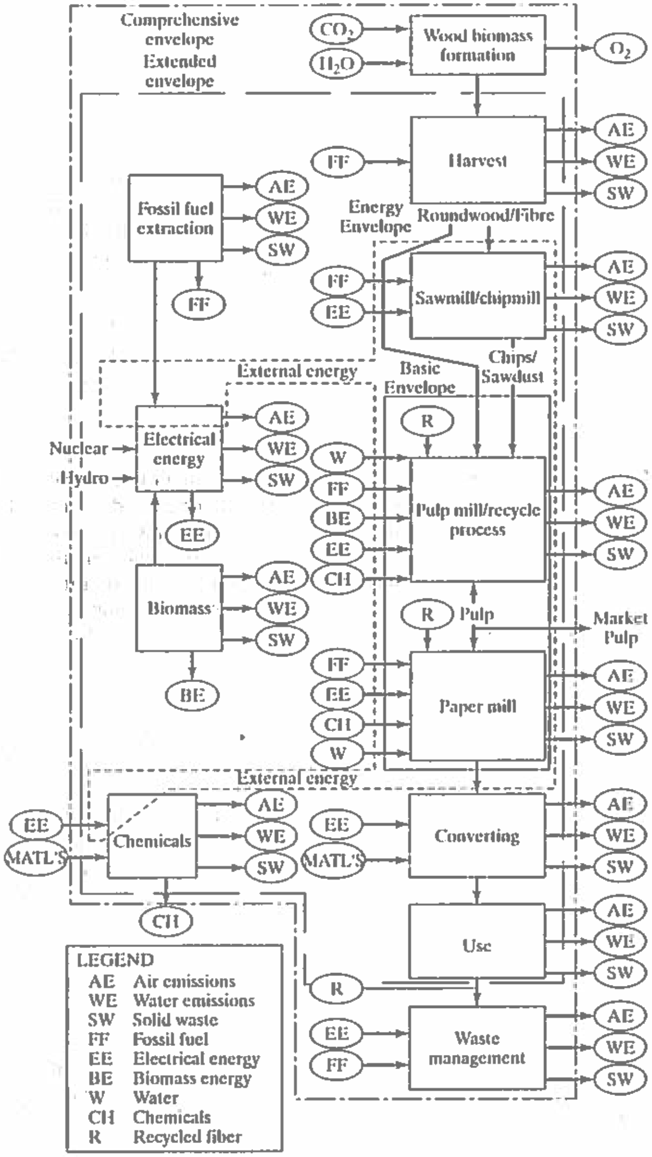


Figure 12.3

A simplified quantitative inventory flow diagram for the manufacture of paper. Four levels of possible detail are shown. (Adapted from a diagram provided by Martin Hocking, University of British Columbia.)

12.4.4 Choosing Boundaries

It should be apparent that the choice of LCA boundaries can have enormous influence on the timescale, cost, results, meaningfulness, and tractability of the LCA. The best guidance that can be given is that the boundaries should be consistent with the goals of the exercise. An LCA for a portable radio would be unlikely to have goals that encompass impacts related to energy extraction, for example, both because the product is not large and because its energy impacts will doubtless be very modest. A national study focusing on flows of a particular raw material might have a much more comprehensive goal, however, and boundaries would be drawn more broadly. The goals of the LCA thus define much of the LCA scope, as well as the depth of the inventory and impact analyses.

12.5 APPROACHES TO DATA ACQUISITION

Once the scope of the LCA has been established, the analyst proceeds to the acquisition of the necessary data. Data acquisition for a product is begun by constructing, in cooperation with the design and manufacturing team, a detailed manufacturing flow diagram. The aim is to list, at least qualitatively but preferably quantitatively, all inputs and outputs of materials and energy throughout all life stages. Figure 8.4 showed an example of such a diagram for the manufacture of a desktop telephone in which the housing is molded in the plant from precolored resin; the electronics boards are constructed from components furnished by suppliers; and those parts and others (microphone, electronic jacks, batteries, etc.) are assembled into the final product. The diagram indicates a number of material and energy by-products (the latter being mostly unused heat). Once the inventory flow diagram is constructed, in as much detail as possible, the actual inventory analysis can begin.

Some of the information needed for an inventory analysis is straightforward, such as the amounts of specific materials needed for a given design or the amount of cooling water needed by a particular manufacturing process. Quantitative data obviously have advantages: They are widely utilized in high-technology cultures; they offer powerful means of manipulating and ordering data; and they simplify choosing among options. However, the state of information in the environmental sciences may not permit the sound quantification of environmental and social impacts because of fundamental data and methodological deficiencies. The result of inappropriate quantification might be that those concerns that cannot be quantified would simply be ignored—thereby undercutting the systemic approach inherent in the LCA concept.

Case Study 1: The Upscale Automobile

The first stage of conducting a life cycle inventory on a product being manufactured is to assess the product itself. What is it made of? How much of each material does it contain? If the product is assembled from components supplied by others, it may be necessary to deal with suppliers to get a complete picture. Especially where potentially hazardous materials are involved, the overall effort can become quite detailed.

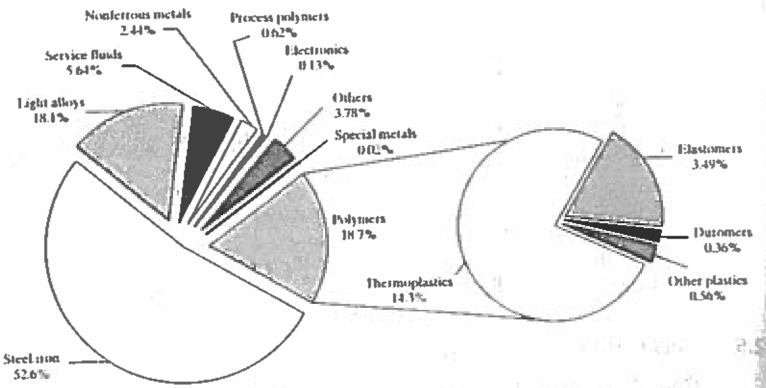


Figure 12.4

The material composition of the Mercedes-Benz S-class sedan. (M. Finkbeiner, et al., Application of life cycle assessment for the environmental certificate of the Mercedes-Benz S-class, *International Journal of Life Cycle Assessment, 11*, 240–246, 2006.)

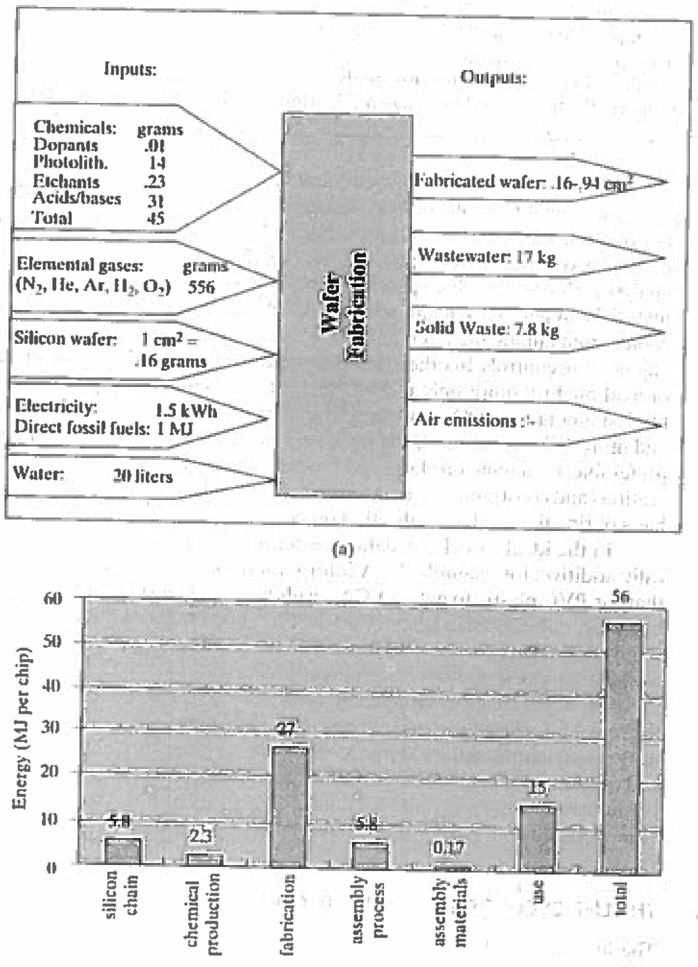
An example of a material assessment is shown in Figure 12.4 for the Mercedes-Benz S-class sedan. About half the weight is seen to be iron and steel, and another 16 percent in a variety of light metal alloys. Nonferrous metals are largely zinc anticorrosion coatings, amounting to 2–3 percent of the weight. Polymers constitute some 19 percent; of this quantity, more than two-thirds is made up of thermoplastics, which have a high recycling potential.

This straightforward diagram by itself provides significant input to the product design team. If similar information is available with each new design, it is possible to track transitions to new mixes of metals and plastics, and the level of diversity of materials within the products of a corporation.

Case Study 2: The 1.7 Kilogram Microchip

The microchips that are at the heart of modern electronics are small, as are their power requirements. This would suggest that their environmental impacts are small as well, but such is not necessarily the case when the full life cycle is considered. Microchips are formed on silicon wafers, and the water used in processing must be very pure. The subsequent fabrication of the transistors and other components on the chip require a large suite of chemicals and frequent deposition, etching, and washing stages, all involving substantial material and energy flows (Figure 12.5a). Once manufactured, the chip consumes energy when it is used, but even over a four-year life its energy requirements are only half those used in its manufacture (Figure 12.5b).

Microchips have been regarded as praiseworthy examples of dematerialization, in which a function (computing, in this case) is performed by a product comprising reduced



(a)

(b)

Figure 12.5

Life cycle inventory information for a 32 MB DRAM memory chip. (a) Input and output material flows for the silicon wafer manufacturing process; (b) Energy consumption in production and use. (Reproduced with permission from E.D. Williams, et al., The 1.7 kg microchip: Energy and material use in the production of semiconductor devices, *Environmental Science & Technology, 36*, 5504–5410, 2002.)

amounts of material. The LCA results of Figure 12.5a indicate that this impression is incomplete at best and that, if all the materials used in its manufacture were added up, the microchip would "weigh" 1.7 kg! As the researchers state: "increasingly complex products require additional secondary materials and energy to realize their lower entropy form." This is an insight that would not have made itself known without a life cycle inventory analysis.

In order to maximize efficiency and innovation and avoid prejudgment of normative issues, an LCA information system should be nonprescriptive. It should provide information that can be used by individual designers and decision makers given the particular constraints and opportunities they face, but should not, at early stages of the analysis, arbitrarily exclude possible design options. In some cases, the use of highly toxic materials might be a legitimate design choice—and an environmentally preferable choice from among the alternatives—where the process designer can adopt appropriate engineering controls. In others, a process choice involving the use of substantial amounts of lead might require only modest amounts of energy use and thus be responsible for modest amounts of CO_2 emissions. The alternative might be less lead, more energy use, and more CO_2 emissions. If the toxic lead can be well contained, the first option may be preferable. Designing products and processes inherently requires balancing such considerations and constraints, and the necessary trade-offs can only be made on a case-by-case basis during the product realization process.

In the ideal case, LCA data at different hierarchical levels should be mathematically additive; for example, LCA information for copper wire could be combined with that for PVC plastic to get an LCA result for plastic-insulated copper wire. In practice, however, differences in scope, timescale, and so on generally require that every LCA stand alone. This obvious deficiency in the methodology emphasizes that LCAs are works in progress and not finished tools.

LCA information should provide not only relevant data but, if possible, also the degree of uncertainty associated with that data. This approach is particularly important in the environmental area, where uncertainty, especially about risks, potential costs, and potential natural system responses to emissions of various types, is endemic. Often the relatively simple ordinal indicators—"high reliability," "moderate reliability," and "low reliability"—will be of substantial use to those actually making design decisions.

12.6 THE LIFE CYCLE OF INDUSTRIAL PRODUCTS

The life-stage outline assumes that a corporation is manufacturing a final product for shipment and sale directly to a customer. Often, however, a corporation's products are intermediates—process chemicals, steel screws, brake systems—made for sale to and incorporation in the products of another firm. How does that concept apply in these circumstances?

Picture the detailed process of manufacture as shown in Figure 12.6. Three different types of manufacture are illustrated: (A) the production of intermediate materials from raw materials (e.g., plastic pellets from petroleum feedstock or rolls of paper from bales of recycled mixed paper), (B) the production of components from intermediate materials (e.g., snap fasteners from steel stock or colored fabric from cotton), and (C) the processing

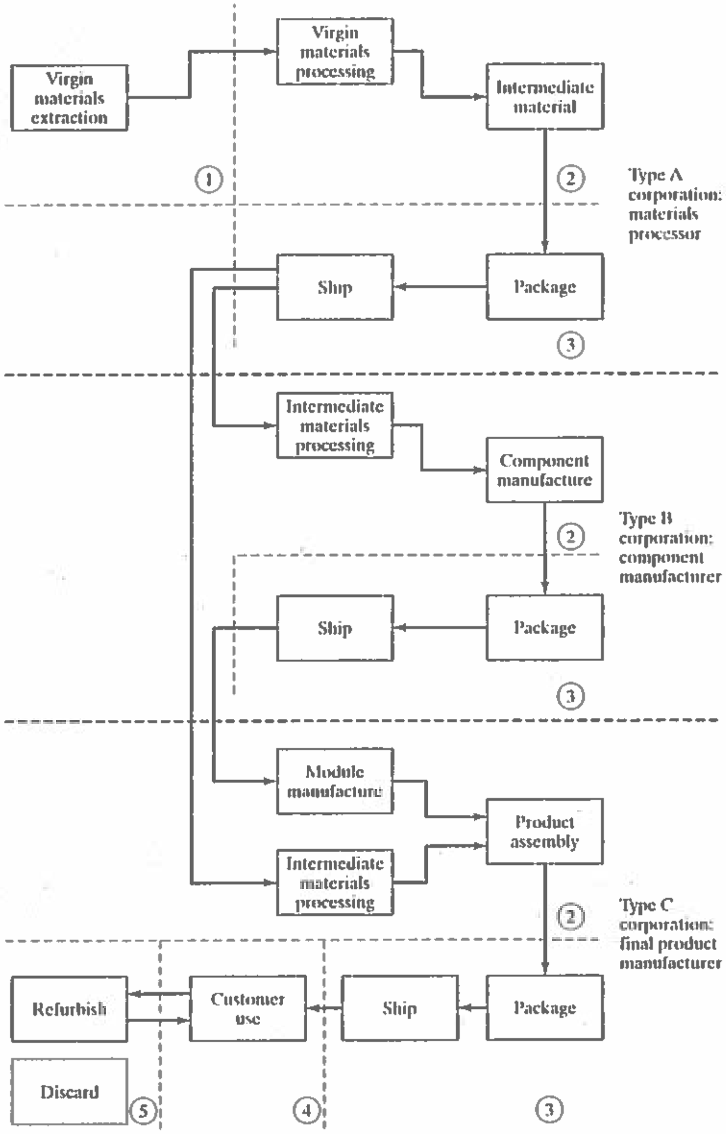


Figure 12.6

The interrelationships of product life stages for corporations of Type A (materials processors), Type B (component manufacturers), and Type C (final product manufacturers).

of intermediate materials (e.g., cotton fabric) or the assembly of processed materials (e.g., plastic housings) into final products (e.g., shirts or tape recorders). An operation of Type C is one in which the design and manufacturing team virtually has total control over all product life stages except Stage 1: Premanufacture. For a corporation whose activities are of Type A or B, the perspective changes for some life stages, but not for others:

Stage 1, Premanufacture. Unless a Type A corporation is the actual materials extractor, the concept of this life stage is identical for corporations of Types A, B, and C.

Stage 2, Manufacture. The concept of this life stage is identical for corporations of Types A, B, and C.

Stage 3, Product Delivery. The concept of this life stage is identical for corporations of Types A, B, and C.

Stage 4, Product Use. For Type A corporations, product use is essentially controlled by the Type B or C receiving corporation, though product properties such as intermediate materials purity or composition can influence such factors as by-product manufacture and residue generation. For Type B corporations, their products can sometimes have direct influence on the in-use stage of the Type C corporation final product, as with energy use by cooling fans or lubricant requirements for bearings.

Stage 5, Refurbishment, Recycling, or Disposal. The properties of intermediate materials manufactured by Type A corporations can often determine the potential for recyclability of the final product. For example, a number of plastics are now formulated with the goal of optimizing recyclability. For Type B corporations, the approach to the fifth life stage depends on the complexity of the component being manufactured. If it can be termed a component, such as a capacitor, the quantity and diversity of its materials and its structural complexity deserve review. If it can be termed a module (such as an electronic circuit board made up of many components), the concerns are the same as those for a manufacturer of a final product ease of disassembly, potential for refurbishment, and the like.

Thus, Type A and B corporations can and should deal with LCAs of their products much as should Type C corporations. The considerations of the first three life stages are, in principle, completely under their control. For the last two life stages, the products of Type A and B corporations are influenced by the Type C corporation, with which they deal and, in turn, their products influence the life stages 4 and 5 characteristics of Type C products.

Case Study 3: Energy Use in Buildings

The use of LCA for buildings and infrastructure is somewhat more challenging than for smaller products. Each construction product can be "one of a kind," the lifetime is long, the minor constituents (electrical equipment, insulation, etc.) may not be clearly specified, and geographical location is important. Most of the studies accomplished to date relate to energy use. An example result is shown below for a three-story generic office building with wood framing in Vancouver, Canada. Even for a revised design that uses only 25 percent of the current standard of energy use in operation, more than half of the overall energy use over the life cycle occurs during the use phase. This result emphasizes the importance of building designs that require little or no operating energy (Figure CS-1).

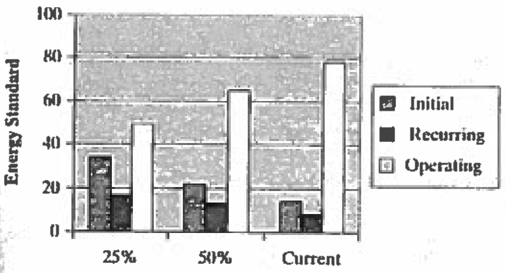


Figure CS-1

The energy use fractions for a three-story office building over 25 years due to initial embedded energy, energy for recurring replacement and repair activities, and operating energy. The calculations are for typical current designs, and for designs that use 25 percent or 50 percent as much energy in operation as current designs. (From R.J. Cole, and P.C. Kernan, Life cycle energy use in office buildings, *Buildings and Environment, 31*, 307–317, 1996.)

12.7 THE UTILITY OF LIFE CYCLE INVENTORY ANALYSIS

The greatest benefit of life cycle inventory analysis, in the minds of many product designers, is that it expands the breadth of their thinking. It is not instinctive to contemplate the flows of materials, energy, and water needed to extract and purify the resources used to manufacture a product, nor to consider a product's use of energy, or its fate at end of life. Merely the recognition of the entire life cycle is enough to stimulate many designers to make environmentally beneficial changes in their designs.

A second benefit comes when quantification of flows is performed. This step enables the analyst and/or designer to answer some relevant questions: What are the relative sizes of emissions? At which life stage is use of energy the most? Can substitute materials minimize any of the environmental aspects of the product? While environmental impact has not been fully analyzed, life cycle inventory studies nonetheless have been shown to raise issues of concern and to stimulate productive responses. As a result, they are standard practice in many corporations, and lessened corporate environmental footprints often follow.

FURTHER READING

Curran, M.A., *Environmental Life-Cycle Assessment*, New York: McGraw-Hill, 1996.

Guinée, J., et al., *Handbook on Life Cycle Assessment–Operational Guide to the ISO Standards*, Dordrecht, The Netherlands: Kluwer Academic Publishers, 2002.

Reap, J., F. Roman, S. Duncan, and B. Bras, A survey of unresolved problems in life cycle assessment. Part 1: Goal and scope and inventory analysis, *International Journal of Life Cycle Assessment, 13*, 290–300, 2008.

Science Applications International Corporation, *Life Cycle Assessment: Principles and Practice*, Report EPA/600/R-06/060, Cincinnati, OH: U.S. Environmental Protection Agency, 2006.

EXERCISES

12.1 You are the LCA analyst for a papermaking company and are asked to do an LCA for a new type of paper to be used for printing currency. Define and describe the scope of your assessment.

12.2 Repeat Exercise 12.1 for the situation in which you work for a forest products company that supplies wood fiber for the paper.

12.3 Several alternative LCA boundary choices are indicated in Figure 12.3. What do you see as the advantages and disadvantages of each choice?

12.4 Reap and colleagues (2008) identify what they term "unresolved problems" in goal, scope, and inventory analysis. Which do you think is potentially the most serious, and why?

CHAPTER 13

The LCA Impact and Interpretation Stages

13.1 LCA IMPACT ANALYSIS

The previous chapter discussed the component of LCA termed "inventory analysis." Quantitative information on materials and energy flows is acquired at that stage in some cases, qualitative information in others. The data presentations in the previous chapter made it obvious that some aspects of life cycle analysis had the potential to be more problematical than others, but the approach begged the question of priorities. One could easily foresee a situation where alternative designs for a product or process each had similar materials use rates, but used different materials. How does the analyst make a rational, defensible decision among such alternatives? The answer is that (1) the influences of the activities revealed by the LCA inventory analysis on specific environmental properties must be accurately assessed, and (2) the relative seriousness of changes in the affected environmental properties must be given some sort of priority ranking. Together these steps constitute LCA's impact assessment.

Assessing environmental influences is a complicated procedure, but it can, in principle at least, be performed by employing relationships between stressors, which are items identified in the inventory analysis that have the potential to produce changes in environmental properties, and the degree of change that is produced (e.g., the generation of carbon dioxide as a result of energy use). The relationships between stressors and the environment are developed by the environmental science community. By combining LCA inventory results with these relationships, a manufacturing process might be found, for example, to have a minimal impact on local water quality, a modest impact on regional smog, and a substantial impact on global climate change. The life cycle impact analysis (LCIA) uses that information to evaluate the relative importance of those impacts.

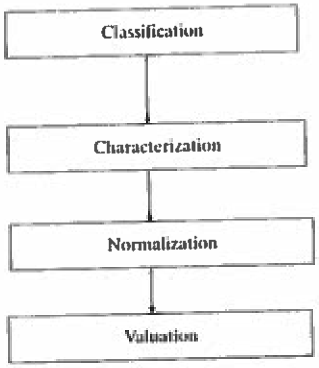


Figure 13.1

The four-step process in life cycle impact assessment.

The LCIA procedure is a four-step process, as shown in Figure 13.1 and discussed below.

Classification. Classification begins with the raw data on flows of materials and energy from the inventory analysis. Given those data, the classification step consists of identifying the environmental concerns ("categories" or "themes") suggested by the inventory analysis flows. For example, emissions from an industrial process using a petroleum feedstock may be known to include methane, butene, and formaldehyde. Classification assigns the first to the global warming category, the second to the smog formation category, the third to the human toxicity category. Table 13.1 lists those impact categories addressed in most LCIAs. Others, such as loss of biodiversity resulting from land development, or waste heat in power plant cooling water, may be added as needed.

TABLE 13.1 A Hypothetical Impact Analysis Including Normalization and Weighting

Impact category	S_j value (kilogram equivalent)	N_j value (year)	Ω_j value	W_j value (year)
Depletion of abiotic resources	3.5 antimony	2.2×10^{-11}	0.01	2.2×10^{-13}
Climate change	3.5 CO_2	2.7×10^{-14}	2.4	1.4×10^{-13}
Human toxicity	3.5 1,4-DCB	1.8×10^{-16}	1.1	1.9×10^{-16}
Freshwater aquatic toxicity	3.5 1,4-DCB	6.7×10^{-15}	0.2	1.3×10^{-15}
Terrestrial ecotoxicity	3.5 1,4-DCB	6.2×10^{-18}	0.4	3.9×10^{-18}
Photooxidant formation	3.5 ethylene	2.6×10^{-15}	0.8	2.1×10^{-15}
Acidification	3.5 SO_2	1.1×10^{-13}	1.3	1.4×10^{-13}
Eutrophication	3.5 phosphate	3.7×10^{-15}	1.0	3.7×10^{-15}

Source: Adapted from J.B. Guineé, Ed., *Handbook on Life Cycle Assessment*, Dordrecht, Netherlands, 2002.

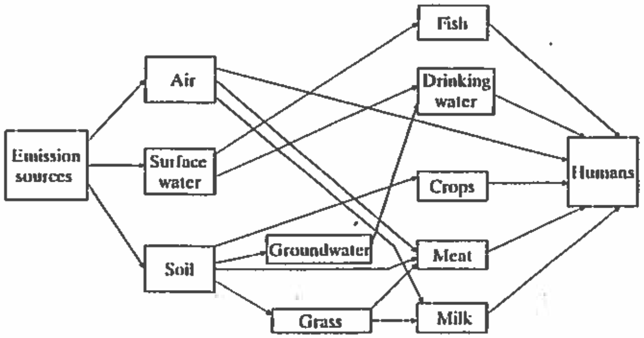


Figure 13.2

A map of the links between emissions and human exposure routes. (Adapted from J.B. Guineé, Ed., *Handbook on Life Cycle Assessment*, Dordrecht, Netherlands, 2002.)

Characterization. Characterization is the process of quantitatively determining the impact resulting from the stress indicated by the inventory values, that is,

$$S_j = \sum_i C_{i,j} \cdot E_i \tag{13.1}$$

where E_i is the mass flow identified for species *i* in the inventory assessment, $C_{i,j}$ is the "characterization factor" for species *i* and category *j* (i.e., what level of environmental stress of category *j* is caused by the emission of a unit mass of species *i*), and S_j is the category stress indicator for category *j*.

An example of a category could be human toxicity; the summation in Equation 13.1 reflects the fact that there could be several flows from the LCA inventory with impact on that category, as depicted in Figure 13.2.

In the *Handbook of Life Cycle Assessment*, an example is given of the results of a hypothetical inventory analysis. We reproduce portions of this example in column 2 of Table 13.1. Note that the S_j values are quantified in terms of a common unit for each category so that the $E_i \cdot C_{i,j}$ products may be summed. Because the common units are so different, there is no sense from the table as to which impacts are important and which are not.

Case Study 1: Alternative Solders

Even a partial LCIA can provide useful information to designers and policy makers. An example is a study of alternative solder compositions for the electronics industry. Inspired by regulations banning the use of lead in solder because of lead's toxicity, the study compared traditional tin–lead solder with a lead-free solder (95.5 weight percent tin, 3.9 percent silver, 0.7 percent copper). The LCIA was restricted to global warming potential (GWP).

The results of the analysis were twofold: (1) use of the lead-free solder eliminates lead from the solder life cycle—an obvious conclusion, and (2) for an equivalent amount of soldering, the lead-free option has 10 percent higher carbon dioxide emissions. The latter occurs because the lead-free solder has a higher melting point and thus requires increased energy use. The two results thus provide useful information for policy, although they comprise only a small portion of an overall LCIA.

Source: T. Ekvall, and A.S.G. Andrae, Attributional and consequential environmental assessment of the shift to lead-free solders, *International Journal of Life Cycle Assessment, 11*, 344–353, 2006.

Case Study 2: Women's Shoes LCA

The production of leather footwear and its subsequent use and end-of-life stages form the basis of a life cycle assessment designed to show the environmental impacts of various stages of the life cycle. Most of the processes of interest refer to the raising of animals and the acquisition and treatment of the hides, but textiles and paper must also be taken into account (Figure CS-1).

The life cycle stages were defined as (1) cattle raising, (2) slaughterhouse, (3) tanning, (4) footwear manufacture, (5) waste management, and (6) transportation. We will not present the inventory results here; they are available in the reference given below. During impact assessment, however, the input/output list items were classified and their contributions to a small number of impacts characterized. The results, expressed as percentages of the total impacts, are shown in Figure CS-2. Normalization and valuation were not performed as part of this process.

The agricultural phase of the life cycle turned out to be important for ecologically related impacts: global climate change, acidification potential, and eutrophication potential. In the case of water consumption, the tannery stage is most important; the tannery stage is also highly significant for eutrophication potential and the depletion of nonrenewable materials. Footwear manufacture is the largest energy-consuming stage, and its impacts are especially significant for energy-related metrics: air pollution, human toxics potential, and fossil-fuel depletion. Thus, two life stages that were not thought particularly significant in environmental terms, agriculture and footwear manufacturing, were identified by the LCA as deserving enhanced attention.

L. Milà, et al., Application of life cycle assessment to footwear, *International Journal of Life Cycle Assessment, 3*, 203–209, 1999.

Normalization. The goal of this step in LCIA is to relate the S_j values derived at the characterization step to some sort of reference value R_j and thereby to arrive at a normalized indicator N_j:

$$N_j = \frac{S_j}{R_j} \tag{13.2}$$

The purpose is to put the S_j values into a broader perspective. The reference value may be selected in a number of different ways, the one chosen being important to the organization conducting the LCIA. For example, a national government might choose the national climate change potential, while a corporation might choose the climate change potential of emissions from individuals, corporations, and governments within the region where it manufactures its products. A typical choice for climate change might be the average global per capita CO_2 emission rate, in kg/yr.

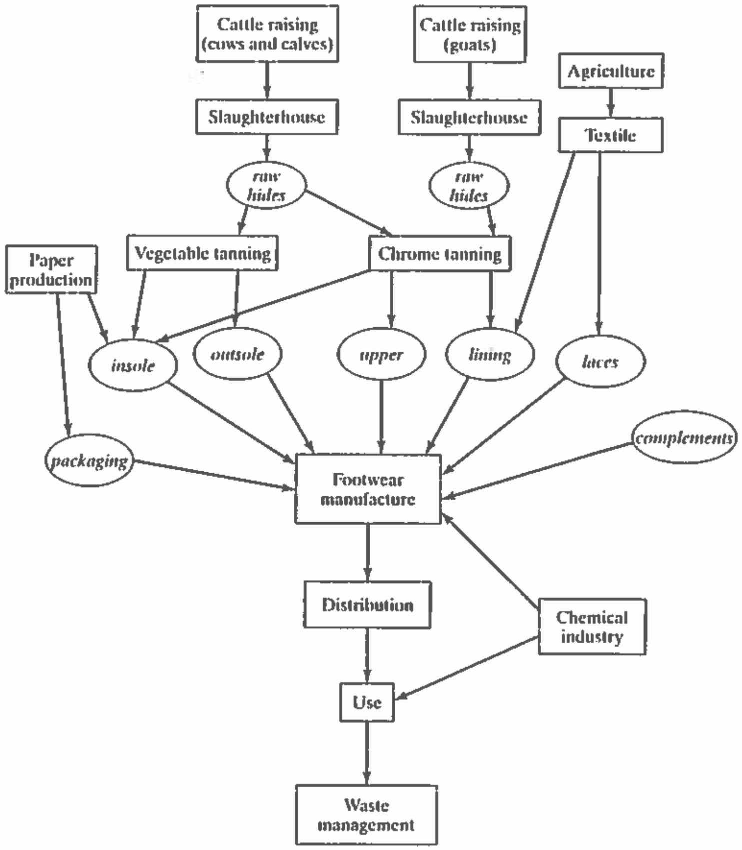


Figure CS-1

A life cycle process diagram for women's footwear. (Reproduced with permission from L. Milà, et al., Application of life cycle assessment to footwear, *International Journal of Life Cycle Assessment, 3*, 203–209, 1999.)

The example of Table 13.1 is continued in column 3 of the table, where R_j values in terms of flow rates (expressed in kg/yr) have been applied. The results

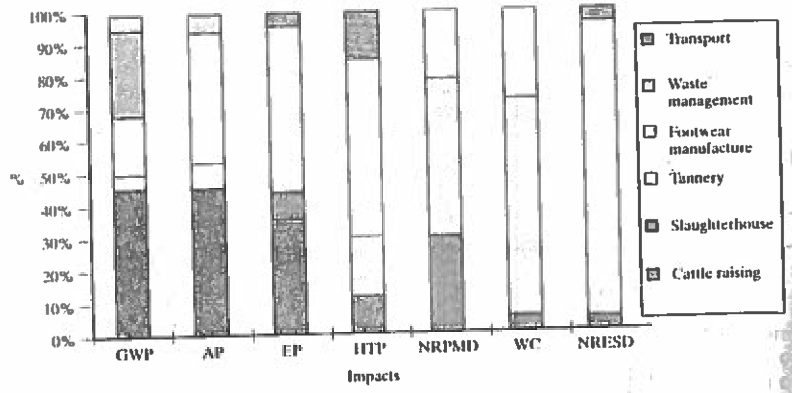


Figure CS-2

Contributions of different life cycle stages in women's footwear to major environmental concerns. GWP = global warming potential; AP = air pollution; EP = eutrophication potential; HTP = human toxicity potential; NRPMD = nonrenewable primary materials depletion; WC = water consumption; NRESD = nonrenewable energy sources depletion. (Reproduced with permission from L. Milà, et al., Application of life cycle assessment to footwear, *International Journal of Life Cycle Assessment, 3*, 203–209, 1999.)

are now in a common unit, and we find depletion of abiotic resources to have the highest value, followed by acidification.

Because the N_j values are dimensionless ratios, they permit the LCIA characterizations to be directly compared with each other. Without this step, one is left with non-normalized S_j values, and it is unclear how they should be interpreted (other than "more important is worse than less important," perhaps). Nonetheless, the choice of the reference values is potentially contentious, and normalization is often omitted from LCIAs.

Valuation. Valuation is the process of assigning weighting factors to the different impact categories based on their perceived relative importance as set by social consensus. For example, an assessor, an international standards organization, or a stakeholder panel might choose to regard climate change impacts as twice as important as acidification, and apply weighting factors to the normalized impacts accordingly. Mathematically, this provides a weighted indicator, given by

$$W_j = \Omega_j N_j \tag{13.3}$$

where the Ω_j values are the weighting factors.

If one wishes, an overall life cycle impact evaluation can then be calculated as

$$I = \sum_j W_j \tag{13.4}$$

The example of Table 13.1 is completed in the last two columns of the table, where weighting factors developed by a panel of participants are listed and applied. Depletion of abiotic resources and acidification continue to be quite important, but climate change is now highlighted as well.

Case Study 3: Palm Oil in Malaysia

An LCA study that employs both normalization and weighting has been performed for the production of crude palm oil in Malaysia. The procedure involves agriculture, transportation, and another industry (for milling of the palm kernels), and involves more than one-third of the country's total cultivated area. The goal of the LCA was to determine the environmental consequences of palm oil production and to serve as an improvement guide for oil palm plantations and palm oil mills.

A very detailed inventory was conducted for the functional unit of 1000 kg of crude palm oil. This inventory was then used as input for LCA software that used generic reference values and weighting factors to compute a final result, which demonstrated that fertilizer production for the palms was the most severe of the impacts, with transportation and boiler emissions also important. The most significant impacts were human toxicity (respiratory inorganics) and depletion of fossil fuels. Climate change, acidification, and eutrophication impacts, which might have been expected to be highly significant, were shown not to be so.

S. Yusoff and S.B. Hansen, Feasibility study of performing an life cycle assessment on crude palm oil production in Malaysia, *International Journal of Life Cycle Assessment, 12*, 50–58, 2007.

The application of weighting factors is controversial, because doing so involves making social, political, and ethical choices. As a result, LCIA evaluations suitable for a particular culture or location or time are unlikely to be useful in other circumstances. Because of this limitation, weighting is often omitted from LCIAs. (Doing so, however, is equivalent to making an implicit weighting with all Ω_j values the same.)

13.2 INTERPRETATION

13.2.1 Identify Significant Issues in the Results

A comprehensive LCA generates a substantial amount of results, only some of which is important. To identify the important issues, the analyst typically addresses the following questions:

- Do particular life stages dominate the results?
- Do particular processes dominate the results?
- Which environmental impacts are identified, and which are likely to be of most concern?
- Are any of the results particularly unusual or surprising?

The result of this review is a short list of issues in the product design or manufacture that deserve special attention.

13.2.2 Evaluate the Data Used in the LCA

With the significant issues identified, the next step in the LCA interpretation phase is to evaluate the completeness and consistency of the data. The goal is to ensure that each identification of significance is backed by adequate, reliable information. This is particularly important if alternative product designs are being evaluated, because the designs need to have comparable bases for comparison.

At the data completeness step, one wishes to confirm that all product life stages have been addressed, as well as all relevant environmental impacts. This information should be verified as meeting the system boundaries established at the beginning of the study, and that the significant raw materials and releases have been incorporated. Next, the uncertainties in the data are reviewed to see if the determination of significant issues is robust. If it is determined that the data are satisfactorily complete, consistent with project goals, and within acceptable uncertainty limits, the analyst can be comfortable in moving on to conclusions and recommendations.

13.2.3 Draw Conclusions and Recommendations

The final step in the LCA improvement stage is to use the information flowing from the LCA inventory and impact stages to develop a set of conclusions relating to the activity under study. An example is the conclusion from the solder study discussed earlier that solder composition substitution decreased lead exposure but increased global warming emissions. If a specific product or alternative products comprise the focus of the LCA, recommendations for improvement are also developed. The intention is to produce environmental benefits or, at least, minimize environmental liabilities. If the LCA stopped at the characterization stage, however (as was the situation with the women's shoes case study discussed earlier), the identification of significant issues is substantially constrained. The results and conclusions can still be useful from the perspective of comparisons against targets, for example, or of identifying issues to be brought to the attention of product designers.

13.3 LCA SOFTWARE

Because of the complexity of the LCA process, a number of research organizations and private consulting companies have developed software to facilitate life cycle assessment. To prepare for employing the software, the user develops a comprehensive description of the product and of the materials involved in its manufacture. If it will require resources when used (gasoline for an automobile, paper for a printer, for example), those resources and their anticipated rates of consumption are identified. In the typical approach, the user enters into a database the identity of the materials used in the product under study, together with the quantities of each. The software, taking advantage of internal databases that relate materials to impacts of various types and at various stages of the life cycle, then computes the stress indicators S_j and, if desired, the normalization indicators Nj, the weighting indicator Ω_j, and the overall impact evaluation I.

LCA software packages are continuously being refined. Many include extensive databases and are quite easy to use. Perhaps their greatest weakness tends to be the need to quantify data of uncertain validity and to compare unlike risks, in the process making assumptions that may gloss over serious value and equity issues. For this reason, some have argued that the uncertainties related either to data or subjective judgment or both in normalization and (especially) in valuation are often so high that it is preferable to make decisions based on the more reliable information at earlier stages of the LCA sequence.

13.4 PRIORITIZING RECOMMENDATIONS

Assume that a set of recommendations has emerged from one or another of the possible approaches to LCA. Those recommendations will be based solely on the perceived importance of the environmental impacts, but a corporation must consider many other factors in determining its LCA-inspired actions. If it is not possible to act upon all the recommendations, or at least not to react to them simultaneously, how might the actions be reviewed and prioritized?

13.4.1 Approaches to Prioritization

Complex products tend to generate long lists of recommendations. For example, here are selections from a list resulting from the LCA of a telecommunications product:

Manufacturing

- Rewrite specifications for equipment frames to encourage or mandate the use of some recycled material in their manufacture.
- Work with suppliers to minimize the diversity of packaging material entering the facility, so that recycling of solid waste may be optimized.
- Use nitrogen inerting on wave-solder machines to reduce solder dross buildup.
- Minimize the diversity of materials in outgoing equipment packaging, and develop labels to indicate appropriate recycling procedures to the customer.
- Develop reusable shipping containers that satisfy physical and electrostatic protective criteria and are ultimately recyclable.

Design

- Eliminate the use of chromate as a metal preservative in favor of removable organic coatings.
- Review specifications and requirements with the goal of using as few different plastics as possible and of using thermoplastics instead of thermosets.
- Mark all plastic parts using ISO standards.

Product Management

- Implement a customer information online service to contain not only the operator's manual but also instructions on recycling of parts, components, and packaging during service life and of the entire unit at end of life.
- Develop and implement a strategy for the recovery of used batteries from the field.

In developing a list of recommendations based on LCA results, it is important for the assessor to be inclusive, and to range widely. Recommendations that subsequently prove to be infeasible for one reason or another will be identified and discarded at the prioritization step, the second activity in improvement analysis. Some items, such as the marking of plastic parts, will not require the procedure of a full LCA to indicate their desirability, but would normally be at least implied by LCA results if not explicitly called out. Both more obvious and less obvious recommendations should be considered.

It is worth noting that some recommendations are very specific (i.e., avoid the use of chromate), while others are much more diffuse (i.e., minimize the diversity of packaging materials). Both types are important to include. The highly specific recommendations are easier to generate, and their accomplishment is more easily measured. The diffuse recommendation may be more difficult to deal with, but may in some cases be very important; their inclusion is crucial to a successful implementation of the LCA improvement stage.

The environmental performance of an assessed product can usually be substantially improved by adopting the bulk of the recommendations made in the assessment report. Complete implementation may not be possible for a variety of reasons, however, and in any case the recommended actions cannot be accomplished simultaneously. Prioritization is thus useful, and in order to prioritize the recommendations one should consider more than just environmentally related characteristics. Some researchers have proposed that the LCA recommendations be prioritized on the basis of how much environmental benefit will result. This procedure does not take into account, however, the fact that industrial decision making incorporates many factors in addition to environmental ones. Thus, actions suggested as a result of an LCA process are properly regarded as a subset of possible actions, both environmental and nonenvironmental.

A broadly tractable prioritization approach is to discard quantification and deal with the "binning" of recommendations, that is, dividing them into a small number of categories on the basis of expert information. For example, one can rank each recommendation on a "+/−" scale ("++" being the most desirable score and "− −" being the least desirable score) across the following product constraints:

- *Technical Feasibility:* Rates the technical facility of implementing a particular recommendation; "++" means the recommendation presents no technical challenges and is therefore very easy to implement.
- *Environmental Improvement:* Judges to what extent implementation of a recommendation will respond to an important environmental concern, the situation being evaluated on both a scientific and social basis; "++" means implementation will strongly support desirable environmental initiatives.
- *Economic Benefit:* Rates the net financial impact for an organization of implementing a particular recommendation; "++" means the product will cost less if the recommendation is incorporated. Here the total life cycle cost to the manufacturer is considered. For example, some parts may cost more due to DfE constraints but will also yield a higher residual value when an item of leased equipment is returned to the manufacturer for recycling.

- *CVA Impact:* Accounts for the customer-perceived value added by implementing a particular recommendation; "++" means the DfE attribute has a very high perceived value.
- *Production Management:* Estimates the production schedule impact or other manufacturing management influence resulting from implementing a particular recommendation; "++" means adoption of the recommendation would reduce the amount of time required to develop and/or manufacture the product; +/− means it would have no significance.

An example of prioritization of the recommendations listed above is given in Table 9.1. The individual scores were assigned by the LCA assessor and the recommendations were then sorted in order of decreasing overall value to the manufacturing organization in each of the three categories: manufacturing, design, and management.

13.4.2 The Action-Agent Prioritization Diagram

Although the prioritization table is helpful in developing additional supporting information relative to LCA recommendations, its extensiveness may make the most significant information difficult to extract readily, particularly if the number of recommendations is larger than shown here. An alternate display of the information is with a prioritization diagram, as shown in Figure 13.3. The first step in constructing the diagram is to normalize the assessment sum of Table 13.2 by reducing each sum by 10; the philosophy is that the maximum score is 20, and a score at or below 10 reflects neutral or negative overall

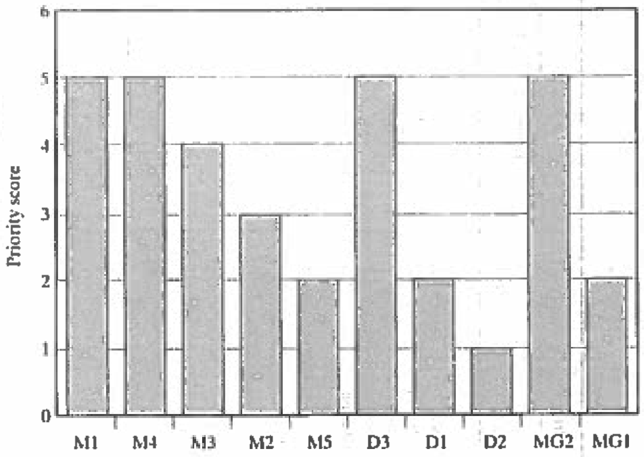


Figure 13.3

An action-agent prioritization diagram of the recommendations from the streamlined life cycle assessment of a telecommunications product. The designations on the x-axis refer to the recommendations (in the order given in Table 13.2) for manufacturing, design, and management. On the *y*-axis, higher numbers indicate greater priority.

TABLE 13.2 A Prioritization Table for DfE Recommendations

Recommendations	Life stage	Technical feasibility	Environmental sensitivity	Economic impact	CVA impact	Production management	Total
Manufacturing:							
Recycled metal specs.	L1.1	++	++	+/−	+	+/−	15
Packaging diversity-inflow	L2.1	++	+	+/−	+/−	+/−	13
Packaging diversity-outflow	L3.1	++	+	+/−	+	+/−	14
Reusable ship containers	L3.2	++	+	+/−	+	+/−	14
Solder bath N_2 inerting	L2.2	++	++	−	+/−	−	12
Design:							
Avoid chromate	L1.2(5)	+	+	+/−	+/−	+/−	12
Less plastic diversity	L5.1	+/−	+	+/−	+	−	11
Mark plastic parts	L5.2	++	++	+/−	+	+/−	15
Management:							
Online information	L4.1	++	+	−	+	−	12
Battery recovery	L4.2	++	++	−	++	+/−	15

Symbol	Value	Points
++	Very good/high	4
+	Good/high	3
+/−	Moderate, average	2
−	Little/bad	1
−−	Very little/bad	0

impacts and thus can be regarded as pertaining to a recommendation that would produce little net benefit. The practical effect of the adjustment is to make it easier to distinguish between and choose among the more highly rated recommendations. The adjusted prioritization sums are plotted in three groups, each group representing recommendations that would need to be carried out by specific "action agents": manufacturing engineers, design engineers, or management personnel.

The highest priority recommendations are quickly distinguished from those of lower priority in Figure 13.3. In the manufacturing area two actions have the highest priority rating: (1) Specify that major metal parts contain recycled content, and (2) use reusable shipping containers for modules and components. Several other actions listed in the table are rated high (though not highest) in priority; accomplishing these would also be well justified. The economic impact for all these actions is small to negligible. In the design area, the recommendation that stands out is to mark the major plastic parts with ISO symbols (as discussed in Chapter 10). For management, one priority action is also identified: the development of a program to efficiently take back discharged batteries from the field.

13.4.3 The Life-Stage Prioritization Diagram

As with the action agent diagram, the basic information is taken from Table 13.2 and normalized. The recommendations are then divided into five groups, one for each life stage: premanufacture, manufacturer, product delivery, product use, and end of life. If a recommendation pertains to more then one life stage, it is included in each life-stage group to which it pertains. The result for the telecommunications product example is shown in Figure 13.4.

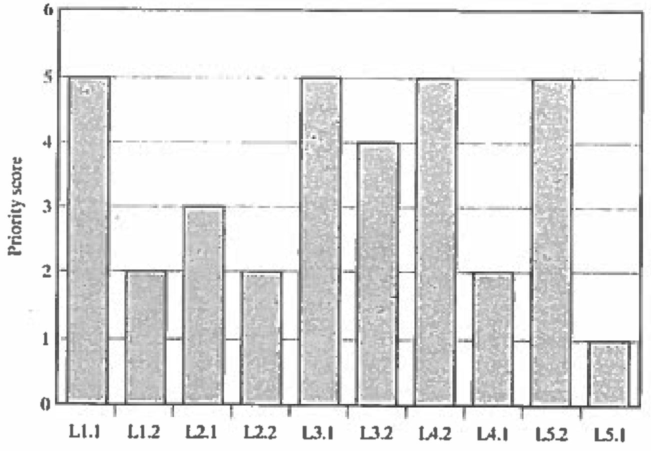


Figure 13.4

A life-stage prioritization diagram of the recommendations from the streamlined life cycle assessment of a telecommunications product. The first digit under each bar refers to the life stage; the second is a recommendation identification number (see Table 13.2).

The life-stage diagram provides a different perspective on the recommendations, one that varies in time and space rather than in the action agents. The environmental aspects of the manufacturing stage, for example, are seen as relatively benign, as the priority scores of the applicable recommendations are low. In contrast, the end-of-life stage has recommendations with higher priority scores. Attention is also indicated for the product use stage. The latter two stages are under the direct control of product designers. The premanufacture stage merits activity that requires the participation of the procurement organization in working with suppliers.

13.5 THE LIMITATIONS OF LIFE CYCLE ASSESSMENT

The great asset of the LCA concept is that it appears inherently to be the ideal way to quantitatively assess the range of environmental impacts attributable to a specific product. As seen in this chapter, however, there prove to be many limitations in practice. The drawing of assessment boundaries is difficult, the specification of the functional unit is not obvious, and it is difficult to recommend a consistent approach to either. Data collection and analysis are also limitations to accuracy and completeness. As a result, inventory analyses by different assessment teams can produce different, though perhaps equally defendable, results.

A partial list of the challenges related to the impact assessment stage includes the following:

- LCIAs do not incorporate locational information (e.g., they assume that emissions of a certain quantity of smog-forming chemicals into the air is just as significant in Oslo as in Los Angeles).
- LCIAs do not incorporate temporal information (e.g., they assume that emissions of a certain quantity of smog-forming chemicals into the air is just as significant at midnight as in midmorning).
- LCIAs routinely omit consideration of environmental impacts for which no agreed-upon characterization factor is available.
- LCA inventory data are often too general (e.g., "VOCs," "metals") to perform an adequate LCIA.
- Linearity of impacts is assumed (e.g., the impact of a 500 g emission of a certain chemical is assumed to be 100 times that of a 5 g emission). This excludes consideration of nonlinear responses and thresholds that are known to exist for some materials (see Chapter 6).
- Recycling loops are difficult to include.

To demonstrate some of the problems with LCIAs at their present state of development, let us elaborate on two examples where difficulties are real and obvious. The first is depletion of abiotic resources such as metals. There is indeed a general supposition that resources are being depleted at excessive rates in some cases. However, there are no satisfactory reference indicators for resource depletion available. Some researchers have multiplied the average concentration of the resource in Earth's crust by the mass of the crust; this is unsatisfactory because mining average crustal rock is unfeasible—miners mine enriched deposits instead. Other workers use estimates of economic resources as a reference; this is unsatisfactory as well, because increased demand as reflected in price, or improved mining technology, tends to increase reserves and thus means that contemporary reserve numbers are likely to be serious underestimates.

A second example relates to ecotoxicity, in which two emissions of equal amount are assumed to have equal impacts. The ecosystems and organisms that receive those emissions can be very different, however. In some cases, organisms can withstand and ultimately reject small doses of a substance. In others, organisms may ingest a material such as copper that is biologically essential rather than harmful (both of these cases violate the principal of linearity). Finally, ecosystems differ in their ability to sequester materials, so neglecting that difference does not take spatial location into account.

Notwithstanding this daunting list of challenges, the most difficult issues of all doubtless relate to normalization and valuation, in which the absolute assignment of value to different environmental impacts is thwarted by differences in societal structure and preferences. These constraints lead at least a few practitioners to say that LCAs can only study burdens placed on the environment and not environmental impacts (as seen in two of the case studies in this chapter). Because quantifying and prioritizing impacts is the purported reason for doing LCAs, however, a retreat to burdens is, in a sense, a retreat from the desired quantitative approach. Finally, no matter how sophisticated a quantitative analysis may be, if it has a subjective basis or uses subjective data, it gives subjective results.

LCA software programs generate results involving the inventories they are given and the environmental impacts for which they are programmed. They may include normalization and valuation steps, which require that they have incorporated "expert opinion" of some kind. The naïve user of the software is often unaware of these nuances, thereby assuming that the results that are presented are as rigorous as an engineering determination of stress or strain. This is potentially dangerous business, especially if results for two rather different ways of satisfying a customer's need are being compared.

Is, then, the concept of a product-level comprehensive LCA, with its scoping, inventory, impact, and interpretation phases, infeasible, at least as a routine tool? In LCA's present form, the answer is "probably." Nonetheless, those who have performed almost any of the types of the LCAs mentioned above have found benefits both for the product being assessed and the environment being affected, because issues are raised that would otherwise be overlooked. That fact suggests that a less doctrinaire and simpler version of an LCA might have substantial utility, whether or not it meets all the lofty goals of the ultimate LCA. This simpler approach, termed "streamlined LCA" (SLCA), is the subject of Chapter 14.

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EXERCISES

13.1 The LCIA sequence can be stopped at any point in the chain of Figure 13.1. How might you defend a decision to terminate the analysis after the characterization step or the valuation step?

13.2 The recommendations that result from the interpretation stage of the LCA of a telecommunications product (Section 13.4.1) are completely qualitative. Is this realistic or does the lack of precision limit the usefulness of the results?

13.3 Reap and colleagues (2008) identify what they term "unresolved problems" in impact assessment and interpretation. Which do you think is potentially the most serious, and why?

CHAPTER 14

Streamlining the LCA Process

14.1 NEEDS OF THE LCA USER COMMUNITY

It is useful at this point to ask, "Who are those who can most benefit from a life cycle assessment?" One group is the policy makers, who find it useful, for example, to know that generic lead-free solder use trades lead exposure for enhanced global warming emissions. A second group consists of academics who are exploring the interactions between technology and the environment. A third group, larger and more focused than either of the others, consists of product designers, process designers, and their managers. This group is interested in whether the technology for which they are responsible has any notable environmental concerns, or, sometimes, whether product A is "greener" than product B.

We discussed earlier in this book the ways in which environmentally informed design takes place, but it is appropriate to present a brief review at this point. A key feature of the process is that product realization involves what has been called "design under constraint"—the art and science of dealing simultaneously with requirements for size, performance, cost, reliability, appearance, and so forth. The time available for design is tightly limited in almost every case. As a result, decisions that will strongly influence many of a product's characteristics are often made on the basis of past experience and rough design concepts. The consequence is that at the time a decision needs to be made, it is often the case that material choices, energy use, and other factors essential to a full LCA are not available. Decisions that have environmental relevance are indeed part of the design optimization at this stage, but the information available is generally qualitative or, at best, semiquantitative.

Industrial Ecology and Sustainable Engineering

T.E. Graedel
Yale University

B.R. Allenby
Arizona State University

The first book of its kind devoted completely to the emerging field of industrial ecology/green engineering, this introduction uses industrial ecology principles and cases to ground the discussion of sustainable engineering—and offers practical and reasonable approaches to design decisions.

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