CHAPTER FIVE

Life Cycle Assessment

5.1 INTRODUCTION

The concept of conducting a detailed examination of the life cycle of a product or a process is a relatively recent one that emerged in response to increased environmental awareness on the part of the general public, industry, and governments. A number of different terms have been coined to describe the processes. **Life cycle assessment** (also known as **life cycle** analysis, ecobalance, and cradle-to-grave analysis) is a technique to assess environmental impacts associated with all the stages of a product's **life** from cradle-to-grave (i.e., from raw material extraction through materials processing, manufacture, distribution, and use). These better reflect the different stages of the process. The life cycle assessment (LCA) method has a fixed structure and is practiced according to international standards (ISO) 14040.

5.2 STAGES IN LIFE CYCLE ASSESSMENT

Life cycle assessment is a technique for assessing the environmental aspects associated with a product over its life cycle. The most important applications are these:

- analysis of the contribution of the life cycle stages to the overall environmental load, usually with the aim to prioritize improvements on products or processes
- comparison between products for internal use

An LCA study consists of four stages:

Stage 1: Goal and scope aims to define how big a part of product life cycle will be taken in assessment and to what end will assessment be serving. The criteria serving to system comparison and specific times are described in this step.

Stage 2: In this step, inventory analysis gives a description of material and energy flows within the product system and especially its interaction with environment, consumed raw materials, and emissions to the environment. All important processes and subsidiary energy and material flows are described later.

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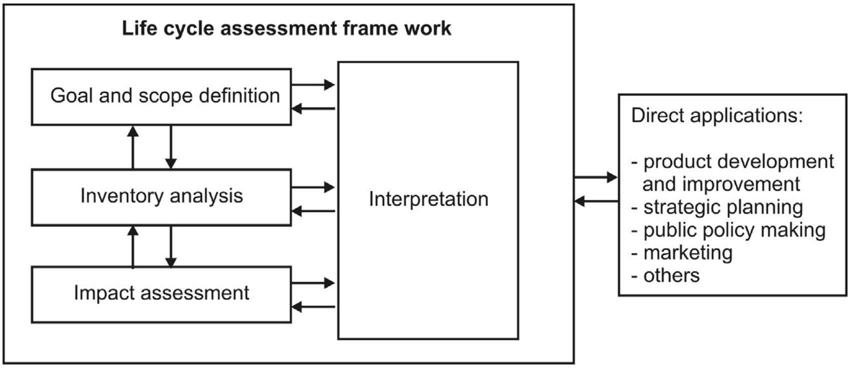

Figure 5.1 Stages of an LCA according EN ISO 14040.

Stage 3: Details from inventory analysis serve for impact assessment. The indicator results of all impact categories are detailed in this step; the importance of every impact category is assessed by normalization and eventually also by weighting.

Stage 4: Interpretation of a life cycle involves critical review, determination of data sensitivity, and result presentation.

Fig. 5.1 gives the four stages under the ISO 14040 guidelines.

When undertaking a life cycle assessment study the following issues need to be addressed:

The burdens imposed on the environment by human activities may be ascertained by accounting for the resources and energy (inputs) consumed at each stage in the life cycle of a product and the resulting pollutants and wastes (outputs) emitted. The inputs and outputs are then assessed for their adverse impacts on long-term sustainability of renewable and nonrenewable resources, human health, and biodiversity, amongst others. Once these are known, measures may be taken to mitigate the impact of the outputs (or inventories) on the environment.

The utilization of LCA method can help in the following:

- searching the most available life cycles, e.g., those with minimal negative impact on environment,
- assuming the decisions in industry, public organizations, or NGOs, which determine direction and priorities in strategic planning, design or design product, or process change,
- choose important indicators of environmental behavior of organization including measurement and assessing techniques, mainly in connection with the assessment of the state of its environment,
- marketing with the link on formulation of environmental declaration or eco-labeling

5.3 LIFE CYCLE ASSESSMENT

5.3.1 Cradle-to-Grave

Cradle-to-grave is the full life cycle assessment from manufacture (cradle) through the use phase to the disposal phase (grave). All inputs and outputs are considered for all the phases of the life cycle.

5.3.2 Cradle-to-Gate

Cradle-to-gate is an assessment of a partial product life cycle from manufacture (cradle) to the factory gate, i.e., before it is transported to the consumer. The use phase and disposal phase of the product are usually omitted. Cradle-to-gate assessments are sometimes the basis for Environmental Product Declarations. The use of biofuel, instead of fossil fuel during transportation, could have an impact on the final evaluation of LCA.

5.3.3 Cradle-to-Cradle

Cradle-to-cradle is a specific kind of cradle-to-grave assessment, where the end-of-life disposal step for the product is a recycling process. From the recycling process originates new, identical products (e.g., aluminum beverage cans from recycled cans), or different products (e.g., glass wool insulation from collected glass bottles).

5.3.4 Life Cycle Energy Analysis

Life cycle energy analysis (LCEA) is an approach in which all energy inputs to a product are accounted for, not only direct energy inputs during manufacture, but also all energy inputs required to produce components, materials, and services needed for the manufacturing process. With LCEA, the total life cycle energy input is established. Also, in this case, it is very important to know the source of energy, whether from fossil fuels or from renewable energies.

Taking the example of the transportation sector, we analyze the society's needs and wants in different spatial scales, as shown in Table 5.1. At the local level, the desire of government for development leads to the construction of rail lines and highways, thus allowing producers ready access to markets and labor supplies. The movement of goods and services is a central focus, and individual transportation becomes less and less central. Transportation as a component of security, and competitiveness assumes interest at the national scale. At the international scale, factors such as the opening of markets and the provision for shipment of large quantities of manufactured goods become elements of transportation planning. A concept for such interactions is true for any activity carried out and is shown in Fig. 5.2.

Table 5.1 Transportation, Evaluated at Different Scales

	Spatial Scale		
Constituency	**Local**	**National**	**International**
Primary producers	Regional development	National security	Trade competitiveness
	Dedicated systems	Dedicated systems	Market diversity, stability of demand
Secondary producers	Labor supply	Product distribution, market access	Exports, market presence
Consumers	Commuting, shopping	Recreation, business	Vacation, business

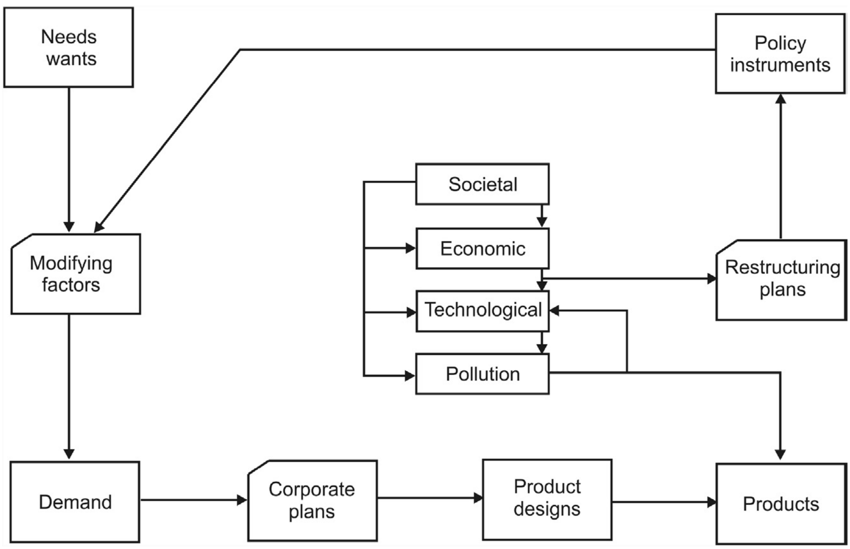

Figure 5.2 Interactions between industrial activities and societal systems.

The flow of information in the figure begins with the needs and wants in the upper left of the diagram. These forces are modified by various societal factors, economic constraints, concerns regarding hazards and environmental impacts, and the state of technology. The result is a demand for specific goods and services.

The concept of life cycle assessment is one that is readily understood and appreciated; its implementation has often proven intractable or at least impractical because of problems related to data needs, time, expense, and uncertainty regarding the defendability of the results. This situation has led to the development of the *streamlined LCA (SLCA)*, which attempts to retain the basic LCA concept while making implementation more efficient and straightforward.

Given either set of guidelines, or any other acceptable set, the relative significance of specific environmental impacts can then be established by consideration of those guidelines in accordance with several related characteristics:

- the spatial scale of the impact,
- the severity of the hazard, i.e., the product of the damage potential of a material, how much material is involved, and the exposed population (highly hazardous substances being of more concern than less highly hazardous substances),
- the degree of exposure (well-sequestered substances being of less concern than readily mobilized substances).

The environmental concerns in the context of LCA are given in Table 5.2, and the target resources and concerns are given in Table 5.3.

Table 5.2 Significant Environmental Concerns

Crucial Environmental Concerns
1. Global climate change
2. Loss of biodiversity
3. Stratospheric ozone depletion
4. Human organism damage
5. Water availability and quality
6. Depletion of fossil fuel resources
Highly Important Environmental Concerns
7. Soil depletion
8. Suboptimal land use
9. Acid deposition
10. Smog
11. Aesthetic degradation
12. Depletion of resources other than fossil fuels
Less Important Environmental Concerns
13. Oil spills
14. Radio nuclides
15. Odor
16. Thermal pollution
17. Landfill exhaustion

Table 5.3 Target Activities in Connection With Environmental Concerns

1. Global climate change	• Fossil fuel combustion (CO_2 emission) • Cement manufacture (CO_2 emission) • Rice cultivation (CH_4 emission) • Coal mining (CH_4 emission) • Ruminant populations (CH_4 emission) • Waste treatment (CH_4 emission) • Biomass burning (CO_2, CH_4 emission) • Emission of CFCs, HFCs, N_2O
2. Loss of biodiversity	• Loss of habitat • Fragmentation of habitat • Herbicide, pesticide use • Discharge of hazardous chemicals to surface waters • Reduction of dissolved oxygen in surface waters • Oil spills • Depletion of water resources • Industrial development in fragile ecosystems
3. Stratospheric ozone depletion	• Emission of CFCs • Emission of HCFCs • Emission of halons • Emission of nitrous oxide
4. Human organism damage	• Emission of hazardous materials to air • Emission of hazardous materials to water • Disposition of hazardous materials in landfills • Depletion of water resources • Physical organism damage
5. Water availability and quality	• Consumptive use of surface water • Use of herbicides and pesticides • Use of agricultural fertilizers • Discharge of hazardous materials to surface or ground waters • Siltation and salinization of surface or ground waters • Depletion of water resources
6. Resource depletion: fossil fuels	• Use of fossil fuels for energy • Use of fossil fuels as feedstocks
7. Soil depletion	• Soil erosion • Discarding or depositing trace metals onto soil • Loss of arable land to development
8. Suboptimal land use	• Loss of arable land to development • Habitat destruction • Abandonment of developed land
9. Acid deposition	• Fossil fuel combustion • Emission of sulfur oxides to air • Emission of nitrogen oxides to air

Table 5.3 Target Activities in Connection With Environmental Concerns—cont'd

10. Smog	• Fossil fuel combustion • Emission of VOCs to air • Emission of nitrogen oxides to air
11. Aesthetic degradation	• Emission of particulate matter to air • Emission of sulfur oxides to air • Incomplete combustion of fossil fuels • Biomass burning • Loss of habitat • Oil spills • Discarding solid residues • Discarding liquid residues
12. Resource depletion other than fossil fuels and soils	• Use of metals in limited supply • Habitat destruction • Use of biomaterials • Discarding solid residues • Discarding liquid residues • Discarding gaseous residues
13. Oil spills	• Transport of petroleum • Refining of petroleum • Distribution of petroleum products
14. Radio nuclides	• Production of nuclear power • Manufacture of products containing radioisotopes
15. Odor	• Odorous industrial emissions • Untreated odorous residues
16. Thermal pollution	• Discharge of heated water to surface waters • Discharge of heated water to groundwater • Discharge of heated air
17. Landfill exhaustion	• Disposition of solid residues in landfills • Disposition of liquid residues in landfills

The LCA covers the environmental and resource impacts of alternative disposal processes, as well as those other processes that are affected by disposal strategies such as different types of collection schemes for recyclables, changed transport patterns, and so on.

The complexity of the task, and the number of assumptions that must be made, is shown in Fig. 5.3.

5.4 THE LIFE CYCLE OF INDUSTRIAL PRODUCTS

The life cycle assessment is an objective process to evaluate the environmental burdens associated with a product, process, or activity by

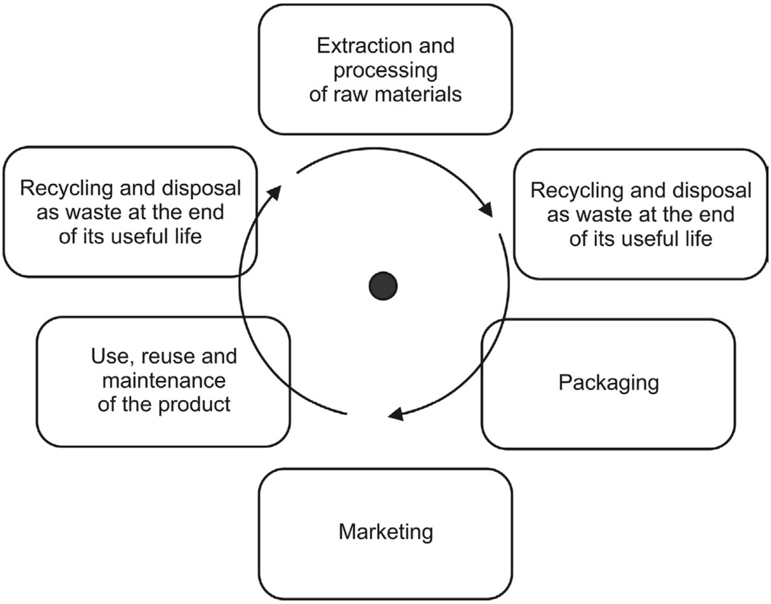

Figure 5.3 Process cycle with reference to LCA.

identifying and quantifying energy and material usage and environmental releases, to assess the impact of those energy and material uses and releases on the environment, and to evaluate and implement opportunities to effect environmental improvements. The assessment includes the entire life cycle of the product, processor activity, encompassing extracting and processing raw materials; manufacturing, transportation, and distribution; use/re-use/maintenance; recycling; and final disposal. An analysis of a typical complex manufactured product is shown schematically in Fig. 5.4.

- Stage 1, pre-manufacturing, is performed by suppliers drawing generally natural resources and producing materials and components,
- Stage 2, the manufacturing operation,
- Stage 3, product delivery; this stage and the previous one are directly under corporate control,
- Stage 4, the customer use stage, is not directly controlled by the manufacturer but is strongly influenced by how products are designed and by the degree of continuing manufacturer interaction,
- Stage 5, a product no longer satisfactory because of obsolescence, component degradation, or changed business or personal circumstances is recycled or discarded.

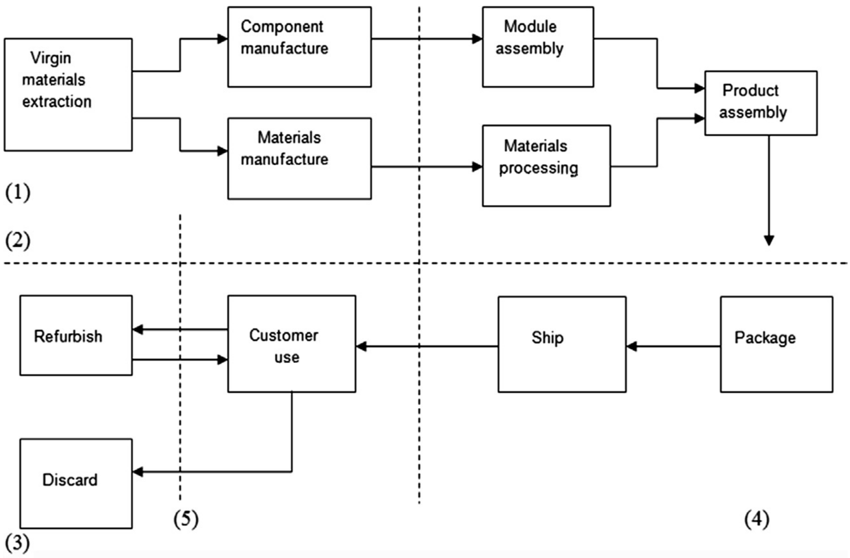

Figure 5.4 Activities in the five life cycle stages.

5.5 THE LCA FRAMEWORK

A life cycle assessment is a large and complex effort, and it has many variations. However, as already mentioned, there is general agreement on the formal structure of LCA, which contains four stages: *goal* and *scope definition*, *inventory analysis*, and *impact analysis*, each stage being followed by *interpretation of results*. LCA normally uses quantitative data to establish the levels and types of energy and materials input to an industrial system and the product output and environmental releases that result, as shown schematically in Fig. 5.5. The main technique used in LCA is that of modeling. In the inventory phase, a model is made of the complex technical system that is used to produce, transport, use, and dispose of a product. This results in a flow sheet or process tree with all the relevant processes. For each process, all the relevant inflows and the outflows are collected. The result is usually a very long list of inflows and outflows that is often difficult to interpret.

5.5.1 Data Collection

The most demanding task in performing LCAs is data collection. Depending on the time and budget available, there are a number of strategies to collect such data. It is useful to distinguish two types of data:

1. Foreground data
2. Background data

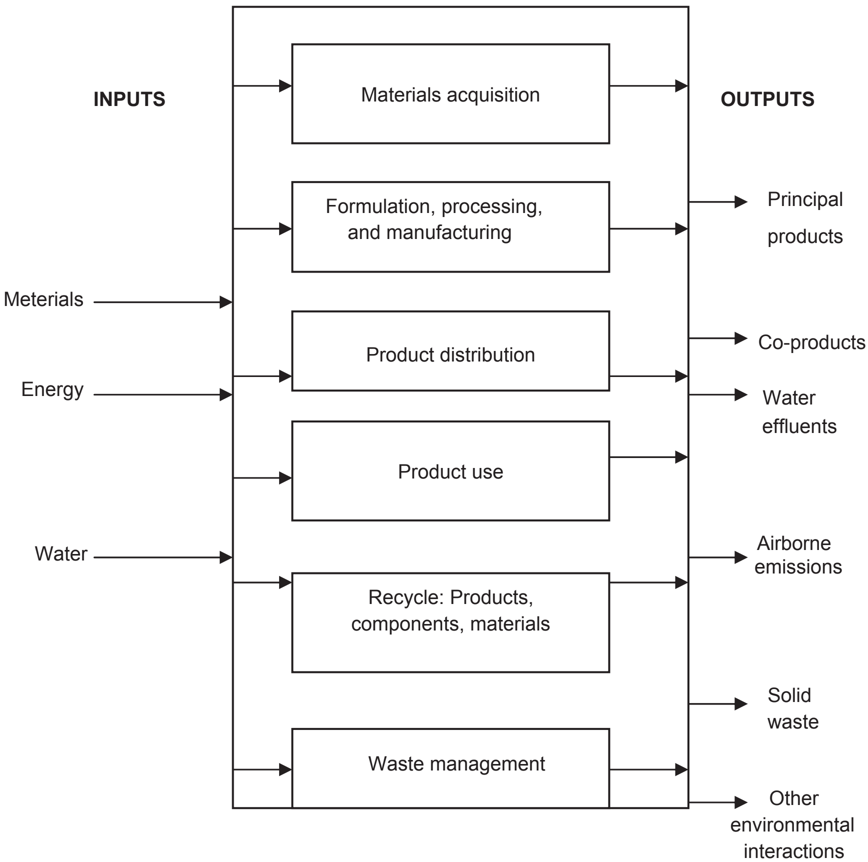

Figure 5.5 The elements of a life cycle inventory analysis. *Adapted from Society of Environmental Toxicology and Chemistry, A Technical Framework for Life Cycle Assessment; Washington, DC 1991.*

Foreground data refers to very specific data needed to model the system. It is typically data that describes a particular product system and particular specialized production system. Background data is data for generic materials, energy, transport, and waste management systems. This is typically data found in databases and literature. Collecting data from other parties is not always easy. It is useful to carefully consider the following points:

- The willingness to supply data is of course determined by the relation you have with these parties. Some parties will be interested as they may have common goals; some will see LCA activities as a threat. In some cases, most of the data collection effort is in the establishing of a good relation, in which parties have trust in each other.

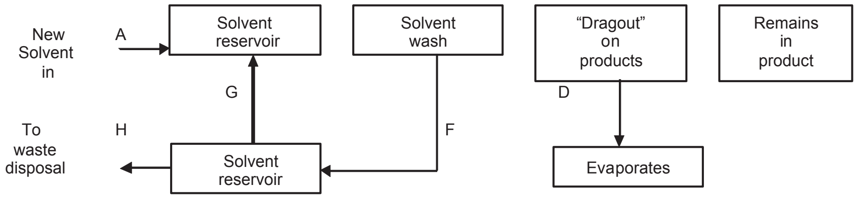

Figure 5.6 Schematic diagram of the flow streams involved in a budget analysis of a chemical solvent in a solvent washing process.

- Confidentiality issues can be very important.
- There are terminology issues in each industry sector; there are different ways of measuring and expressing things. If one develops a questionnaire for a party, it may be applicable within that sector only.
- Questionnaires are often used as a means to collect data. The development of a questionnaire should be done with great care, and it should well connect to the target groups one is addressing.

Once the data is collected and analyzed the budgets and mass balance studies need to be carried out. One of the simple materials budgets is that for a manufacturing process (Fig. 5.6). It shows a chemical process involving the cleaning of a product or product component with a liquid solvent. The process begins with the addition of new solvent to a solvent reservoir, followed by piping or otherwise moving the solvent to the product line where the solvent wash occurs. Most of the solvent eventually enters a recycling (disposal) stream, but a portion (known as "drag out") is retained on the product. Some of the drag out material remains on the product, while a fraction is lost to the atmosphere by evaporation.

5.5.2 Life Cycle Inventory (LCI)

The second phase, "Inventory," involves the modeling of the product system, data collection, as well as the description and verification of data. This implies that data for inputs and outputs for all affected unit processes that compose the product system are available. The inputs and outputs include inputs of materials, energy, chemicals, and "other" and outputs in the form of air emissions, water emissions, or solid waste. Other types of exchanges or interventions such as radiation or land use should also be included if applicable.

The data must be related to the functional unit defined in the goal and scope definition. Data can be presented in tables, and some interpretations can be made at this early stage. The results of the inventory is an LCI that provides information about all inputs and outputs in the form of elementary flow to and from the environment from all the unit processes involved in the study.

Mass balance equations can be set up around any boundary of the system. For example, it is clear that the rate at which the solvent leaves the faculty must be equal to the rate at which it enters: A = D + E + H.

A detailed product and process budget is shown in Fig. 5.7.

5.5.3 LAC Impact Analysis

The third phase, "life cycle impact assessment" (LAC), is aimed at evaluating the contribution to impact categories such as global warming, acidification, etc. Characterization is the first step and involves calculation of potential impacts on the basis of the LCI results. The next steps are normalization and weighting, but these are both voluntary according the ISO standard. Normalization provides a basis for comparing different types of environmental impact categories. Weighting implies assigning a weighting factor to each impact category depending on their relative importance. The problem of applying weighting factors is that they distort the scale of values without adding anything to the overall assessment. Impact assessment considerations include thresholds and nonlinearities, temporal scales, spatial scales, and valuation.

The impact assessment can be structured according to the following steps:

- *Classification*: Classification begins with the raw data from the inventory analysis on flows of materials and energy. Given that data, the classification step consists of identifying environmental concerns 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 primarily to global warming, the second to smog formation, and the third to human toxicity.
- *Localization*: Localization is the operation of comparing environmental impacts occurring in different regions with different characteristics. For example, the process of localization attempts to compare the emission of moderately toxic material into a pristine ecosystem with the impact of the same emission into a highly polluted ecosystem. The first consideration is the relationship of emissions from the product or process being assessed relative to all similar emissions in the region. The second is the degree to which the region possesses assimilative capacity for the emitant.

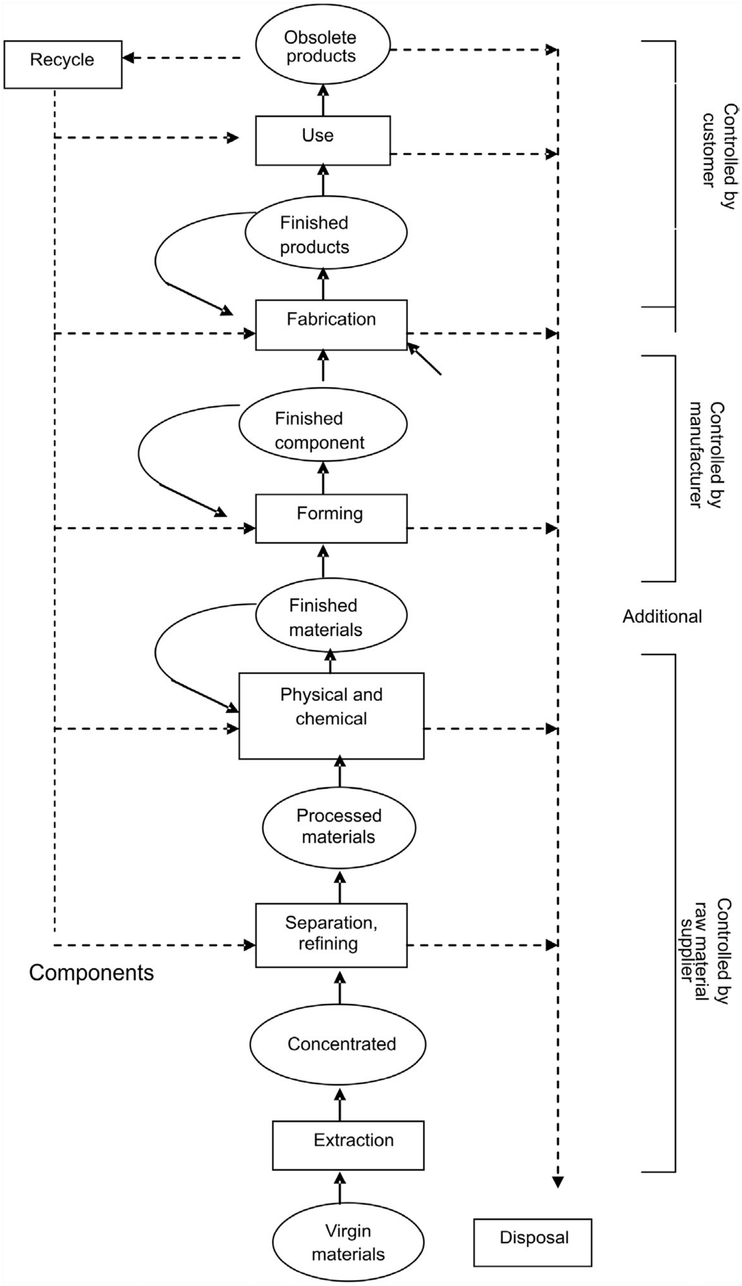

Figure 5.7 Process and product budgets.

- *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 or some international organization might choose to regard ozone depletion impacts as twice as important as loss of visibility, and apply weighting factors to the normalized impacts accordingly.

5.5.4 Interpretation

The phase stage "interpretation" is the most important. An analysis of major contributions, sensitivity analysis, and uncertainty analysis leads to the conclusion whether the ambitions from the goal and scope can be met. All conclusions are drafted during this phase.

ISO 14040:2006 describes the principles and framework for LCA, including definition of the goal and scope of the LCA, the LCI analysis phase, the life cycle impact assessment phase, the life cycle interpretation phase, reporting and critical review of the LCA, limitations of the LCA, the relationship between the LCA phases, and conditions for use of value choices and optional elements.

5.6 STREAMLINED LIFE CYCLE ASSESSMENT

Techniques that purposely adopt some sort of simplified approach to life cycle assessment, *streamlined life cycle assessments*, form part of a continuum of assessment effort, with the degree of detail and expense generally decreasing as one moves from the left extreme toward the right, as shown in Fig. 5.8. Somewhere within the SLCA region is the ideal

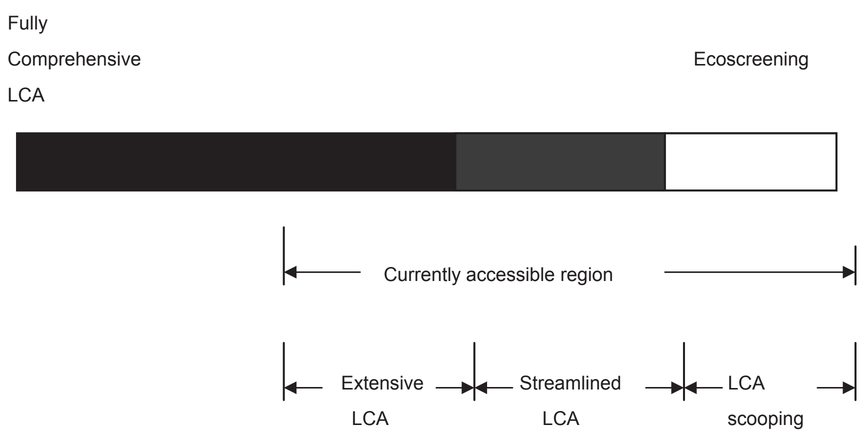

Figure 5.8 The LCA/SLCA continuum.

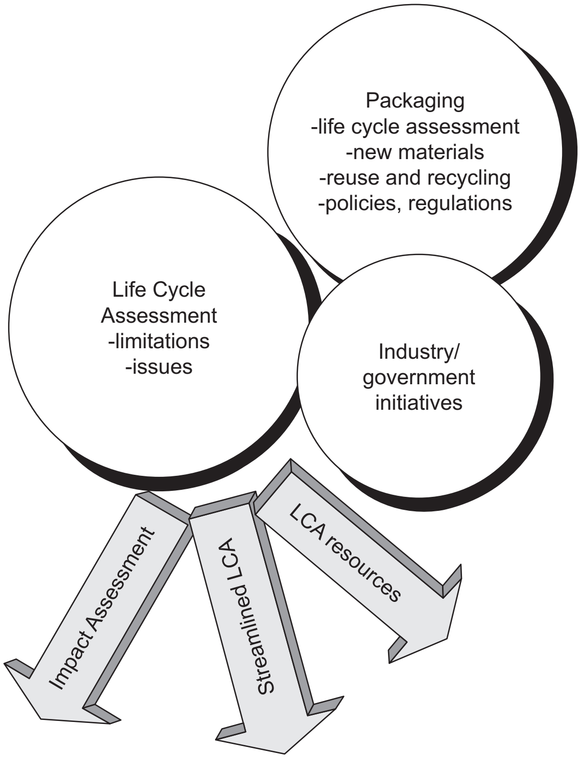

Figure 5.9 Summary of the role of stakeholders and resources in LCA.

point: the assessment is complete and rigorous enough to be a definite guide to industry and an aid to the environment, yet not so detailed as to be difficult or impossible to perform.

Many SLCA approaches have gravitated toward a matrix, one dimension of which is life cycle stages and the other is a list of environmental impacts, potential employee health concerns, or other relevant parameters. The role of the various stakeholders and the resources are shown in Fig. 5.9. The SCLA is an effective tool to assess the impact of the product/activity on the environment. The methods used for the assessment are given next.

5.6.1 Battelle's Pollution Prevention Factors Approach

Battelle has developed what it calls a *P2 approach* to SLCA that also utilizes a matrix tool. The rows in the matrix are 24 items attempting to cover cradle-to-grave aspects of the life cycle (energy use–raw materials, energy use–product assembly, etc.), and the columns are individual components in the products.

5.6.2 Jacobs Engineering's SLCA Approach

Jacobs Engineering has developed a matrix tool utilizing five environmental stresses and seven "risk areas" (global warming, etc.). It has thus far been applied to manufacturing processes, but not to products. The matrix is evaluated for the influence of the process on spatial scales, both at local and global levels. The existing operation is used as a basis from which to evaluate process changes, and the matrix element scores are +1, 0, or −1 depending on whether the alternative proposed is better than, equivalent, or poorer than the base case from an environmental standpoint.

5.6.3 Matrix Calculations

Regardless of how matrix element values are derived, an LCA or SLCA analysis using a matrix-based procedure can be represented mathematically as an exercise in matrix manipulation. To demonstrate, consider the matrix of Table 5.4, which is an SLCA tool devised for ecolabel certification of products. If the matrix elements $f_{m,n}$ are filled with inventory analysis data, the result is a form of an inventory analysis matrix that can be called **F**. Similarly, matrix elements $S_{m,n}$ can be filled with impact assessment data

Table 5.4 The Environmentally Responsible Process Matrix

	Environmental Stressor				
Life Stage	**Materials Selection**	**Energy Use**	**Solid Residues**	**Liquid Residues**	**Gaseous Residues**
Resource provisioning	1,1	1,2	1,3	1,4	1,5
Process implementation	2,1	2,2	2,3	2,4	2,5
Primary process operation	3,1	3,2	3,3	3,4	3,5
Complementary process operation	4,1	4,2	4,3	4,4	4,5
Refurbishment, recycling, disposal	5,1	5,2	4,4	5,4	5,5

The numbers are the matrix element indices i,j.

(a one-time operation except for revisions) to give an impact analysis matrix called **S**.

The (S) LCA assessment for a single critical environmental property n is then given by

$$L_n = \sum_{1}^{n} f_{(m\,,\,n)} \times S_{(m\,,\,n)}$$

In the same fashion, the (S)LCA assessment for a single life stage m is given by

$$L_n = \sum_{1}^{m} f_{(m\,,\,n)} \times S_{(m\,,\,n)}$$

The overall assessment is given by

$$L_n = \sum_{1}^{m} \sum_{1}^{n} f_{(m\,,\,n)} \times S_{(m\,,\,n)}$$

As with any matrix, some of the **F** matrix elements may contain zeros. This situation will occur in either of two situations: a null inventory value might be listed for such factors as anticipated soil pollution and degradation during the distribution of a product, or where an inventory value may be deemed unimportant. Similarly, zeros will occur in the **S** matrix if no impact is foreseen from a product or process.

5.7 STAGES IN PROCESS LIFE CYCLES

As with products, industrial processes can be evaluated by SLCA matrix techniques simple enough to permit relatively quick and inexpensive assessments to be made in which all stages of product life cycles and all relevant environmental stressors are encompassed. Fig. 5.10 summarizes the life cycle stages in a process.

Resource provisioning: The first stage in the life cycle of any process is the provisioning of the materials used to produce the consumable resources that are used throughout the life of the product being assessed.

Process implementation: Coincident with resource provisioning is process implementation, which looks at the environmental impacts that result from the activities necessary to make the process happen.

Primary process operation: A process should be designed to be environmentally responsible in operation. Such a process would ideally limit

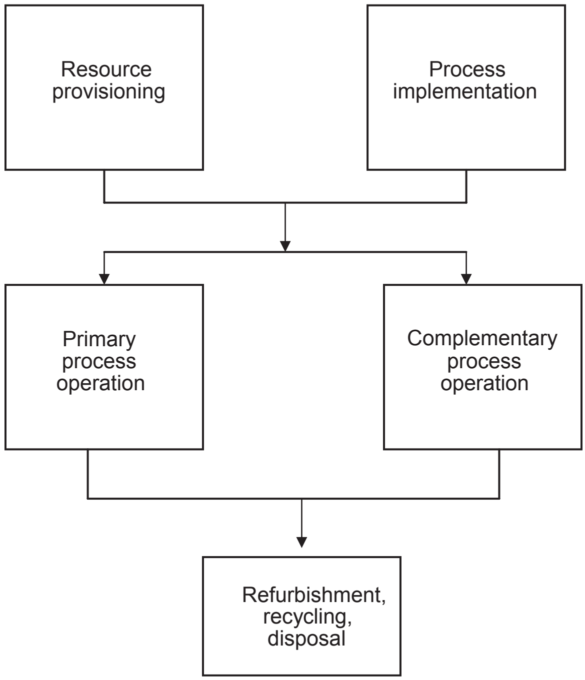

Figure 5.10 The life cycle stages of a process.

the use of hazardous materials, minimize the consumption of energy, avoid or minimize the generation of solid, liquid, or gaseous residues, and ensure that any residues that are produced can be used elsewhere in the economy.

Complementary process operation: It is often the case that several manufacturing processes form a symbiotic relationship, each assuming and depending on the existence of others. Thus, a comprehensive process valuation needs to consider not only the environmental attributes of the primary process itself but also those of the complementary processes that precede and follow.

Refurbishment, recycling, disposal: The process designer must recognize that all process equipment will eventually become obsolete, and it must therefore be designed to optimize disassembly and reuse, either of modules (the preferable option) or materials.

The rating matrix: In arriving at an individual matrix element assessment for processes, or in offering advice to designers seeking to improve the rating of a particular matrix element, the assessor can refer for guidance to underlying checklists and protocols. After an evaluation has been made for each matrix element, the overall environmentally responsible process rating is computed, as in the case of products, as the sum of the matrix element values:

$$R_{ERPS} = \sum \sum Mij$$

Because the process matrix has 25 matrix elements, each with a maximum value of 4, the maximum process assessment rating is 100.

The results from SLCA are often regarded as "approximately correct"; if they even come close to that characterization, carrying out the assessment and implementing their recommendations will be of much value.

SLCA Advantages Over LCA	SLCA Disadvantages When Compared to LCA
SLCA take less time and can be completed in days when compared to months for LCA	SLCA has little capability to track overall material flows
SLCA is less expensive and can use existing staff	It has minimum capacity to compare completely dissimilar approaches to fulfilling a need
Most SLCAs are usable in the early stage of design, when opportunities for change are high	It has minimum capability to track improvements over time
SLCAs are likely to be carried out routinely and applied over a wide variety of products and industrial activities	

In summary, all life cycle analyses collect inventory data on raw material consumption, energy and water use, and waste production. However, a meaningful LCA should contain more than a mere inventory of inputs and outputs: it should also consider the overall contributions and risks to the environment and public health, as well as the social, cultural, and economic impacts of each option.

FURTHER READING

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