EPA/600/R-06/060
May 2006

# LIFE CYCLE ASSESSMENT: PRINCIPLES AND PRACTICE

by

Scientific Applications International Corporation (SAIC)
11251 Roger Bacon Drive
Reston, VA 20190

Contract No. 68-C02-067
Work Assignment 3-15

Work Assignment Manager
Mary Ann Curran
Systems Analysis Branch
National Risk Management Research Laboratory
Cincinnati, Ohio 45268

NATIONAL RISK MANAGEMENT RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

# Notice

The U.S. Environmental Protection Agency through its Office of Research and Development funded and managed the research described here under contract no. 68-C02-067 to Scientific Applications International Corporation (SAIC). It has been subjected to the Agency's review and has been approved for publication as an EPA document. Mention of trade names or commercial products does not constitute endorsement or recommendation for use. Use of this methodology does not imply EPA approval of the conclusions of any specific life cycle assessment.

# Foreword

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory (NRMRL) is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threaten human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments and ground water; prevention and control of indoor air pollution; and restoration of ecosystems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's research provides solutions to environmental problems by: developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

**Sally Gutierrez, Director**
**National Risk Management Research Laboratory**

# Abstract

The following document provides an introductory overview of Life Cycle Assessment (LCA) and describes the general uses and major components of LCA. This document is an update and merger of two previous EPA documents on LCA ("Life Cycle Assessment: Inventory Guidelines and Principles," EPA/600/R-92/245, and "LCA101" from the *LCAccess*, website, http://www.epa.gov/ORD/NRMRL/lcaccess). It presents the four basic stages of conducting an LCA: goal and scope definition, inventory analysis, impact assessment, and improvement analysis. The major stages in an LCA study are raw material acquisition, materials manufacture, production, use/reuse/maintenance, and waste management. The system boundaries, assumptions, and conventions to be addressed in each stage are presented. This document is designed to be an educational tool for someone who wants to learn the basics of LCA, how to conduct an LCA, or how to manage someone conducting an LCA. Companies, federal facilities, industry organizations, or academia can benefit from learning how to incorporate environmental performance based on the life cycle concept into their decision-making processes. This report was submitted in fulfillment of contract 68-C02-067 by Scientific Applications International Corporation (SAIC) under the sponsorship of the United States Environmental Protection Agency. This report covers a period from December 2005 to May 2006, and work was completed as of May 30, 2006.

## Contents

## Exhibits

## Tables

## Abbreviations

| | |
|---|---|
| BOD | biological oxygen demand |
| Btu | British thermal unit |
| CO | carbon monoxide |
| COD | chemical oxygen demand |
| $CO_2$ | carbon dioxide |
| DQIs | data quality indicators |
| EPA | United States Environmental Protection Agency |
| GWh | gigawatt-hour |
| ISO | International Standards Organization (International Organization of Standardization) |
| kWh | kilowatt-hour |
| LCA | life cycle assessment |
| LCI | life cycle inventory |
| LCIA | life cycle impact assessment |
| LCM | life cycle management |
| MJ | megajoule |
| $NO_2$ | nitrogen dioxide |
| NRMRL | National Risk Management Research Laboratory |
| REPA | Resource and Environmental Profile Analysis |
| SETAC | Society of Environmental Toxicology and Chemistry |
| $SO_2$ | sulfur dioxide |
| TRACI | Tool for the Reduction and Assessment of Chemical and other environmental Impacts |
| TRI | Toxics Release Inventory |
| VOCs | volatile organic compounds |

# Chapter 1
# Life Cycle Assessment

## What is Life Cycle Assessment (LCA)?

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

Life cycle assessment is a "cradle-to-grave" approach for assessing industrial systems. "Cradle-to-grave" begins with the gathering of raw materials from the earth to create the product and ends at the point when all materials are returned to the earth. LCA evaluates all stages of a product's life from the perspective that they are interdependent, meaning that one operation leads to the next. LCA enables the estimation of the cumulative environmental impacts resulting from all stages in the product life cycle, often including impacts not considered in more traditional analyses (e.g., raw material extraction, material transportation, ultimate product disposal, etc.). By including the impacts throughout the product life cycle, LCA provides a comprehensive view of the environmental aspects of the product or process and a more accurate picture of the true environmental trade-offs in product and process selection.

The term "life cycle" refers to the major activities in the course of the product's life-span from its manufacture, use, and maintenance, to its final disposal, including the raw material acquisition required to manufacture the product. Exhibit 1-1 illustrates the possible life cycle stages that can be considered in an LCA and the typical inputs/outputs measured.

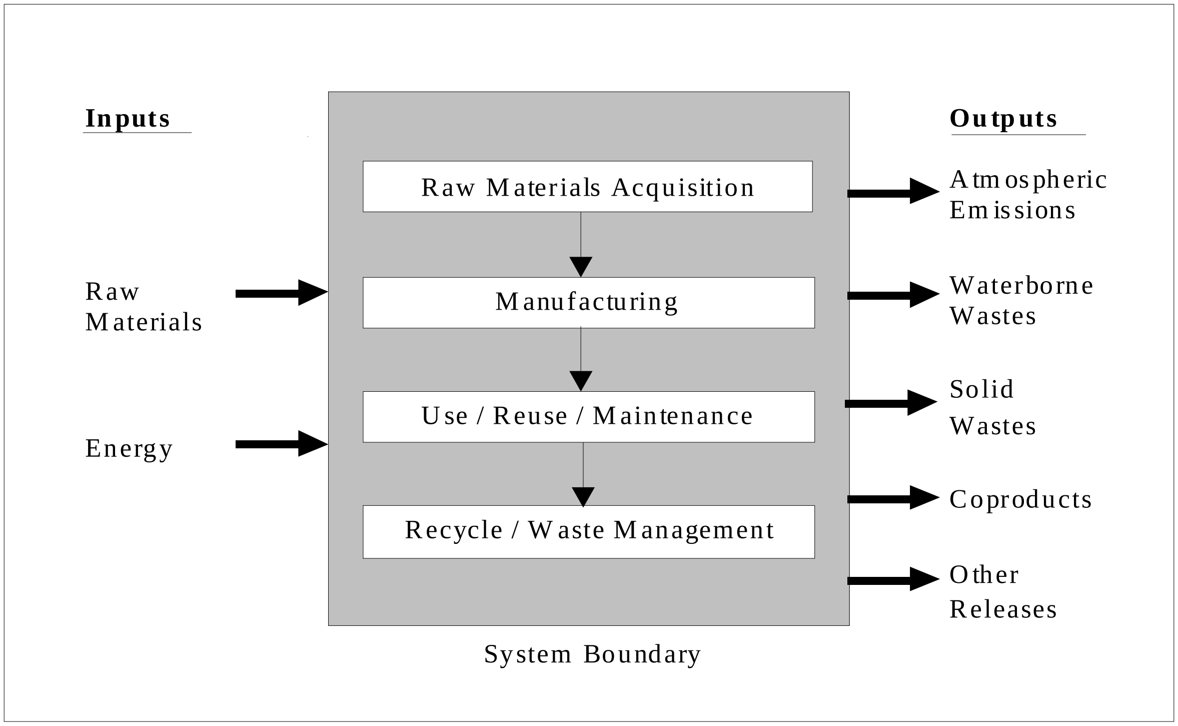


**Exhibit 1-1. Life Cycle Stages** (Source: EPA,1993)

Specifically, LCA is a technique to assess the environmental aspects and potential impacts associated with a product, process, or service, by:

- Compiling an inventory of relevant energy and material inputs and environmental releases
- Evaluating the potential environmental impacts associated with identified inputs and releases
- Interpreting the results to help decision-makers make a more informed decision.

The LCA process is a systematic, phased approach and consists of four components: goal definition and scoping, inventory analysis, impact assessment, and interpretation as illustrated in Exhibit 1-2:

1. *Goal Definition and Scoping* - Define and describe the product, process or activity. Establish the context in which the assessment is to be made and identify the boundaries and environmental effects to be reviewed for the assessment.

2. *Inventory Analysis* - Identify and quantify energy, water and materials usage and environmental releases (e.g., air emissions, solid waste disposal, waste water discharges).

3. *Impact Assessment* - Assess the potential human and ecological effects of energy, water, and material usage and the environmental releases identified in the inventory analysis.

4. *Interpretation* - Evaluate the results of the inventory analysis and impact assessment to select the preferred product, process or service with a clear understanding of the uncertainty and the assumptions used to generate the results.

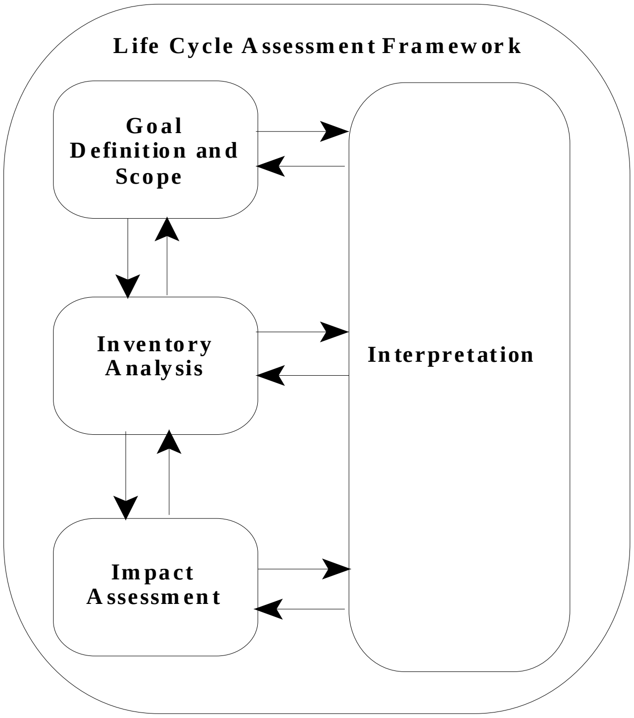


**Exhibit 1-2. Phases of an LCA** (Source: ISO, 1997)

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

### What Are the Benefits of Conducting an LCA?

An LCA can help decision-makers select the product or process that results in the least impact to the environment. This information can be used with other factors, such as cost and performance data to select a product or process. LCA data identifies the transfer of environmental impacts from one media to another (e.g., eliminating air emissions by creating a wastewater effluent instead) and/or from one life cycle stage to another (e.g., from use and reuse of the product to the raw material acquisition phase). If an LCA were not performed, the transfer might not be recognized and properly included in the analysis because it is outside of the typical scope or focus of product selection processes.

### LCA Helps to Avoid Shifting Environmental Problems from One Place to Another

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

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

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

### A Brief History of Life-Cycle Assessment

Life Cycle Assessment (LCA) had its beginnings in the 1960's. Concerns over the limitations of raw materials and energy resources sparked interest in finding ways to cumulatively account for energy use and to project future resource supplies and use. In one of the first publications of its kind, Harold Smith reported his calculation of cumulative energy requirements for the production of chemical intermediates and products at the World Energy Conference in 1963.

Later in the 1960's, global modeling studies published in *The Limits to Growth* (Meadows *et al* 1972) and *A Blueprint for Survival* (Goldsmith *et al* 1972) resulted in predictions of the effects of the world's changing populations on the demand for finite raw materials and energy resources. The predictions for rapid depletion of fossil fuels and climatological changes resulting from excess waste heat stimulated more detailed calculations of energy use and output in industrial processes. During this period, about a dozen studies were performed to estimate costs and environmental implications of alternative sources of energy.

In 1969, researchers initiated an internal study for The Coca-Cola Company that laid the foundation for the current methods of life cycle inventory analysis in the United States. In a comparison of different beverage containers to determine which container had the lowest releases to the environment and least affected the supply of natural resources, this study quantified the raw materials and fuels used and the environmental loadings from the manufacturing processes for each container. Other companies in both the United States and Europe performed similar comparative life cycle inventory analyses in the early 1970's. At that time, many of the available sources were derived from publicly-available sources such as government documents or technical papers, as specific industrial data were not available.

The process of quantifying the resource use and environmental releases of products became known as a Resource and Environmental Profile Analysis (REPA), as practiced in the United States. In Europe, it was called an Ecobalance. With the formation of public interest groups encouraging industry to ensure the accuracy of information in the public domain, and with the oil shortages in the early 1970's, approximately 15 REPAs were performed between 1970 and 1975. Through this period, a protocol or standard research methodology for conducting these studies was developed. This multi-step methodology involves a number of assumptions. During these years, the assumptions and techniques used underwent considerable review by EPA and major industry representatives, with the result that reasonable methodologies were evolved.

From 1975 through the early 1980's, as interest in these comprehensive studies waned because of the fading influence of the oil crisis, environmental concerns shifted to issues of hazardous and household waste management. However, throughout this time, life cycle inventory analysis continued to be conducted and the methodology improved through a slow stream of about two studies per year, most of which focused on energy requirements. During this time, European interest grew with the establishment of an Environment Directorate (DG X1) by the European Commission. European LCA practitioners developed approaches parallel to those being used in the USA. Besides working to standardize pollution regulations throughout Europe, DG X1 issued the Liquid Food Container Directive in 1985, which charged member companies with monitoring the energy and raw materials consumption and solid waste generation of liquid food containers.

When solid waste became a worldwide issue in 1988, LCA again emerged as a tool for analyzing environmental problems. As interest in all areas affecting resources and the environment grows, the methodology for LCA is again being improved. A broad base of consultants and researchers across the globe has been further refining and expanding the methodology. The need to move beyond the inventory to impact assessment has brought LCA methodology to another point of evolution (SETAC 1991; SETAC 1993; SETAC 1997).

In 1991, concerns over the inappropriate use of LCAs to make broad marketing claims made by product manufacturers resulted in a statement issued by eleven State Attorneys General in the USA denouncing the use of LCA results to promote products until uniform methods for conducting such assessments are developed and a consensus reached on how this type of environmental comparison can be advertised non-deceptively. This action, along with pressure from other environmental organizations to standardize LCA methodology, led to the development of the LCA standards in the International Standards Organization (ISO) 14000 series (1997 through 2002).

In 2002, the United Nations Environment Programme (UNEP) joined forces with the Society of Environmental Toxicology and Chemistry (SETAC) to launch the Life Cycle Initiative, an international partnership. The three programs of the Initiative aim at putting life cycle thinking into practice and at improving the supporting tools through better data and indicators. The Life Cycle Management (LCM) program creates awareness and improves skills of decision-makers by producing information materials, establishing forums for sharing best practice, and carrying out training programs in all parts of the world. The Life Cycle Inventory (LCI) program improves global access to transparent, high quality life cycle data by hosting and facilitating expert groups whose work results in web-based information systems. The Life Cycle Impact Assessment (LCIA) program increases the quality and global reach of life cycle indicators by promoting the exchange of views among experts whose work results in a set of widely accepted recommendations.

### Limitations of Conducting an LCA

Performing an LCA can be resource and time intensive. Depending upon how thorough an LCA the user wishes to conduct, gathering the data can be problematic, and the availability of data can greatly impact the accuracy of the final results. Therefore, it is important to weigh the availability of data, the time necessary to conduct the study, and the financial resources required against the projected benefits of the LCA.

LCA will not determine which product or process is the most cost effective or works the best. Therefore, the information developed in an LCA study should be used as one component of a more comprehensive decision process assessing the trade-offs with cost and performance, e.g., Life Cycle Management.

### Life Cycle Management

Life Cycle Management (LCM) is the application of life cycle thinking to modern business practice, with the aim to manage the total life cycle of an organization’s product and services toward more sustainable consumption and production (Jensen and Remmen 2004). It is an integrated framework of concepts and techniques to address environmental, economic, technological, and social aspects of products, services, and organizations. LCM, as any other management pattern, is applied on a voluntary basis and can be adapted to the specific needs and characteristics of individual organizations (SETAC 2004).

There are a number of ways to conduct Life Cycle Impact Assessment. While the methods are typically scientifically-based, the complexity of environmental systems has led to the development of alternative impact models. Chapter 4 expands on this.

As mentioned earlier, an LCA can help identify potential environmental tradeoffs. However, converting the impact results to a single score requires the use of value judgments, which must be applied by the commissioner of the study or the modeler. This can be done in different ways such as through the use of an expert panel, but it cannot be done based solely on natural science.

# Chapter 2
# Goal Definition and Scoping

## What is Goal Definition and Scoping?

Goal definition and scoping is the phase of the LCA process that defines the purpose and method of including life cycle environmental impacts into the decision-making process. In this phase, the following items must be determined: the type of information that is needed to add value to the decision-making process, how accurate the results must be to add value, and how the results should be interpreted and displayed in order to be meaningful and usable.

## How Does Goal Definition and Scoping Affect the LCA Process?

The LCA process can be used to determine the potential environmental impacts from any product, process, or service. The goal definition and scoping of the LCA project will determine the time and resources needed. The defined goal and scope will guide the entire process to ensure that the most meaningful results are obtained. Every decision made throughout the goal definition and scoping phase impacts either how the study will be conducted, or the relevance of the final results. The following section identifies the decisions that must be made at the beginning of the LCA study and the impact of these decisions on the LCA process.

## Getting Started

The following six basic decisions should be made at the beginning of the LCA process to make effective use of time and resources:

1. Define the Goal(s) of the Project
2. Determine What Type of Information Is Needed to Inform the Decision-Makers
3. Determine the Required Specificity
4. Determine How the Data Should Be Organized and the Results Displayed
5. Define the Scope of the Study
6. Determine the Ground Rules for Performing the Work

Each decision and its associated impact on the LCA process are explained below in further detail.

## Define the Goal(s) of the Project

LCA is a versatile tool for quantifying the overall (cradle-to-grave) environmental impacts from a product, process, or service. The primary goal is to choose the best product, process, or service with the least effect on human health and the environment. Conducting an LCA also can help guide the development of new products, processes, or activities toward a net reduction of resource requirements and emissions. There may also be secondary goals for performing an LCA, which would vary depending on the type of project. The following are examples of possible applications for life-cycle inventories, most of which require some level of impact assessment in addition to the inventory:

- *Support broad environmental assessments* - The results of an LCA are valuable in understanding the relative environmental burdens resulting from evolutionary changes in given processes, products, or packaging over time; in understanding the relative environmental burdens between alternative processes or materials used to make, distribute, or use the same product; and in comparing the environmental aspects of alternative products that serve the same use.

- *Establish baseline information for a process* - A key application of an LCA is to establish a baseline of information on an entire system given current or predicted practices in the manufacture, use, and disposal of the product or category of products. In some cases, it may suffice to establish a baseline for certain processes associated with a product or package. This baseline would consist of the energy and resource requirements and the environmental loadings from the product or process systems that are analyzed. The baseline information is valuable for initiating improvement analysis by applying specific changes to the baseline system.

- *Rank the relative contribution of individual steps or processes* - The LCA results provide detailed data regarding the individual contributions of each step in the system studied to the total system. The data can provide direction to efforts for change by showing which steps require the most energy or other resources, or which steps contribute the most pollutants. This application is especially relevant for internal industry studies to support decisions on pollution prevention, resource conservation, and waste minimization opportunities.

- *Identify data gaps* - The performance of an LCA for a particular system reveals areas in which data for particular processes are lacking or are of uncertain or questionable quality. Inventory followed by impact assessment aids in identifying areas where data augmentation is appropriate for both stages.

- *Support public policy* - For the public policymaker, LCA can help broaden the range of environmental issues considered in developing regulations or setting policies.

- *Support product certification* - Product certifications have tended to focus on relatively few criteria. LCA, only when applied using appropriate impact assessment, can provide information on the individual, simultaneous effects of many product attributes.

- *Provide information and direction to decision-makers* - LCA can be used to inform industry, government, and consumers on the tradeoffs of alternative processes, products, and materials. The data can give industry direction in decisions regarding production materials and processes and create a better informed public regarding environmental issues and consumer choices.

- *Guide product and process development* - LCA can help guide manufacturers in the development of new products, processes, and activities toward a net reduction of resource requirements and emissions.

### Determine What Type of Information Is Needed to Inform the Decision-Makers

LCA can help answer a number of important questions. Identifying the questions that the decision-makers care about will help define the study parameters. Some examples include:

- What is the impact to particular interested parties and stakeholders?
- Which product or process causes the least environmental impact (quantifiably) overall or in each stage of its life cycle?
- How will changes to the current product/process affect the environmental impacts across all life cycle stages?
- Which technology or process causes the least amount of acid rain, smog formation, or damage to local trees (or any other impact category of concern)?
- How can the process be changed to reduce a specific environmental impact of concern (e.g., global warming)?

Once the appropriate questions are identified, it is important to determine the types of information needed to answer the questions.

**Attributional LCA versus Consequential LCA**

During a workshop held in 2003, specifically on life cycle inventory for electricity generation, participants recognized the need to choose an allocation method depending considerably upon whether the life cycle assessment is being performed from an *attributional* or a *consequential* point of view. The term “attributional life cycle assessment” was defined as an attempt to answer “how are things (i.e. pollutants, resources, and exchanges among processes) flowing within the chosen temporal window?” while “consequential life cycle assessment” attempts to answer “how will flows beyond the immediate system change in response to decisions?” For example, an attributional LCA would examine the consequences of using green power compared to conventional sources. A consequential LCA would consider the consequences of this choice in that only a certain amount of green power may be available to customers, causing some customers to buy conventional energy once the supply of greener sources was gone. The choice between conducting an attributional or a consequential assessment depends on the stated goal of the study (Curran, Mann, & Norris 2005).

### Determine the Required Specificity

At the outset of every study, the level of specificity must be decided. In some cases, this level will be obvious from the application or intended use of the information. In other instances, there may be several options to choose from, ranging from a completely generic study to one that is product-specific in every detail. Most studies fall somewhere in between.

An LCA can be envisioned as a set of linked activities that describe the creation, use, and ultimate disposal of the product or material of interest. At each life cycle stage, the analyst should begin by answering a series of questions: Is the product or system in the life cycle stage specific to one company or manufacturing operation? Or does the product or system represent common products or systems generally found in the marketplace and produced or used by a number of companies?

Such questions help determine whether data collected for the inventory should be specific to one company or manufacturing facility, or whether the data should be more general to represent common industrial practices.

The appropriate response to these questions often rests on whether the life cycle is being performed for internal organizational use or for a more public purpose. Accessibility to product- or facility-specific data may also be a factor. A company may be more interested in examining its own formulation and assembly operations, whereas an industry group or government agency may be more interested in characterizing industry-wide practice. LCAs can have a mix of product-specific and industry-average information. For example, a cereal manufacturer performing an analysis of using recycled paperboard for its cereal boxes might apply the following logic. For operations conducted by the manufacturer, such as box printing, set up, and filling, data specific to the product would be obtained because average data for printing and filling across the cereal industry or for industry in general would not be as useful.

Stepping back one stage to package manufacturing, the cereal manufacturer is again faced with the specificity decision. The data could be product-specific, or generic data for the manufacturing stage could be used. The product-specific approach has these advantages: the aggregated data reflect the operations of the specific paper mills supplying the recycled board, and the energy and resources associated with this stage can be compared with those of similar specificity for the filling, packaging, and distribution stage. A limitation of this option is the additional cost and time associated with collecting product-specific data from the mills and the level of cooperation that needs to be established with the upstream vendors. Long-term confidentiality agreements with vendors may also represent unacceptable burdens compared with the value added by the more specific data.

### Determine the Data Requirements

The required level of data accuracy for the project depends on the use of the final results and the intended audience (i.e. will the results be used to support decision-making in an internal process or in a public forum?). For example, if the intent is to use the results in a public forum to support product/process selection to a local community or regulator, then estimated data or best engineering judgment for the primary material, energy, and waste streams may not be sufficiently accurate to justify the final conclusions. In contrast, if the intent of performing the LCA is for internal decision-making purposes only, then estimates and best engineering judgment may be applied more frequently. This may reduce the overall cost and time required to perform the LCA, as well as enable completion of the study in the absence of precise, first-hand data.
In addition to the intended audience, the required level of data accuracy could be based on the criticality of the decision to be made and the amount of money involved in the decision.

The alternative decision path, using industrial average data for making recycled paperboard, has a parallel mix of advantages and limitations. Use of average, or generic, data may be advantageous for a manufacturer considering use of recycled board for which no current vendors have been identified. If the quality of these average data can be determined and is acceptable, their use may be preferable. The limitation is that data from this stage may be less comparable to that of more product-specific stages. This limitation is especially important in studies that mix product-specific and more general analyses in the same life-cycle stage. For example, comparing virgin and recycled paperboard using product-specific data for one material and generic data for the other could be problematic.

Another limitation is that the generic data may mask technologies that are more environmentally burdensome. Even with some measure of data variability, a decision to use a particular material made on the basis of generic data may misrepresent true loadings of the actual suppliers. Opportunities to identify specific facilities operating in a more environmentally sound manner are lost. Generic data do not necessarily represent industry-wide practices. The extent of representation depends on the quality and coverage of the available data and is impossible to state as a general rule.

It is recommended that the level of specificity be very clearly defined and communicated so that readers are more able to understand the differences in the final results. Before initiating data collection and periodically throughout the study, the analyst should revisit the specificity decision to determine if the approach selected for each stage remains valid in view of the intended use.

### Foreground and Background Data

An important element in LCA practice is the distinction that has been made between foreground and background data. The foreground system refers to the system of primary concern. The background system delivers energy and materials to the foreground system as aggregated data sets in which individual plants and operations are not identified. The selection of foreground or background data decides if either marginal or average data are to be used.

### Determine How the Data Should Be Organized and the Results Displayed

LCA practitioners define how data should be organized in terms of a *functional unit* that appropriately describes the function of the product or process being studied. Careful selection of the functional unit to measure and display the LCA results will improve the accuracy of the study and the usefulness of the results.

When an LCA is used to compare two or more products, the basis of comparison should be equivalent use, i.e., each system should be defined so that an equal amount of product or equivalent service is delivered to the consumer. In the handwashing example, if bar soap were compared to liquid soap, the logical basis for comparison would be an equal number of handwashings. Another example of equivalent use would be in comparing cloth diapers to disposable diapers. One type of diaper may typically be changed more frequently than the other, and market/use studies show that often cloth diapers are doubled, whereas disposables are not. Thus, throughout a day, more cloth diapers will be used. In this case, a logical basis for comparison between the systems would be the total number of diapers used over a set period of time.

Equivalent use for comparative studies can often be based on volume or weight, particularly when the study compares packaging for delivery of a specific product. A beverage container study might consider 1,000 liters of beverage as an equivalent use basis for comparison, because the product may be delivered to the consumer in a variety of different-size containers having different life-cycle characteristics.

#### An Example of Selecting a Functional Unit

An LCA study comparing two types of wall insulation to determine environmental preferability must be evaluated on the same function, the ability to decrease heat flow. Six square feet of four-inch thick insulation Type A is not necessarily the same as six square feet of four-inch thick insulation Type B. Insulation type A may have an R factor equal to ten, whereas insulation type B may have an R factor equal to 20. Therefore, type A and B do not provide the same amount of insulation and cannot be compared on an equal basis. If Type A decreases heat flow by 80 percent, you must determine how thick Type B must be to also decrease heat flow by 80 percent.

### Define the Scope of the Study

As Chapter 1 explained, an LCA includes all four stages of a product or process life cycle: raw material acquisition, manufacturing, use/reuse/maintenance, and recycle/waste management. These product stages are explained in more detail below. To determine whether one or all of the stages should be included in the scope of the LCA, the following must be assessed: the goal of the study, the required accuracy of the results, and the available time and resources. Exhibit 2-1 provides an example of life cycle stages that could be included in a project related to treatment technologies.

#### Raw Materials Acquisition

The life cycle of a product begins with the removal of raw materials and energy sources from the earth. For instance, the harvesting of trees or the mining of nonrenewable materials would be considered raw materials acquisition. Transportation of these materials from the point of acquisition to the point of processing is also included in this stage.

### Manufacturing

During the manufacturing stage, raw materials are transformed into a product or package. The product or package is then delivered to the consumer. The manufacturing stage consists of three steps: materials manufacture, product fabrication, and filling/packaging/distribution.

> *Materials Manufacture* - The materials manufacture step involves the activities that convert raw materials into a form that can be used to fabricate a finished product.
>
> *Product Fabrication* - The product fabrication step takes the manufactured material and processes it into a product that is ready to be filled or packaged.
>
> *Filling/Packaging/Distribution* - This step finalizes the products and prepares them for shipment. It includes all of the manufacturing and transportation activities that are necessary to fill, package, and distribute a finished product. Products are transported either to retail outlets or directly to the consumer. This stage accounts for the environmental effects caused by the mode of transportation, such as trucking and shipping.

### Use/Reuse/Maintenance

This stage involves the consumer’s actual use, reuse, and maintenance of the product. Once the product is distributed to the consumer, all activities associated with the useful life of the product are included in this stage. This includes energy demands and environmental wastes from both product storage and consumption. The product or material may need to be reconditioned, repaired or serviced so that it will maintain its performance. When the consumer no longer needs the product, the product will be recycled or disposed.

### Recycle/Waste Management

The recycle/waste management stage includes the energy requirements and environmental wastes associated with disposition of the product or material.

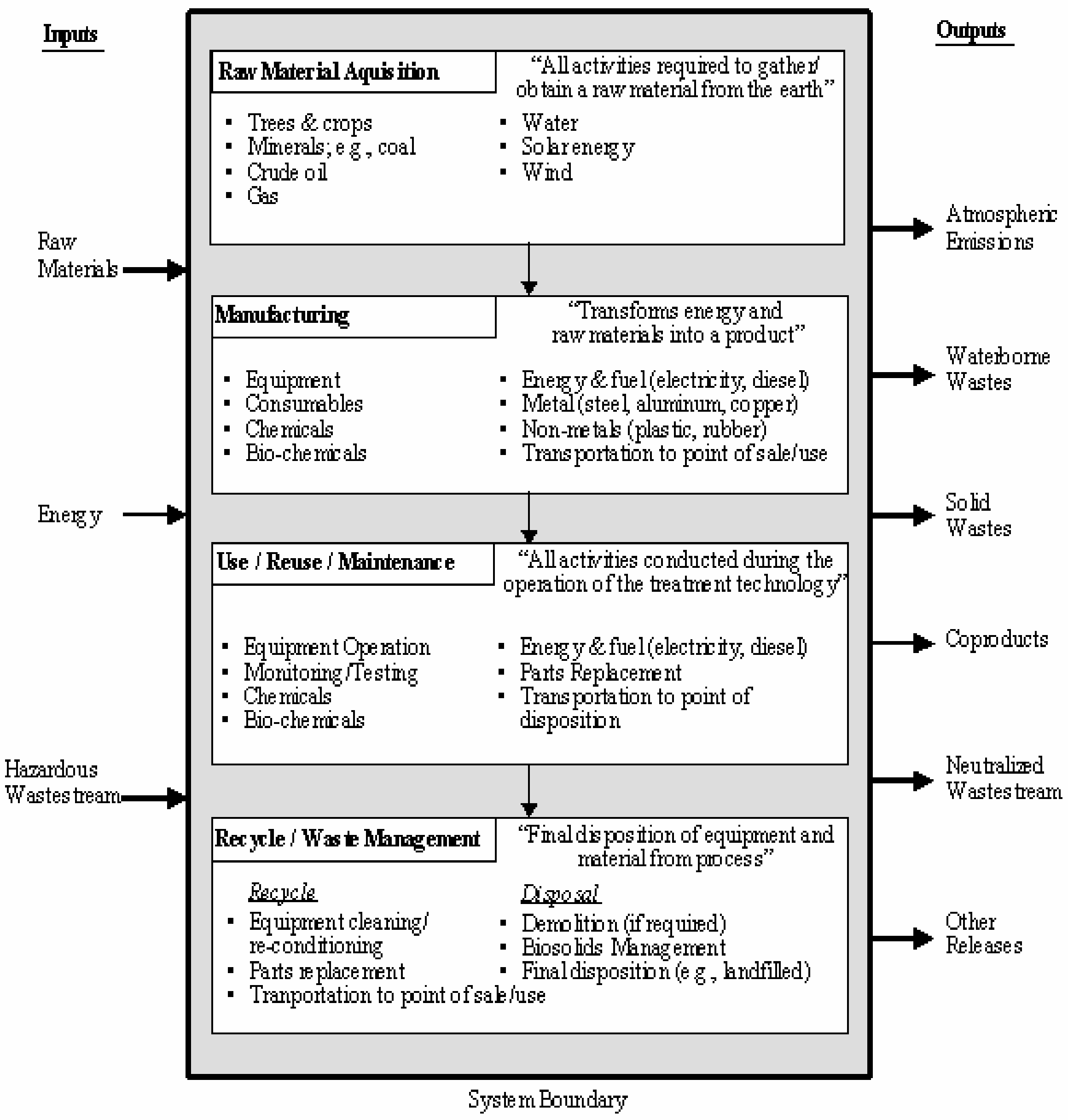


**Exhibit 2-1. Sample Life Cycle Stages for a Treatment Project**

Each step in the life cycle of a product, package, or material can be categorized within one and only one of these life-cycle stages. Each step or process can be viewed as a subsystem of the total product system. Viewing the steps as subsystems facilitates data gathering for the inventory of the system as a whole. The boundaries of subsystems are defined by life-cycle stage categories in Chapter 3. The rest of this chapter deals with defining boundaries of the whole product system. Many decisions must be made in defining the specific boundaries of each system.

Product systems are easier to define if the sequence of operations associated with a product or material is broken down into primary and secondary categories. The primary, or zero-order, sequence of activities directly contributes to making, using, or disposing of the product or material. The secondary category includes auxiliary materials or processes that contribute to making or doing something that in turn is in the primary activity sequence. Several tiers of auxiliary materials or processes may extend further and further from the main sequence. In setting system boundaries, the analyst must decide where the analysis will be limited and be very clear about the reasons for the decision. The following questions are useful in setting and describing specific system boundaries:

- *Does the analysis need to cover the entire life cycle of the product?* A theoretically complete life-cycle system would start with all raw materials and energy sources in the earth and end with all materials back in the earth or at least somewhere in the environment but not part of the system. Any system boundary different from this represents a decision by the analyst to limit it in some way. Understanding the possible consequences of such decisions is important for evaluating tradeoffs between the ability of the resulting inventory to thoroughly address environmental attributes of the product constraints on cost, time, or other factors that may argue in favor of a more limited boundary. Too limited a boundary may exclude consequential activities or elements.

  Depending on the goal of the study, it is possible to exclude certain stages or activities and still address the issues for which the life-cycle assessment is being performed. For example, it may be possible to exclude the acquisition of raw materials without affecting the results. Suppose a company wishes to perform an LCA to evaluate alternative drying systems for formulating a snack food product. If the technologies are indifferent to the feedstock, it is possible to assume the raw materials acquisition stage will be identical for all options. If the decision will be based on selecting a drying system with lower energy use or environmental burdens, it may be acceptable to analyze such a limited system. However, with this system boundary, the degree of absolute differences in the overall system energy or environmental impact cannot be determined. The difference in the product manufacturing stage may represent a minor component of the total system. Therefore, statements about the total system cannot be made.

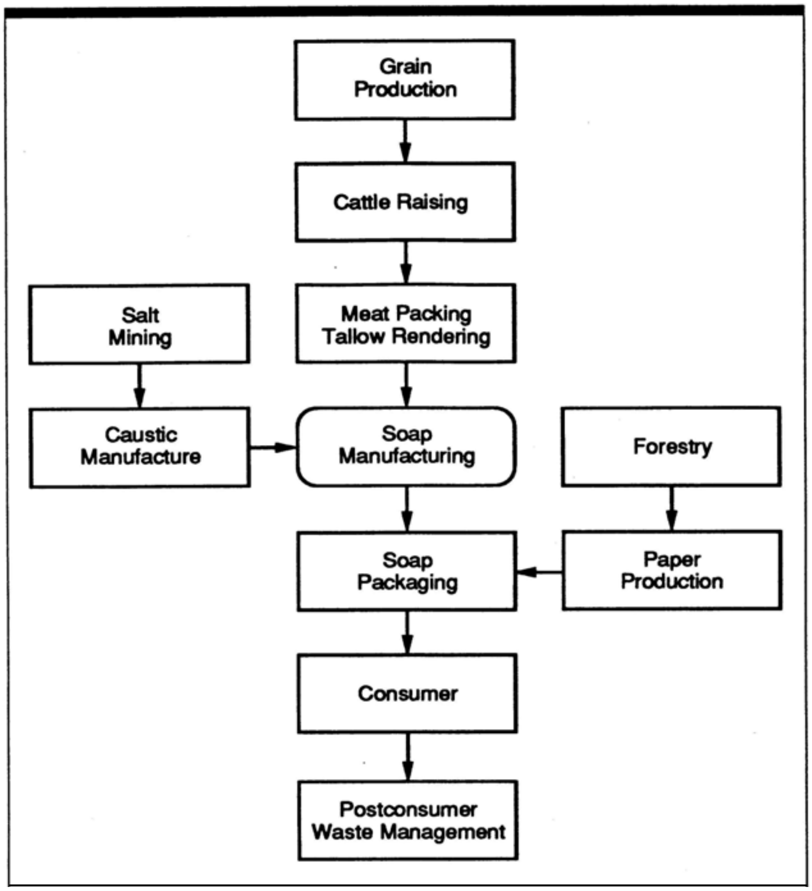
- *What will be the basis of use for the product or material?* Is the study intended to compare different product systems? If the products or processes are used at different rates, packaged in varying quantities, or come in different sizes, how can one accurately compare them? Can equivalent use ratios be developed? Should market shares be considered to estimate proportionate burden form each product in a given category? Is the study intended to compare service systems? Are the service functions clearly defined so that the input and outputs are properly proportioned?

- *What ancillary materials or chemicals are used to make or package the products or run the processes?* Might these ancillary materials or chemicals contribute more than a minor fraction of the energy or emissions of the system to be analyzed? How do they compare by weight with other materials and chemicals in the product systems?

- *In a comparative analysis, are any extra products required to allow one product to deliver equivalent or similar performance to another?* Are any extra materials or services required for one service to be functionally equivalent to another or to a comparable product?

Exhibit 2-2 shows an example of setting system boundaries for a product baseline analysis for a hypothetical bar soap system. Tallow is the major raw material for soap production, and its primary raw material source is the grain fed to cattle. Production of paper for packaging soap is also included. The fate of both the soap and its packaging end the life cycle of this system. Minor inputs could include, for example, the energy required to fabricate the tires on the combine used to plant and harvest the grain.

**Exhibit 2-2. Example Flow Diagram of a Hypothetical Bar Soap System**



In an LCA to create a baseline for future product development or improvement, the unit upon which the analysis is performed can be almost anything that produces internally consistent data. In the bar soap example, one possible usage unit could be a single bar. However, if the product packaging were being analyzed at the same time, it would be important for consistency to consider packaging in different amounts such as single bars, three-packs, and so on.

If the LCA were intended to analyze whether bar soap should be manufactured using an animal-derived or vegetable-derived raw material source, the system boundaries and units of analysis would be more complicated. First, the system flow diagram would have to be expanded to include the growing, harvesting, and processing steps for the alternative feedstock. Then the performance of the finished product would have to be considered. Do the options result in a bar that gets used up at different rates when one material or the other is chosen? If this were the case, a strict comparison of equal-weight bars would not be appropriate.

Suppose an analyst wants to compare bar soap made from tallow with a liquid hand soap made from synthetic ingredients. Because the two products have different raw material sources (cattle and petroleum), the analysis should begin with the raw materials acquisition step. Because the two products are packaged differently and may have different chemical formulas, the materials manufacture and packaging steps would need to be included. Consumer use and waste management options also should be examined because the different formulae could result in varying usage patterns. Thus for this comparative analysis, the analyst would have to inventory the entire life cycle of the two products.

Again, the analyst must determine the basis of comparison between the systems. Because one soap is a solid and the other is a liquid, each with different densities and cleansing abilities per unit amount, it would not make sense to compare them based on equal weights or volumes. The key factor is how much of each is used in one handwashing to provide an equivalent level of function or service. An acceptable basis for comparison might be equal numbers of handwashings. Because these two products may be used at different rates, it would be important to find data that give an equivalent use ratio. For example, a research lab study may show that five cubic millimeters of bar soap and ten cubic millimeters of liquid soap are used per handwashing. If the basis for comparison were chosen at 1,000 handwashings, 5,000 cubic millimeters of bar soap would be compared to 10,000 cubic millimeters of liquid soap. Thus, the equivalent use ratio is 1 to 2.

Because the two soap product types are packaged in different quantities and materials, the analyst would need to include packaging in the system. Contributions of extra ingredients, such as perfumes, might also be considered. The analyst may or may not find that any extra raw materials are used in one or the other. Soaps typically must meet a minimum standard performance level.

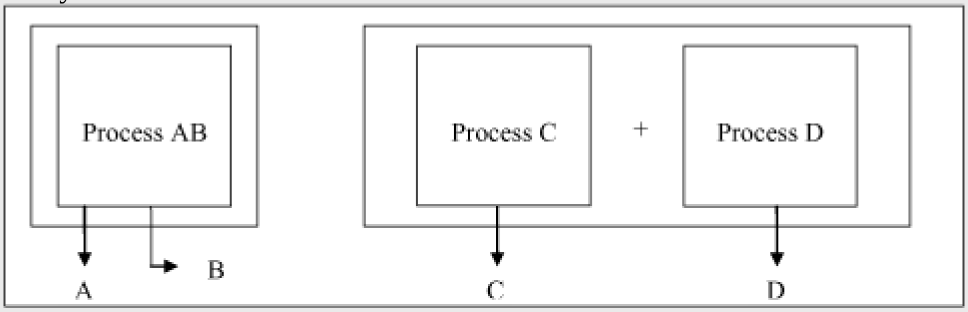
However, if the liquid hand soap also had a skin moisturizer in its formula, the analyst would need to include a moisturizing lotion product in the boundary of the bar soap system on two conditions. The first condition would apply if the environmental issues associated with this component were germane to the purpose of the LCA. The second condition, which is not as clear-cut, is if there is actual value received by the consumer from inclusion of the moisturizer. If market studies indicate that consumers purchase the product in preference to an identical product without a moisturizer, or if they subsequently use a moisturizing lotion after using a non-moisturizing soap, then equivalent use would entail including the separate moisturizing lotion. Including the moisturizing lotion would move the comparison beyond equivalent handwashing to equivalent hand washing and skin moisturizing.

In defining system boundaries, it is important to include every step that could affect the overall interpretation or ability of the analysis to address the issues for which it is being performed. Only in certain well-defined instances can life-cycle elements such as raw materials acquisition or waste management be excluded. In general, only when a step is exactly the same in process, materials, and quantity in all alternatives considered, can that step be excluded from the system. In addition, the framework for the comparison must be recognized as relative because the total system values exclude certain contributions. This rule is especially critical for LCAs used in public forums rather than for internal company decision making. For example, a company comparing alternative processes for producing one petrochemical product may not need to consider the use and disposal of the product if the final composition is identical. The company may also find that each process uses exactly the same materials in the same amounts per unit of product output. Therefore, the company may consider the materials it uses as having no impact in the study results. Another example is a filling operation for bottles. A company interested in using alternative materials for its bottles while maintaining the same size and shape may not need to include filling bottles. However, if the original bottles were compared to boxes of a different size and shape, the filling step would need to be included.

### Applications of System Expansion

System expansion broadens the system boundaries and introduces a new functional unit to make the two systems being compared equal in scope. Take for example Product A which is produced by Process AB along with co-product B. Product A is to be compared to Product C which is the only product to be produced by Process C. Using system expansion, an alternative way to produce Product B is added to Process C. The comparison is now between Process AB and Process C plus Process D.

Another approach to applying system expansion is by subtracting the environmental burdens of an alternative way of producing Product B (using the same example as before) so that only Product A is compared to Product C. This approach is also referred to as the ***avoided burden*** approach since it is reasoned that the production of any alternative products is no longer needed and the resultant environmental burdens are avoided. The environmental burdens allocated to the product of interest are then calculated as the burdens from the process minus the burdens of an alternative co-product. For example, a process that also generates heat, such as a refrigerator, offsets some of the need for space heating which would be supplied by some other source. The emissions avoided through this reduced demand might include emissions such as carbon dioxide, sulfur dioxide, nitrogen oxide, carbon monoxide and hydrocarbons that are typically emitted from power generation facilities. This process can result in negative accounting of burdens if the subtracted releases do not occur in the main product system.



Resource constraints for the life-cycle inventory may be considerations in defining the system boundaries, but in no case should the scientific basis of the study be compromised. The level of detail required to perform a thorough inventory depends on the size of the system and the purpose of the study. In a large system encompassing several industries, certain details may not be significant contributors given the defined intent of the study. These details may be omitted without affecting the accuracy or application of the results. However, if the study has a very specific focus, such as a manufacturer comparing alternative processes or materials for inks used in packaging, it would be important to include chemicals used in very small amounts.

Additional areas to consider in setting boundaries include the manufacture of capital equipment, energy and emissions associated with personnel requirements, and precombustion impacts for fuel usage. These are discussed later.

After the boundaries of each system have been determined, a system flow diagram, as shown in Exhibit 2-2, can be developed to depict the system and direct efforts to gather data for the life cycle inventory.

Each system step should be represented individually in the diagram, including the production steps for ancillary inputs or outputs such as chemicals and packaging.

### Determine the Ground Rules for Performing the Work

Prior to moving on to the inventory analysis phase it is important to define some of the logistical procedures for the project.

1. *Documenting Assumptions* - All assumptions or decisions made throughout the entire project must be reported along side the final results of the LCA project. If assumptions are omitted, the final results may be taken out of context or easily misinterpreted. As the LCA process advances from phase to phase, additional assumptions and limitations to the scope may be necessary to accomplish the project with the available resources.

2. *Quality Assurance Procedures* - Quality assurance procedures are important to ensure that the goal and purpose for performing the LCA will be met at the conclusion of the project. The level of quality assurance procedures employed for the project depends on the available time and resources and how the results will be used. If the results are to be used in a public forum, a formal review process is recommended. A formal review process may consist of internal and external review by LCA experts and/or a review by interested parties to better ensure their support of the final results. If the results are to be used for internal decision-making purposes only, then an internal reviewer who is familiar with LCA practices and is not associated with the LCA study may effectively meet the quality assurance goals. It is recommended that a formal statement from the reviewer(s) documenting their assessment of each phase of the LCA process be included with the final report for the project.

3. *Reporting Requirements* - Defining “up front” how the final results should be documented and exactly what should be included in the final report helps to ensure that the final product meets the appropriate expectations. When reporting the final results, or results of a particular LCA phase, it is important to thoroughly describe the methodology used in the analysis. The report should explicitly define the systems analyzed and the boundaries that were set. The basis for comparison among systems and all assumptions made in performing the work should be clearly explained. The presentation of results should be consistent with the purpose of the study. The results should not be oversimplified solely for the purposes of presentation.

# Chapter 3
# Life Cycle Inventory

## What is a Life Cycle Inventory (LCI)?

A life cycle inventory is a process of quantifying energy and raw material requirements, atmospheric emissions, waterborne emissions, solid wastes, and other releases for the entire life cycle of a product, process, or activity.

## Why Conduct an LCI?

In the life cycle inventory phase of an LCA, all relevant data is collected and organized. Without an LCI, no basis exists to evaluate comparative environmental impacts or potential improvements. The level of accuracy and detail of the data collected is reflected throughout the remainder of the LCA process.

Life cycle inventory analyses can be used in various ways. They can assist an organization in comparing products or processes and considering environmental factors in material selection. In addition, inventory analyses can be used in policy-making, by helping the government develop regulations regarding resource use and environmental emissions.

## What Do the Results of the LCI Mean?

An inventory analysis produces a list containing the quantities of pollutants released to the environment and the amount of energy and material consumed. The results can be segregated by life cycle stage, media (air, water, and land), specific processes, or any combination thereof.

## Key Steps of a Life Cycle Inventory

EPA’s 1993 document, “Life-Cycle Assessment: Inventory Guidelines and Principles,” and 1995 document, “Guidelines for Assessing the Quality of Life Cycle Inventory Analysis,” provide the framework for performing an inventory analysis and assessing the quality of the data used and the results. The two documents define the following four steps of a life cycle inventory:

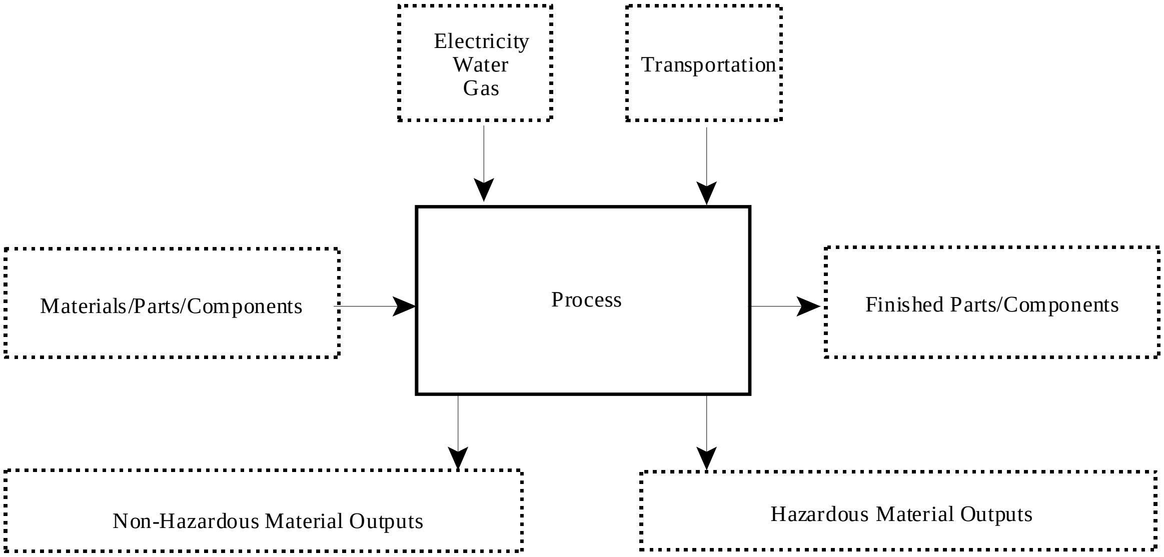
1. Develop a flow diagram of the processes being evaluated.
2. Develop a data collection plan.
3. Collect data.
4. Evaluate and report results.

Each step is summarized below.

### Step 1: Develop a Flow Diagram

A flow diagram is a tool to map the inputs and outputs to a process or system. The “system” or “system boundary” varies for every LCA project. The goal definition and scoping phase establishes initial boundaries that define what is to be included in a particular LCA; these are used as the system boundary for the flow diagram. Unit processes inside of the system boundary link together to form a complete life cycle picture of the required inputs and outputs (material and energy) to the system. Exhibit 3-1 illustrates the components of a generic unit process within a flow diagram for a given system boundary.

**Exhibit 3-1. Generic Unit Process**



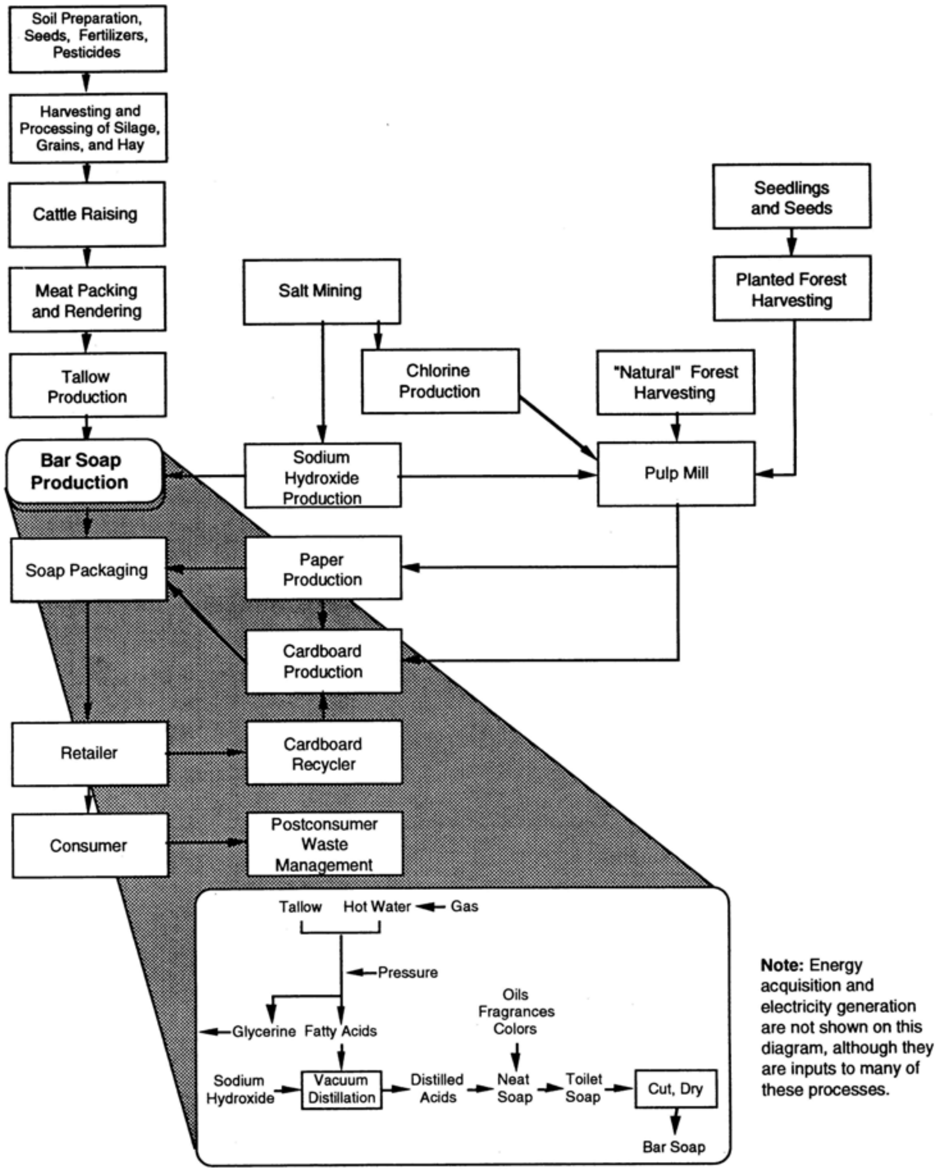
The more complex the flow diagram, the greater the accuracy and utility of the results. Unfortunately, increased complexity also means more time and resources must be devoted to this step, as well as the data collecting and analyzing steps.

Flow diagrams are used to model all alternatives under consideration (e.g., both a baseline system and alternative systems). For a comparative study, it is important that both the baseline and alternatives use the same system boundary and are modeled to the same level of detail. If not, the accuracy of the results may be skewed.

For data-gathering purposes it is appropriate to view the system as a series of subsystems. A “subsystem” is defined as an individual step or process that is part of the defined production system. Some steps in the system may need to be grouped into a subsystem due to lack of specific data for the individual steps. For example, several steps may be required in the production of bar soap from tallow (see Exhibit 3-2). However, these steps may all occur within the same facility, which may not be able to or need to break data down for each individual step. The facility could however, provide data for all the steps together, so the subsystem boundary would be drawn around the group of soap production steps and not around each individual one.

Each subsystem requires inputs of materials and energy; requires transportation of product produced; and has outputs of products, co-products, atmospheric emissions, waterborne wastes, solid wastes, and possibly other releases. For each subsystem, the inventory analyst should describe materials and energy sources used and the types of environmental releases. The actual activities that occur should also be described. Data should be gathered for the amounts and kinds of material inputs and the types and quantities of energy inputs. The environmental releases to air, water, and land should be quantified by type of pollutant. Data collected for an inventory should always be associated with a quality measure. Although formal data quality indicators (DQIs) such as accuracy, precision, representativeness, and completeness are strongly preferred, a description of how the data were generated can be useful in judging quality.

**Exhibit 3-2. Detailed System Flow Diagram for Bar Soap**



**Note:** Energy acquisition and electricity generation are not shown on this diagram, although they are inputs to many of these processes.

Co-products from the process should be identified and quantified. Co-products are process outputs that have value, i.e., those not treated as wastes. The value assigned to a co-product may be a market value (price) or may be imputed. In performing co-product allocation, some means must be found to objectively assign the resource use, energy consumption, and emissions among the co-products, because there is not a physical or chemical way to separate the activities that produce them. Generally, allocation should allow technically sound inventories to be prepared for products or materials using any particular output of a process independently and without overlap of the other outputs.

In the meat packing step of the bar soap example, several co-products could be identified: meat, tallow, bone meal, blood meal, and hides. Other examples of co-products are the trim scraps and off-spec materials from a molded plastic plate fabricator. If the trim scraps and off-spec materials are used or marketed to other manufacturers, they are considered as co-products. Industrial scrap is the common name given to such materials. If the trim is discarded into the solid waste stream to be landfilled, it should be included in the solid waste from the process. If the trim or off-spec materials are reused within the process, they are considered “home scrap,” which is part of an internal recycling loop. These materials are not included in the inventory, because they do not cross the boundaries of the subsystem.

All transportation from one process location to another is included in the subsystem. Transportation is quantified in terms of distance and weight shipped, and identified by the mode of transport used.

### Step 2: Develop an LCI Data Collection Plan

As part of the goal definition and scoping phase (discussed in Chapter 2), the required accuracy of data was determined. When selecting sources for data to complete the life cycle inventory, an LCI data collection plan ensures that the quality and accuracy of data meet the expectations of the decision-makers.

Key elements of a data collection plan include the following:

- Defining data quality goals
- Identifying data sources and types
- Identifying data quality indicators
- Developing a data collection worksheet and checklist.

Each element is described below.

*Define Data Quality Goals* - Data quality goals provide a framework for balancing available time and resources against the quality of the data required to make a decision regarding overall environmental or human health impact (EPA 1986). Data quality goals are closely linked to overall study goals and serve two primary purposes:

- Aid LCA practitioners in structuring an approach to data collection based on the data quality needed for the analysis.
- Serve as data quality performance criteria.

No pre-defined list of data quality goals exists for all LCA projects. The number and nature of data quality goals necessary depends on the level of accuracy required to inform the decision-makers involved in the process.

**Examples of Data Quality Goals**

The following is a sample list of hypothetical data quality goals:

- Site-specific data are required for raw materials and energy inputs, water consumption, air emissions, water effluents, and solid waste generation.
- Approximate data values are adequate for the energy data category.
- Air emission data should be representative of similar sites in the U.S.
- A minimum of 95 percent of the material and energy inputs should be accounted for in the LCI.

*Identify Data Quality Indicators* - Data quality indicators are benchmarks to which the collected data can be measured to determine if data quality requirements have been met. Similar to data quality goals, there is no pre-defined list of data quality indicators for all LCIs. The selection of data quality indicators depends upon which ones are most appropriate and applicable to the specific data sources being evaluated. Examples of data quality indicators are precision, completeness, representativeness, consistency, and reproducibility.

*Identify Data Sources and Types* - For each life cycle stage, unit process, or type of environmental release, specify the necessary data source and/or type required to provide sufficient accuracy and quality to meet the study's goals. Defining the required data sources and types prior to data collection helps to reduce costs and the time required to collect the data.

Examples of data sources include the following:

- Meter readings from equipment
- Equipment operating logs/journals
- Industry data reports, databases, or consultants
- Laboratory test results
- Government documents, reports, databases, and clearinghouses
- Other publicly available databases or clearinghouses
- Journals, papers, books, and patents
- Reference books
- Trade associations
- Related/previous life cycle inventory studies
- Equipment and process specifications
- Best engineering judgment.

Examples of data types include:

- Measured
- Modeled
- Sampled
- Non-site specific (i.e., surrogate data)
- Non-LCI data (i.e., data not intended for the purpose of use in an LCI)
- Vendor data.

The required level of aggregated data should also be specified, for example, whether data are representative of one process or several processes.

A number of sources should be used in collecting data. Whenever possible, it is best to get well-characterized industry data for production processes. Manufacturing processes often become more efficient or change over time, so it is important to seek current data. Inventory data can be facility-specific or more general and still remain current.

Several categories of data are often used in inventories. Starting with the most disaggregated, these are:

- Individual process- and facility-specific: data from a particular operation within a given facility that are not combined in any way.
- Composite: data from the same operation or activity combined across locations.

- Aggregated: data combining more than one process operation.
- Industry-average: data derived from a representative sample of locations and believed to statistically describe the typical operation across technologies.
- Generic: data whose representativeness may be unknown but which are qualitatively descriptive of a process or technology.

Complete and thorough inventories often require use of data considered proprietary by either the manufacturer of the product, upstream suppliers or vendors, or the LCA practitioner performing the study. Confidentiality issues are not relevant for life-cycle inventories conducted by companies using their own facility data for internal purposes. However, the use of proprietary data is a critical issue in inventories conducted for external use and whenever facility-specific data are obtained from external suppliers for internal studies. As a consequence, current studies often contain insufficient source and documentation data to permit technically sound external review. Lack of technically sound data adversely affects the credibility of both the life-cycle inventories and the method for performing them. An individual company's trade secrets and competitive technologies must be protected. When collecting data (and later when reporting the results), the protection of confidential business information should be weighed against the need for a full and detailed analysis or disclosure of information. Some form of selective confidentiality agreements for entities performing life-cycle inventories, as well as formalization of peer review procedures, is often necessary for inventories that will be used in a public forum. Thus, industry data may need to undergo intermediate confidential review prior to becoming an aggregated data source for a document that is to be publicly released.

The purpose, scope, and boundary of the inventory help the analyst determine the level or type of information that is required. For example, even when the analyst can obtain actual industry data, in what form and to what degree should the analyst show the data (e.g., the range of values observed, industry average, plant-specific data, and best available control techniques)? These questions or decisions can usually be answered if the purpose or scope has been well defined. Typically, most publicly available life-cycle documents present industry averages, while many internal industrial studies use plant-specific data. Recommended practice for external life-cycle inventory studies includes the provision of a measure of data variability in addition to averages. Frequently, the measure of variability will be a statistical parameter, such as a standard deviation.

Examples of private industry data sources include independent or internal reports, periodic measurements, accounting or engineering reports or data sets, specific measurements, and machine specifications. One particular issue of interest in considering industrial sources, whether or not a formal public data set is established, is the influence of industry and related technical associations to enhance the accuracy, representativeness, and currentness of the collected data. Such associations may be willing, without providing specific data, to confirm that certain data (about which their members are knowledgeable) are realistic.

Government documents and data bases provide data on broad categories of processes and are publicly available. Most government documents are published on a periodic basis, e.g., annually, biennially, or every four years. However, the data published within them tend to be at least several years old. Furthermore, the data found in these documents may be less specific and less accurate than industry data for specific facilities or groups of facilities. However, depending on the purpose of the study and the specific data objectives, these limitations may not be critical. All studies should note the age of the data used. Some useful government documents include:

- U.S. Department of Commerce, Census of Manufacturers
- U.S. Bureau of Mines, Census of Mineral Industries

- U.S. Department of Energy, Monthly Energy Review
- U.S. Environmental Protection Agency, Toxics Release Inventory (TRI) Database.

Government data bases include both non-bibliographic types where the data items themselves are contained in the data base and bibliographic types that consist of references where data may be found.

Technical books, reports, conference papers, and articles published in technical journals can also provide information and data on processes in the system. Most of these are publicly available. Data presented in these sources are often older, and they can be either too specific or not specific enough. Many of these documents give theoretical data rather than real data for processes. Such data may not be representative of actual processes or may deal with new technologies not commercially tested. In using the technical data sources in the following list, the analyst should consider the date, specificity, and relevancy of the data:

- *Encyclopedia of Chemical Technology*, Kirk-Othmer
- Periodical technical journals such as *Journal of the Water Environment Federation*
- Proceedings from technical conferences
- Textbooks on various applied sciences.

Surveys designed to capture information on a representative sample of end users can provide current information on the parameters of product or service use. Surveys typically center around a question:

- How long or how many times is a product or service used before it is discarded (e.g., the number of years a television set has been in use and is expected to be in use)?
- What other materials and what quantities of these materials are used in conjunction with product use or maintenance (e.g., moisturizing lotion used after hand washing)?
- How frequent is the need for product repair or maintenance (e.g., how often is an appliance repaired over its lifetime, and who does the repair)?
- What other uses does the product have beyond its original purpose?
- What does the end user do with the product when he or she is through with it?

Frequently, the end user will not be able to supply specific information on inputs and outputs. However, the end user can provide data on user practices from which inputs and outputs can be derived. Generally, the end user can be the source of related information from which the energy, materials, and pollutant release inventory can be derived. (An exception would be an institutional or commercial end user who may have some information on energy consumption or water effluents.) Market research firms can often provide qualitative and quantitative usage and customer preference data without the analyst having to perform independent market surveys.

Recycling provides an example of some of the strengths and limitations encountered in gathering data. For some products, economic-driven recycling has been practiced for many years, and an infrastructure and markets for these materials already exist. Data are typically available for these products, including recycling rates, the consumers of the reclaimed materials, and the resource requirements and environmental releases form the recycling activities (collection and reprocessing). Data for materials currently at low recycling rates with newly forming recycling infrastructures are more difficult to obtain. In either case, often the best source for data on resource requirements and environmental releases is the processors themselves. For data on recycling rates and recycled material, consumers and processors may be helpful, but trade associations as well as the consumers of the recycled materials can also provide data. For materials that are recycled at low rates, data will be more difficult to find.

Two other areas for data gathering relate to the system as a whole and to comparisons between and among systems. It is necessary to obtain data on the weights of each component in the product evaluated, either by obtaining product specifications from the manufacturer or by weighing each component. These data are then used to combine the individual components in the overall system analysis. Equivalent use ratios for the products compared can be developed by surveying retailers and consumers, or by reviewing consumer or trade association periodicals.

*Develop a Data Collection Spreadsheet* – The next step is to develop a life cycle inventory spreadsheet that covers most of the decision areas in the performance of an inventory (see Appendix A which shows a sample inventory spreadsheet). A spreadsheet can be prepared to guide data collection and validation and to enable construction of a database to store collected data electronically. The following eight general decision areas should be addressed in the inventory spreadsheet:

- Purpose of the inventory
- System boundaries
- Geographic scope
- Types of data used
- Data collection procedures
- Data quality measures
- Computational spreadsheet construction
- Presentation of results.

The spreadsheet is a valuable tool for ensuring completeness, accuracy, and consistency. It is especially important for large projects when several people collect data from multiple sources. The spreadsheet should be tailored to meet the needs of a specific LCI.

The overall system flow diagram, derived in the previous step, is important in constructing the computational spreadsheets because it numerically defines the relationships of the individual subsystems to each other in the production of the final product. These numerical relationships become the source of "proportionality factors," which are quantitative relationships that reflect the relative contributions of the subsystems to the total system. For example, data for the production of a particular ingredient X of bar soap are developed for the production of 1,000 tons of X. To produce 1,000 tons of bar soap, 250 tons of X are needed, accounting for losses and inefficiencies. Thus, to find the contributions of X to the total system, the data for 1,000 tons of X are multiplied by 0.250.

The spreadsheet can be used to make other computations beyond weighting the contributions of various subsystems. It can be used to translate energy fuel value to a standard energy unit, such as million British thermal unit (Btu) or gigajoule (GJ). Precombustion or resource acquisition energy can be computed by applying a standard factor to a unit quantity of fuel to account for energy used to obtain and transport the fuel. Energy sources, as well as types of wastes, can be categorized. Credits or charges for incineration can be derived. Fuel-related wastes should also be calculated based on the fuels used throughout the system. The spreadsheet should also incorporate waste management options, such as recycling, composting, and landfilling.

It is important that each subsystem be incorporated in the spreadsheet with its related components and that each be linked together in such as way that inadvertent omissions and double-counting do not occur. The spreadsheet can be organized in several different ways to accomplish this purpose. These can include allocating certain fields or areas in the spreadsheet to certain types of calculations or using one type of spreadsheet software to actually link separate spreadsheets in hierarchical fashion. It is imperative, however, once a system of organization is used, that it be employed consistently. Haphazard organization of data sets and calculations generally leads to faulty inventory results.

Many decisions must be made in every life-cycle inventory analysis. Every inventory consists of a mix of factual data and assumptions. Assumptions allow the analyst to evaluate a system condition when factual data either cannot be obtained within the context of the study or do not exist. Each piece of information (e.g., the weight of paperboard used to package the soap, type of vehicle and distance for shipping the tallow, losses incurred when rendering tallow, or emissions resulting from the animals at the feedlot), fall into one or the other category and each plays a role in developing the overall system analysis. Because assumptions can substantially affect study results, a series of “what if” calculations or sensitivity analyses are often performed on the results to examine the effect of making changes in the system. A sensitivity analysis will temporarily modify one or more parameters and affect the calculation of the results. Observing the change in the results will help determine how important the assumptions are with respect to the results. The computational spreadsheet is also used to perform these sensitivity analysis calculations.

### Decision Points within Life Cycle Inventory

During the 2003 InLCA/LCM conference in Seattle, Washington, a session was organized with the specific intent of initiating open discussion on inventory methodology and determining if there was support behind the idea of developing international procedural guidelines for inventory, going beyond the ISO 14040 and 14041 guidance. The general consensus of the group in Seattle was that there is a need and desire for more detailed guidance, especially around the following list of suggested key decision points within life cycle inventory:

- Co-product allocation
- Recycling allocation
- Exclusion of small amounts
- Exclusion of spills and losses
- Age-appropriateness of data
- Surrogate and estimated data
- Inventory for impact assessment
- Matching the goal to the method
- Collecting primary data
- Report format
- Iterative procedure for data collection
- Choosing boundaries
- Capital equipment/infrastructure exclusions
- Time and location meta data.

Sometimes it is helpful to think ahead about how the results will be presented. This can direct some decisions on how the spreadsheet output is specified. The analyst must remember the defined purpose for performing the analysis and tailor the data output to those expressed needs. For example, the analyst might ask: Is the purpose of the life-cycle inventory to evaluate the overall system results? Or is it expected that detailed subsystem information will be analyzed in relation to the total? Will the study be used in a public forum? If so, how? How much detail is required? Answers to questions such as these will help determine the complexity and the degree of generalization to build into the spreadsheet, as well as the appropriate presentation of results.

### Step 3: Collect Data

Data collection efforts involve a combination of research, site-visits and direct contact with experts, which generates large quantities of data. As an alternative, it may be more cost effective to buy a commercially available LCA software package (see Appendix B). Prior to purchasing an LCA software package the decision-makers or LCA practitioner should insure that it will provide the level of data analysis required.

A second method to reduce data collection time and resources is to obtain non-site specific inventory data. Several organizations have developed databases specifically for LCA that contain some of the basic data commonly needed in constructing a life cycle inventory. Some of the databases are sold in conjunction with LCI data collection software; others are stand-alone resources (see Appendix B). Many companies with proprietary software also offer consulting services for LCA design. The use of commercial software risks losing transparency in the data. Often there is no record of assumptions or computational methods that were used. This may not be appropriate if the results are to be used in the public domain. Revisiting the goal statement is needed in order to determine if such data are appropriate.

All industrial processes have multiple input streams and many generate multiple output streams. Usually only one of the outputs is of interest for the life cycle assessment study being conducted, so the analyst needs to determine how much of the energy and material requirements and the environmental releases associated with the process should be attributed, or allocated, to the production of each co-product. For example, steam turbine systems may sell both electricity and low-pressure steam as useful products. When co-products are present, the practitioner must determine how much of the burdens associated with operating and supplying the multi-output process should be allocated to each co-product. The practitioner must also decide how to allocate environmental burdens across co-products when one is a waste stream that can be sold for other uses.

The guidance provided by the International Standards Organization (ISO) recognizes the variety of approaches that can be used to treat the allocation issue and, therefore, requires a step-wise approach (see text box on ISO 14041). The standard calls for practitioners to avoid allocation if possible; and secondly, to model approaches which reflect the physical relationships between the process outputs and its inputs. Proper application of the ISO guidelines on allocation requires a good understanding of the physical relationships between co-products in a process.

Although avoiding allocation is favored by the ISO standard, it is not always possible to expand systems in all cases. And, as alluded to earlier, allocation cannot be totally avoided even in a system expansion approach. Therefore, other options must be used.

Although mass has most often been used as a basis for allocation, allocation by volume is done in a similar way. Methods based on market value usually include expected economic gain based on gross sales. However, none of these methods offers a general solution. Allocation may seem impractical in cases where one product far outweighs another. Although market value in most cases reflects the use of energy and therefore many of the associated burdens, allocation on this basis covers only one aspect of the system. Also, market value is highly variable over time, sometimes up to 50 percent in a short time period. Allocation on an equal basis (50/50) or on an “all or none” basis (100 percent to one product) can be considered to be a highly arbitrary choice.

Environmental burdens related to the alternative systems must still be modeled using an appropriate method where co-products are generated. A lot has been published in the open literature on the subject in an effort to better understand the consequences of allocation choices.

**ISO 14041: 6.5.3 Allocation Procedure**

On the basis of the principles mentioned above, the following stepwise procedure shall be applied.

Step 1: Wherever possible, allocation should be avoided by:

1) Dividing the unit process to be allocated into two or more subprocesses and collecting the input and output data related to these subprocesses.
2) Expanding the product system to include the additional functions related to the co-products, taking into account the requirements of (function, functional unit, and reference flow).

Step 2: Where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions in a way which reflects the underlying physical relationships between them, i.e., they shall reflect the way in which the inputs and outputs are changed by quantitative changes in the products or functions delivered by the system. The resulting allocation will not necessarily be in proportion to any simple measurement such as mass or molar flows of coproducts.

Step 3: Where physical relationship alone cannot be established or used as the basis for allocation, the inputs should be allocated between the products and functions in a way which reflects other relationships between them. For example, input and output data might be allocated between coproducts in proportion to the economic value of the products.

The flow diagram(s) developed in Step 1 provides the road map for data to be collected. Step 2 specifies the required data sources, types, quality, accuracy, and collection methods. Step 3 consists of finding and filling in the flow diagram and worksheets with numerical data. This may not be a simple task. Some data may be difficult or impossible to obtain, and the available data may be difficult to convert to the functional unit needed. Therefore, the system boundaries or data quality goals of the study may have to be refined based on data availability. This iterative process is common for most LCAs.

*Inputs in the Product Life-Cycle Inventory Analysis*
The decision on which raw/intermediate material requirements to include in a life-cycle inventory is complex, but several options are available:

- Incorporate all requirements, no matter how minor, on the assumption that it is not possible *a priori* to decide to exclude anything.
- Within the defined scope of the study, exclude inputs of less than a predetermined and clearly stated threshold.
- Within the defined scope of the study, exclude inputs determined likely to be negligible, relative to the intended use of the information, on the basis of a sensitivity analysis.
- Within the defined scope, consistently exclude certain classes or types of inputs, such as capital equipment replacement.

The advantage of the first option is that no assumptions are made in defining and drawing the system boundary. The analyst does not have to explain or defend what has been included or excluded. The disadvantage is that application of this approach could be an endless exercise. The number of inputs could be very large and could include some systems only distantly related to the product system of interest. Besides the computational complexity, interpretation of the results with respect to the single desired product, package, or activity could be difficult.

The second option, if implemented with full explanation of what the threshold is and why it was selected, would have the advantages of consistency and lower cost and time investments. Two suboptions can be identified, depending on the nature of the threshold. One suboption is to specify a percentage contribution below which the material will be excluded, for example, one percent of the input to a given subsystem or to the entire system. The one percent rule historically has been useful in limiting the extent of the analysis in inventories where the environmental consequences of quantitatively minor materials are not considered. The disadvantage of the one percent rule is that the possible presence of an environmentally damaging activity associated with these materials could be overlooked. Also, when used with mixed percentages (e.g., percent of system energy, percent of subsystem input), the result may be confusing or inconsistent. The scoping analysis should provide a rationale for choosing to apply such a rule.

The second suboption is to set a threshold based on the number of steps that the raw/intermediate material is removed from the main process sequence. Consider the bar soap example discussed earlier. Caustic manufacture from brine electrolysis is part of the main process sequence and would clearly be included. Sodium carbonate is an input material for the production of caustic is therefore a secondary input. Applying a "one-step back" decision rule would include the steps associated with sodium carbonate production. Ammonium chloride is an input material for the production of sodium carbonate using the Solvay process. Relative to caustic, ammonium chloride is a tertiary input and would be excluded if a "one-step back" decision rule were applied. As in the first option, the "one-step back" decision rule has the advantages of clarity and consistent application. For some inputs that are analyzable in exact mathematical terms, the "one-step back" rule may be justifiable. If the inputs to a given process bear a fixed relationship to the next-tier process, one step is all that may be necessary to obtain a sufficiently accurate value (Boustead and Hancock 1979).

Consider the example of a refinery. Most of the refinery's output is sold for production of petroleum-based materials. However, a small portion, say eight percent, is used to run the refinery. This portion, termed the parasitic fraction, is mathematically related to the refinery output as:

$$M(1+f)$$

where:
M is the output product and
f is the parasitic fraction (0.08)

For a life-cycle inventory on a petroleum-based plastic, the primary output of the refinery clearly would be included within the system boundary. Suppose the data quality indicators showed that the data were accurate to ± 5 percent. Because of the first-tier use of the material represents an eight percent difference, a "one-step back" rule would include the refinery material (fuel) output used to run the refinery. However, to produce the material (fuel) to run the refinery requires a further fraction of the output two steps back for the plastic raw material. This is calculated as:

$$M(1+f+f^2).$$

Thus, the incremental contribution of the second step back is 0.6 percent, which is less than the data accuracy. That is, there is no significant difference in the system data after the first step. Disadvantages of this approach include the lack of simple geometric relationships for many inputs and the increased effort to analyze more tiers as data quality increases.

The third option, drawing boundaries based on sensitivity analysis, adds the advantage of being systematic rather than arbitrary in assigning the threshold. The disadvantages of a sensitivity analysis-based approach are that the analyst needs to be very clear in describing how the analysis was used and, unless a large existing database is available to supply preliminary values that can be used in the sensitivity analysis, the required analysis effort may not be limited by a very large amount. A more in-depth discussion of sensitivity analysis is provided later in this chapter.

The final option, excluding certain classes or types of input, also has been found through experience to apply to many systems. For example, in the bar soap inventory, a decision may be made to exclude the equipment used to cut the bars of soap. The justification is that the allocation of inputs and outputs from the manufacture of the machine is minuscule when the millions of bars of soap produced by the machine are considered. The advantage of this option is that many complex subsystems can often be excluded. The disadvantages are the same as those for the first option, namely, that a highly significant activity may be eliminated. Capital equipment is the most commonly excluded input type. The analyst should perform a preliminary analysis to characterize the basic activities in each class or type of input to ensure that a significant contribution is not left out.

### Energy

Energy represents a combination of energy requirements for the subsystem. Three categories of energy are quantifiable: process, transportation, and energy of material resources (inherent energy).

Process energy is the energy required to operate and run the subsystem process(es), including such items as reactors, heat exchangers, stirrers, pumps, blowers, and boilers. Transportation energy is the energy required to power various modes of transportation such as trucks, rail carriers, barges, ocean vessels, and pipelines. Conveyors, forklifts, and other equipment that could be considered with transportation or process are labeled according to their role in the subsystem. For example, power supplied to a conveyor used to carry material from one point in the subsystem would be labeled process energy. On the other hand, the power supplied to a conveyor used to transport material from one subsystem to a different subsystem would be considered transportation energy.

Two alternatives exist for incorporating energy inputs in a subsystem module. One is to report the actual energy forms of the inputs, e.g., kilowatt-hours (kWh) of electricity or cubic feet of natural gas. The other is to include the specific quantities of fuels used to generate the produced energy forms in the module.

The advantage of the first approach is that the specific energy mix is available for each subsystem. For example, a company may want to evaluate the desirability of installing a natural gas-fired boiler to produce steam compared to using its electrically heated boiler powered by a combination of purchased and on-site generated electricity. A specific fuel mix could be applied to compute the energy and fuel resource use. The second approach, incorporating specific fuel quantities, allows a subsystem comparison of primary energy fuels. For example, “x” kilowatt-hours of electricity would be specified as “y” cubic feet of natural gas and “z” pounds of uranium.

Within each subsystem, the energy input data should be given as specific quantities of fuel and then converted into energy equivalents according to the conversion factors discussed in the following two sections. For example, the energy requirements attributed to a polyethylene resin plant may be specified as 500 pounds of ethylene for feedstock, 500 cubic feet of natural gas, 50 kilowatt-hours of electricity to run the process equipment, and 50 gallons of diesel fuel to transport the resin to consumers. In this case, the 50 kilowatt-hours would be converted to 180 megajoules.

### Combustion and Precombustion Values

To report all energy usage associated with the subsystem of concern, the analyst may need to consider energy data beyond the primary process associated with combustion of the fuel. The energy used in fuel combustion is only part of the total energy associated with the use of fuel. The amount of energy expended to acquire the fuel also may be significant in comparison to other energy expenditures. Energy to acquire fuel raw materials (e.g., mining coal or drilling for oil), process these raw materials into usable fuels, and transport them is termed by various practitioners as "precombustion energy" or "energy of fuel acquisition." Precombustion energy is defined as the total amount of energy necessary to deliver a usable fuel to the consumer of the fuel.

Including precombustion energy is analogous to extending the system boundaries for fuels to raw material inputs. For example, suppose the combustion of fuel oil in an industrial boiler results in the release of about 150,000 Btu per gallon. However, crude oil drilling and production, refining, and transporting the fuel oil require an additional 20,000 Btu per gallon. This additional energy is the precombustion energy. Thus, the total energy expended (precombustion energy plus combustion energy) when a gallon of fuel oil is consumed would be 170,000 Btu. Generally, a complete inventory will include precombustion energy contributions because they represent the true energy demand of the system. Inclusion or exclusion of this contribution should be clearly stated.

### Energy Sources

Energy is obtained from a variety of sources, including coal, nuclear power, hydropower, natural gas, petroleum, wind, solar energy, solid waste, and wood biomass. Fuels are interchangeable, to a high degree, based on their energy content. For example, an electric utility decides which fuel or other energy source to use based on the cost per energy unit. Utilities can and do use multiple forms of energy sources, making possible an economic decision based on the energy cost per kilowatt-hour of electricity generated. Manufacturing companies also choose among energy sources on the same basis. However, reasons other than cost, such as scarcity or emissions to the environment, also affect the energy source decision. For example, during periods of petroleum shortages, finding products that use predominantly non-petroleum energy sources may be desirable. For that reason, the inventory should characterize energy requirements according to basic sources of energy. Thus, it would consider not only electricity, but also the basic sources (such as coal, nuclear power, hydropower, natural gas, and petroleum) that produce the electricity.

*Electricity:* Considerations associated with electricity include the source of fuel used to generate the electricity and the efficiency of the generating system. Power utilities typically use coal, nuclear power, hydropower, natural gas, or oil to generate electricity. Non-utility generation sources can include wind power, waste-to-energy, and geothermal energy. Accurately determining electrical energy use and associated emissions raises several complications, such as relating the actual electricity use of a single user to the actual fuel used.

Although a given company pays its bills to a particular utility, the company is not simply purchasing power from the nearest plant. Once electricity is generated and fed into power lines, it is indistinguishable from electricity from any other source. Individual generating stations owned by a given utility may use different fuels. The electricity generated by these stations is "mixed" in the transmission lines of that utility. The utility is interconnected with neighboring utilities (also using various types of fuel), to form regional grids, which then interconnect to form a national grid.

Computational models currently used to perform life-cycle inventories of electricity in the United States are based on the fuel mix in regional grids or on a national average. In many cases where an industry is scattered throughout the United States, the fuel mix for the national grid (available from the U.S.

Department of Energy) can be used, making calculations easier without sacrificing accuracy. Data for 2004 are shown in Table 3-1.

**Table 3-1. U.S. National Electrical Grid Fuel Mix for 2004**

| Fuel | Gigawatt-hours (GWh) | Percent |
|---|---:|---:|
| Coal | 1,976,333 | 50 |
| Nuclear | 788,556 | 19.9 |
| Hydro | 261,545 | 6.6 |
| Natural Gas | 714,600 | 18.1 |
| Oil | 117,591 | 3 |
| Biomass | 60,042 | 1.5 |
| Other* | 34,741 | 0.9 |
| Total | 3,953,408 | 100 |

Source: Edison Electric Institute, http://www.eei.org/industry_issues/industry_overview_and_statistics/industry_statistics/index.htm#fuelmix

* Includes geothermal, solar and wind power.

One exception to the national grid assumption is the electroprocess industries which use vast amounts of electricity. Aluminum smelting is the primary example. It and the other electroprocessing industries are not distributed nationally, so a national electricity grid does not give a reasonable approximation of their electricity use. They are usually located in regions of inexpensive electric power. Some plants have purchased their own electric utilities. In recognition of this fact, specific regional grids or data from on-site facilities are commonly used for life-cycle inventories of the electroprocessing industries.

The energy efficiency of the electricity-generating and delivery system must also be considered. The theoretical conversion from the common energy unit of kilowatt-hour to common fuel units (megajoules) is 3.61 MJ per kWh. Ideally, the analyst would compute a specific efficiency based on the electrical generation fuel mix actually used. This value is derived by comparing the actual fuels consumed by the electricity-generating industry in the appropriate regional or national grid to the actual kilowatt-hours of electricity delivered for useful work. The value includes boiler inefficiencies and transmission line losses. However, a conversion of 11.3 MJ per kWh may be used in most cases to reflect the actual use of fuel to deliver electricity to the consumer from the national grid.

*Nuclear Power:* Nuclear power substitutes for fossil fuels in the generation of electricity. There is no measurement of nuclear power directly equivalent to the joules of fossil fuel, so nuclear power typically is measured as its fossil fuel equivalency. The precombustion energy of nuclear power is usually added to the fuel equivalency value. The precombustion energy includes that for mining and processing, as well as the increased energy requirement for power plant shielding.

*Hydropower:* Most researchers traditionally have counted hydropower at its theoretical energy equivalence of 3.61 MJ per kWh, with no precombustion impacts included. No precombustion factors are used for hydropower because water does not have an inherent energy value from which line transmission losses, etc., can be subtracted. The contribution of the capital equipment is small in light of the amount of hydroelectric energy generated using the equipment. Disruption to ecosystems typically has not been considered in the inventory. However, quantitative inventory measures that may be suitable for characterizing related issues, such as habitat loss due to land use conversion, potentially could be included. Factors addressing area damage, recovery time, and ecosystem function are under consideration for inclusion in the impact analysis.

### Water

Water volume requirements should be included in a life-cycle inventory analysis. In some locations, water is plentiful. Along the coasts, seawater is usable for cooling or other manufacturing purposes. However, in other places water is in short supply and must be allocated for specific uses. Some areas have abundant water in some years and limited supplies in other years. Some industrial applications reuse water with little new or makeup water required. In other applications, however, tremendous amounts of new water inputs are required.

How should water be incorporated in an inventory? The goal of the inventory is to measure, per unit of product, the gallons of water required that represent water unavailable for beneficial uses (such as navigation, aquatic habitat, and drinking water). Water withdrawn from a stream, used in a process, treated, and replaced in essentially the same quality and in the same location should not be included in the water-use inventory data. Ideally, water withdrawn from groundwater and subsequently discharged to a surface water body should be included, because the groundwater is not replaced to maintain its beneficial purposes. Data to make this distinction may be difficult to obtain in a generic study where site-specific information is not available.

In practice, the water quantity to be estimated is net consumptive usage. Consumptive usage as a life-cycle inventory input is the fraction of total water withdrawal from surface or groundwater sources that either is incorporated into the product, co-products (if any), or wastes, or is evaporated. As in the general case of renewable versus nonrenewable resources, valuation of the degree to which the water is or is not replenishable is best left to the impact assessment.

### *Outputs of the Product Life-Cycle Inventory Analysis*

A traditional inventory qualifies three categories of environmental releases or emissions: atmospheric emissions, waterborne waste, and solid waste. Products and co-products also are quantified. Each of these areas is discussed in more detail in the following sections. Most inventories consider environmental releases to be actual discharges (after control devices) of pollutants or other materials from a process or operation under evaluation. Inventory practice historically has included only regulated emissions for each process because of data availability limitations. It is recommended that analysts collect and report all available data in the detailed tabulation of subsystem outputs. In a study not intended for product comparisons, all of these pollutants should be included in the summary presentations.

A comparative study offers two options. The first is to include in the summary presentation only data available for alternatives under consideration. The advantage of this option is that it gives a comparable presentation of the loadings from all the alternatives. The disadvantage is that potentially consequential information, which is available only for some of the alternatives, may not be used. The second option is to report all data whether uniformly available or not. In using this option, the analyst should caution the user not to draw any conclusions about relative effects for pollutants where comparable data are not available. “Comparable” is used here to mean the same pollutant. For example, in a summary of data on a bleached paper versus plastic packaging alternatives, data on dioxin emissions may be available only for the paper product. The second option is recommended for internal studies and for external studies where proper context can be provided.

### Atmospheric Emissions

Atmospheric emissions are reported in units of weight and include all substance classified as pollutants per unit weight of product output. These emissions generally have included only those substances required by regulatory agencies to be monitored but should be expanded where feasible. The amounts reported represent actual discharges into the atmosphere after passing through existing emission control devices. Some emissions, such as fugitive emissions from valves or storage areas, may not pass through control devices before release to the environment. Atmospheric emissions from the production and combustion of fuel for process or transportation energy (fuel-related emissions), as well as the process emissions, are included in the life-cycle inventory.

Typical atmospheric emissions are particulates, nitrogen oxides, volatile organic compounds (VOCs), sulfur oxides, carbon monoxide, aldehydes, ammonia, and lead. This list is neither all-inclusive nor is it a standard listing of which emissions should be included in the life-cycle inventory. Recommended practice is to obtain and report emissions data in the most speciated form possible. Some air emissions, such as particulates and VOCs, are composites of multiple materials whose specific makeup can vary from process to process. All emissions for which there are obtainable data should be included in the inventory. Therefore, the specific emissions reported for any system, subsystem, or process will vary depending on the range of regulated and nonregulated chemicals.

Certain materials, such as carbon dioxide and water vapor losses due to evaporation (neither of which is a regulated atmospheric emission for most processes), have not been included in most inventory studies in the past. Regulations for carbon dioxide are changing as the debate surrounding the greenhouse effect and global climate change continues and the models used for its prediction are modified. Inclusion of these emerging emissions of concern is recommended.

### Waterborne Wastes

Waterborne wastes are reported in units of weight and include all substances generally regarded as pollutants per unit of product output. These wastes typically have included only those items required by regulatory agencies, but the list should be expanded as data are available. The effluent values include those amounts still present in the waste stream after wastewater treatment, and represent actual discharges into receiving waters. For some releases, such as spills directly into receiving waters, treatment devices do not play a role in what is reported. For some materials, such as brine water extracted with crude oil and reinjected into the formation, current U.S. regulations do not define such materials as waterborne wastes, although they may be considered in solid waste regulations under the Resource Conservation and Recovery Act (RCRA). Other liquid wastes may also be deep well injected and should be included. In general, the broader definition of emissions in a life-cycle inventory, in contrast to regulations, would favor inclusion of such streams. It can be argued, from a systems analysis standpoint, that materials such as brine should count as releases from the subsystem because they cross the subsystem boundary. If wastes and spills that occur are discharged to the ocean or some other body of water, these values are always reported as wastes.

As with atmospheric wastes, waterborne wastes from the production and combustion of fuels (fuel-related emissions), as well as process emissions, are included in the life-cycle inventory.

Some of the most commonly reported waterborne wastes are biological oxygen demand (BOD), chemical oxygen demand (COD), suspended solids, dissolved solids, oil and grease, sulfides, iron, chromium, tin, metal ions, cyanide, fluorides, phenol, phosphates, and ammonia. Again, this listing of emissions is not meant to be a standard for what should be included in an inventory. Some waterborne wastes, such as BOD and COD, consist of multiple materials whose composition can vary from process to process. Actual waterborne wastes will vary for each system depending on the range of regulated and nonregulated chemicals.

### Solid Waste

Solid waste includes all solid material that is disposed from all sources within the system. U.S. regulations include certain liquids and gases in the definition as well. Solid wastes typically are reported by weight. A distinction is made in data summaries between industrial solid wastes and post-consumer solid wastes, as they are generally disposed of in different ways and, in some cases, at different facilities. *Industrial solid waste* refers to the solid waste generated during the production of a product and its packaging and is typically divided into two categories: process solid waste and fuel-related solid waste. *Post-consumer solid waste* refers to the product/packaging once it has met its intended use and is discarded into the municipal solid waste stream.

*Process solid waste* is the waste generated in the actual process, such as trim or waste materials that are not recycled, as well as sludges and solids from emissions control devices. *Fuel-related waste* is solid waste produced from the production and combustion of fuels for transportation and operating the process. Fuel combustion residues, mineral extraction wastes, and solids from utility air control devices are examples of fuel-related wastes.

In the United States, mine tailings and overburden generally are not regulated as solid waste. However, the regulations require overburden to be replaced in the general area from which it was removed. Furthermore, environmental consequences associated with the removal of mine tailings and overburden should be included. The regulations do not require industrial solid waste to be handled off site. Therefore, researchers try to report all solid waste from industrial processes destined for disposal, whether off site or local. Historically, no distinctions have been made between hazardous and nonhazardous solid waste, nor have individual wastes been specifically characterized. However, in view of the potentially different environmental effects, analysts will find it useful to account for these wastes separately, especially if an impact assessment is to be conducted.

### Products

The products are defined by the subsystem and/or system under evaluation. In other words, each subsystem will have a resulting product, with respect to the entire system. This subsystem product may be considered either a raw material or intermediate material with respect to another system, or the finished product of the system.

Again using the bar soap example, when examining the meat packaging subsystem, meat, tallow, hides, and blood would all be considered product outputs. However, because only tallow is used in the bar soap system, tallow is considered the only product from that subsystem. All other material outputs (not released as wastes or emissions) are considered co-products. If the life-cycle assessment were performed on a product such as a leather purse, hides would be considered the product from the meat packaging subsystem, and all other outputs would be considered co-products.

Although for bar soap the tallow is considered the product from the meat packaging subsystem, it is simultaneously an intermediate material within the bar soap system. Thus, from these examples one can see that classifying a material as a product in a life-cycle study depends, in part, on the extent of the system being examined, i.e., the position from which the material is viewed or the analyst's point of view.

### Transportation

The life-cycle inventory includes the energy requirements and emissions generated by the transportation requirements among subsystems for both distribution and disposal of wastes. Transportation data are reported in miles or kilometers shipped. This distance is then converted into units of ton-miles or tonne-kilometers, which is an expression involving the weight of the shipment and the distance shipped. Materials typically are transported by rail, truck, barge, pipeline, and ocean transport. The efficiency of each mode of transport is used to convert the units of ton-miles into fuel units (e.g., gallons of diesel fuel). The fuel units are then converted to energy units, and calculations are made to determine the emissions generated from the combustion of the fuels.

Exhibit 3-2 shows that transportation is evaluated for the product leaving each subsystem. This method of evaluating transportation avoids any inadvertent double-counting of transportation energy or emissions. Transportation is reported only for the product of interest from a subsystem and not for any co-products of the subsystem, because the destination of the co-products is not an issue. The raw materials for the bar soap production system, for example, include salt from salt mining and trees from natural forest harvesting. Applying the template to these two subsystems shows that the transport of salt from the mining operation and the transport of trees from the logging operation must be included in the data collected for these subsystems.

The salt is transported to chlorine/sodium hydroxide plants, and the trees are transported to pulp mills. Applying the template to these subsystems shows that the transport of chlorine and sodium hydroxide from those plants to pulp mills is part of the chlorine production and sodium hydroxide subsystems. Likewise, the transport of pulp to paper mills is part of the pulp mill subsystem. The transport of raw materials, salt, and trees into the subsystems (chlorine production, sodium hydroxide production, and pulp mills) now being evaluated has already been accounted for in the evaluation of the salt mining and natural forest harvesting subsystems. Applying the template throughout the bar soap system shows the evaluation of transportation ending with the post-consumer waste management subsystem, where wastes may be transported to a final disposal site.

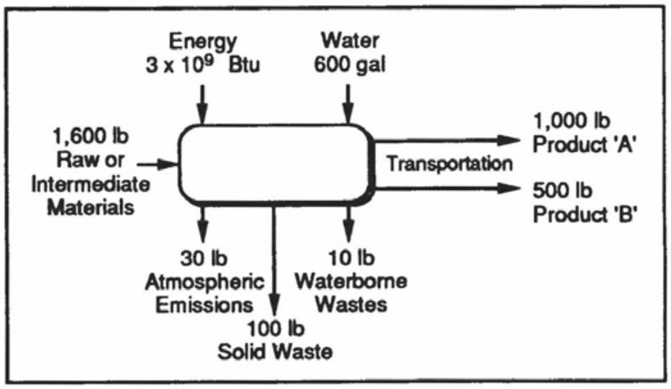
Backhauling may be a situation where there is some overlap between the transportation associated with product distribution and the transportation associated with recycling of the product or a different product after consumer use. A backhaul has been described as occurring when a truck or rail carrier has a profitable load in one direction and is willing to accept a reduced rate for a move in the return direction. Backhaul opportunities occur when the demand for freight transportation in one area is relatively low and carriers have a financial incentive to move their vehicles, loaded or empty, to a place where the demand for freight transportation is higher. Due to the lowered transportation rates, recycled materials, especially paper and aluminum, are often transported by backhauling. Thus, a carrier may take a load of new paper from a mill to customers in a metropolitan area and pick up loads of scrap paper in the same area to bring them back to the mill. In this scenario, backhauling may reduce the energy and emissions associated with distribution of a product (made from new paper) by assigning energy and emissions associated with an empty return trip to the recycled scrap paper.

### Co-Product Allocation

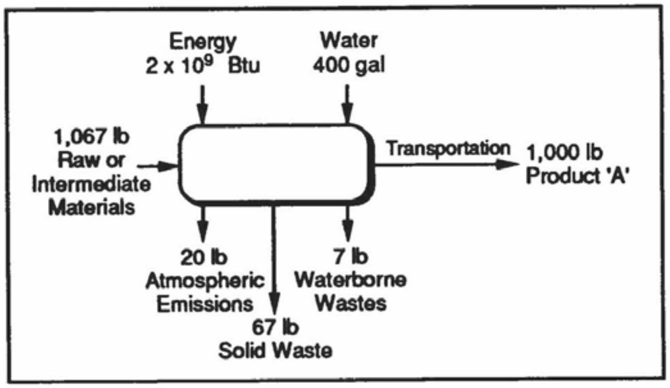
Most industrial processes are physical and/or chemical processes. The fundamentals of life-cycle inventory are based on modeling a system in such a way that calculated values reasonably represent actual (measurable) occurrences. Some processes generate multiple output streams in addition to waste streams. In attributional LCAs, only certain of these output streams are of interest with respect to the primary product being evaluated (see the text box in Chapter 2 on the distinction between attributional and consequential LCAs). The term co-product is used to define all output streams other than the primary product that are not waste streams and that are not used as raw materials elsewhere in the system examined in the inventory. Co-products are of interest only to the point where they no longer affect the primary product, i.e. the product that is part of the life cycle system being studied. Subsequent refining of co-products is beyond the scope of the analysis, as is transport of co-products to facilities for further refining. A basis for co-product allocation needs to be selected with careful attention paid to the specific items calculated. Each industrial system must be handled on a case-by-case basis since no allocation basis exists that is always applicable.

**Exhibit 3-3. Allocating Resources and Environmental Burdens on a Mass Basis for a Product and Co-Product (Source: EPA 1993)**

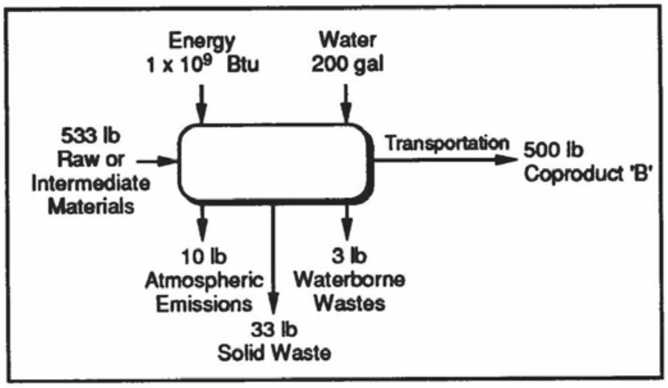
Co-Product Allocation for Product "A" and Product "B"



Co-Product Allocation for Product "A"



Co-Product Allocation for Product "B"



In effect, the boundary for the analysis is drawn between the primary product and co-products, with all materials and environmental loadings attributed to co-products being outside the scope of the analysis. For example, the production of fatty acids from tallow for soap manufacture generates glycerine, a secondary stream that is collected and sold. Glycerine, therefore, is considered a co-product, and its processing and use would be outside the scope of the bar soap analysis.

### Basis for Co-Product Allocation

The first step is to investigate any complex process in detail and attempt to identify unit subprocesses that produce the product of interest. If sufficient detail can be found, no co-product allocation will be necessary. The series of subprocesses that produce the product can simply be summed. Many metal manufacturing plants illustrate this approach. In steel product manufacture, all products are made by melting the raw materials, producing iron, and then producing raw steel. These steps are followed by a series of finishing operations that are unique to each product line. It is generally possible to identify the particular subprocesses in the finishing sequence of each product and to collect sufficient data to carry out the life-cycle inventory without co-product allocation. In many cases, a careful analysis of unit systems will avoid the need to make co-product allocations. Still, in some cases, such as a single chemical reaction vessel that produces several different products, there is no analytical method for cleanly separating the subprocesses. In this example, co-product allocation is necessary.

The analyst needs to determine the specific resource and environmental categories requiring study. For a given product, different co-product allocations may be made for different resource and environmental categories. To find the raw materials needed to produce a product, a simple mass balance will help track the various input materials into the output materials. For instance, if a certain amount of wood is needed to produce several paper products, and the analysis concerns only one of the products, then a mass allocation scheme, as demonstrated in Exhibit 3-3, will be used to determine the amount of wood required for the target product.

If a process produces several different chemical products, care must be taken in the analysis. It will be necessary to write balanced chemical equations and trace the chemical stoichiometry from the raw materials into the products. A simple mass allocation method frequently gives reasonable results, but not always. In calculating energy, heat of reaction may be the appropriate basis for allocating energy to the various co-products.

If the various co-product chemicals are quite different in nature, some other allocation method may be needed. For example, an electrolytic cell can produce hydrogen and oxygen from water. Each water molecule requires two electrons to produce two hydrogen atoms and one oxygen atom. On a macroscopic basis, electricity that produces one mole (or two grams) of hydrogen only produces one-half mole (or 16 grams) of oxygen. Thus, the input electrical energy would be allocated between the hydrogen and oxygen co-products on a molar basis. That is, two-thirds of the energy would be allocated to the hydrogen and one-third to the oxygen, resulting in an energy per unit mass for hydrogen that is 16 times that of oxygen. However, conservation of mass is used to determine the material requirements. Each mole of water (18 grams) contains two grams of hydrogen atoms and 16 grams of oxygen atoms, and the dissociation of the water results in two grams of hydrogen and 16 grams of oxygen. Thus, a mass allocation would be appropriate for raw material calculations in this example.

For environmental emissions from a multiple-product process, allocation to different co-products may not be possible. For example, in a brine cell that produces sodium, chlorine, and hydrogen as co-products, it may be tempting to associate any emissions containing chlorine with the chlorine co-product alone. However, because the sodium and hydrogen are also produced by the same cell and cannot be produced from this cell without also producing chlorine, all emissions should be considered as joint wastes. The question arises as to how to allocate chlorine emissions (as well as other emissions) to all three products.

It has been suggested that the selling price of the co-products could be used as a basis for this allocation. Because the selling prices of the various co-products can vary greatly with time and with independent competitive markets for each co-product, a market-based approach would have to accommodate such variations, by using an average value ranged over several years, or similar method.

Further, it has been suggested that the notion of ‘demand product’ could be used to avoid allocation. The idea is to recognize when a process was created with the intent of producing a single main product of interest, i.e. the one in demand. By-products and wastes that are created as a result of manufacturing this demand product are considered to be incidental, including those that may have found a market over the years. Therefore, all of the environmental burdens are allocated to the demand product.

One final issue is the distinction between marginal wastes and co-products. In some cases it is not clear whether a material is a waste or a co-product. A hypothetical example might be a valuable mineral that occurs as 0.1 percent of an ore. For each pound of mineral product, 999 pounds of unneeded material is produced. This discarded material might find use as a road aggregate. As such, it has value and displaces other commercial aggregates and appears to be a co-product along with the valuable mineral. However, its value is so low that in some cases it may simply be dumped back on the ground because of limited markets. Whether this material is considered a waste or a co-product may have a significant effect on the results of a product life-cycle inventory. It does not seem reasonable to use a simple mass allocation scheme here. It is more reasonable to assume that all of the energy and other resources and emissions associated with this process are incurred because of the desire for the valuable product mineral. However, there are some cases where the “waste” has marginal, but greater value than the example used here.

It becomes difficult in some instances to determine precisely which of the co-product allocation methodologies discussed above is most “correct.” One important role of an inventory is to provide information upon which impact assessment and improvement analysis can be based. In cases where there is no clear methodological solution, the inventory should include reasonable alternative calculations or apply sensitivity analysis to determine the effect of allocation on the final results. It remains at some later time to make the judgments as to which of several reasonable alternatives is the correct one. In any event, it should be made clear what assumptions were made and what procedures were used.

### Industrial Scrap

One co-product stream of particular interest is *industrial scrap*. This term is used to specifically identify process wastes of value (trim scraps and off-spec materials) that are produced as an integral part of a manufacturing process. Further, the wastes have been collected and used as input materials for additional manufacturing processes. The last criterion is that these scrap materials have never been used as originally intended when manufactured. For example, a common polyurethane foam product is seat cushions for automobiles. The trim from cutting the cushions is never incorporated into seat cushions. Likewise, off-spec seat cushions sold as industrial scrap are never used as seat cushions, but are used as input material for another process.

A careful distinction must be made between industrial scrap and post-consumer waste for proper allocation in the inventory. If the industrial scrap is to be collected and used as a material input to a production system or process, it is credited in the life-cycle inventory as a co-product at the point where it was produced. Unfortunately, systems that use material more efficiently, i.e., that produce lesser amounts of salable co-products, assume a higher percentage of the upstream energy and releases using the criterion.

When the consumption of a co-product falls within the boundaries of the analysis, it must no longer be considered as a co-product, but as a primary product carrying with it all the energy requirements and environmental releases involved with producing it, beginning with raw materials acquisition. For example, a study of carpet underlayment made from polyurethane scrap would include the manufacturing steps for producing the polyurethane scrap. Its production must be handled, as is any other subsystem of a life-cycle inventory. Industrial scrap does not displace virgin raw materials, because the consumption of the industrial scrap redefines the system to include the virgin materials for its production (isocyanates and polyalcohols in the case of polyurethane foam). Tallow is another example of a material that would be defined as an industrial scrap/co-product. Historically, the thinking has been that once a material shifts from the waste category to being a utilized material, or a co-product, then it should bear some of the burden (energy, raw/intermediate material input, and environmental releases) for its own production.

### Data Time Period

The time period that data represents should be long enough to smooth out any deviations or variations in the normal operations of a facility. These variations might include plant shutdowns for routine maintenance, startup activities, and fluctuation in levels of production. Often data are available for a fiscal year of production, which is usually a sufficient time period to cover such variations.

### Specific Data versus Composite Data

When the purpose of the inventory is to find ways to improve internal operations, it is best to use data specific to the system that is being examined. These types of data are usually the most accurate and also the most helpful in analyzing potential improvements to the environmental profile of a system. However, private data typically are guarded by a confidentiality agreement, and must be protected from public use by some means. Composite, industry-average data are preferable when the inventory results are to be used for broad application across the industry, particularly in studies performed for public use. Although composite data may be less specific to a particular company, they are generally more representative of an industry as a whole. Such composite data can also be made publicly available, are more widely usable, and are more general in nature. Composite data can be generated from facility-specific data in a systematic fashion and validated using a peer review process. Variability, representativeness, and other data quality indicators can still be specified for composite data.

### Geographic Specificity

Natural resource and environmental consequences occur at specific sites, but there are broader implications. It is important to define the scope of interest (regional vs. national vs. international) in an inventory. A local community may be more interested in direct consequences to itself than in global concerns.

In general, most inventories done domestically relate only to that country. However, if the analysis considers imported oil, the oilfield brines generated in the Middle East should be considered. It has been suggested that the results of life-cycle inventories indicate which energy requirements and environmental releases (of the total environmental profile of a product) are local. However, due to the fact that industries are not evenly distributed, this segmenting can be done only after an acceptable level of accuracy is agreed on. The United States, Canada, Western Europe, and Japan have the most accurate and most readily available information on resource use and environmental releases. Global aspects should be considered when performing a study on a system that includes foreign countries or products, or when the different geographic locations are a key difference among products or processes being compared. As a compromise, when no specific geographical data exist, practices that occur in other countries typically are assumed to be the same as for their domestic counterparts. These assumptions and the inherent limitations associated with their application should be documented within the inventory report. In view of the more stringent environmental regulations in developed countries, this assumption, while necessary, often is not correct. Energy use and other consequences associated with importing materials should also be included.

### Technology Mixes/Energy Types

For inventory studies of processes using various technology mixes, market share distribution of the technologies may be necessary to accurately portray conditions for the industry as a whole. The same is true of energy sources. Most inventories can be based on data involving the fuel mix in the national grid for electricity. There are exceptions, such as the aluminum electroprocessing industry previously discussed. Variations of this kind must be taken into account when applying the life-cycle inventory methodology. Also, as previously mentioned, conditions can differ greatly across international borders.

### Data Categories

Environmental emission databases usually cover only those items or pollutants required by regulatory agencies to be reported. For example, as previously mentioned, the question of whether to report only regulated emissions or all emissions is complicated by the difficulty in obtaining data for unregulated emissions. In some cases, emissions that are suspected health hazards may not be required to be reported by a regulatory agency because the process of adding them to the list is slow. A specific example of an unregulated emission is carbon dioxide, which is a greenhouse gas suspected as a primary agent in global warming. There is no current requirement for reporting carbon dioxide emissions, and it is difficult to obtain measured data on the amounts released from various processes. Thus, results for emissions reported in a life-cycle inventory may not be viewed as comprehensive, but they can cover a wide range of pollutants. As a rule, it is recommended that data be obtained on as broad a range as possible. Calculated or qualitative information, although less desirable and less consistent with the quantitative nature of an inventory, may still be useful.

### Routine/Fugitive/Accidental Releases

Whenever possible, routine, fugitive, and accidental emissions data should be considered in developing data for a subsystem. If data on fugitive and accidental emissions are not available, and quantitative estimates cannot be obtained, this deficiency should be noted in the report on the inventory results. Often estimates can be made for accidental emissions based on historical data pertaining to frequency and concentrations of accidental emissions experienced at a facility.

When deciding whether to include accidents, they should be divided into two categories based on frequency. For the low-frequency and high-magnitude events, e.g., major oil spills, tools other than life-cycle inventory may be appropriate. Unusual circumstances are difficult to associate with a particular product or activity. More frequent, lower magnitude events should be included, with perhaps some justification for keeping their contribution separate from routine operations.

### Special Case Boundary Issues

In all studies, boundary conditions limiting the scope must be established. The areas of capital equipment, personnel issues, and improper waste disposal typically are not included in inventory studies, because they have been shown to have little effect on the results. Earlier studies did consider them in the analysis; later studies have verified their minimal contribution to the total system profile. Thus, exclusion of contributions from capital equipment manufacture, for example, is not excluded *a priori*. The decision to include or not to include them should be clearly noted by the analyst.

*Capital Equipment* - The energy and resources that are required to construct buildings and to build process equipment should be considered. However, for most systems, capital expenditures are allocated to a large number of products manufactured during the lifetime of the equipment. Therefore, the resource use and environmental effluents produced are usually small when attributed to the system of interest. The energy and emissions involved with capital equipment can be excluded when the manufacture of the item itself accounts for a minor fraction of the total product output over the life of the equipment.

*Personnel Issues* - Inventory studies focus on the comprehensive results of product consumption, including manufacturing. At any given site, there are personnel-related effluents from the manufacturing process as well as wastes from lunchroom trash, energy use, air conditioning emissions, water pollution from sanitary facilities, and others. In addition, inputs and outputs during transportation of personnel from their residence to the workplace can be significant, depending on the purpose and scope of the inventory. In many situations, the personnel consequences are very small and would probably occur whether or not the product was manufactured. Therefore, exclusion from the inventory may be justified. The analyst should be explicit about including or excluding this category. For these issues, the goals of the study should be considered. If the study is comparative, and one option is significantly different in personnel or capital equipment requirements, then at least a screening-level evaluation should be performed to support an inclusion or exclusion decision.

*Improper Waste Disposal* - For most studies it is assumed that wastes are properly disposed into the municipal solid waste stream or wastewater treatment system. Illegal dumping, littering, and other improper waste disposal methods typically are not considered in life-cycle inventories as a means of solid waste disposal. Where improper disposal is known to occur and where environmental effects are known or suspected, a case may be made to include these activities.

### Economic Input/Output Approach to Life Cycle Inventory

Economic Input/Output offers an alternative way to create life cycle inventory. The input/output model divides an entire economy into distinct sectors and represents them in table, or matrix, form so that each sector is represented by one row and one column. The matrix represents sales from one sector to another. Most nations have created input/output tables although few are as detailed as the U.S. model which provides 480 sectors. The economic input-output model is linear so that the effects of purchasing $1,000 from one sector will be ten times greater than the effects of purchasing $100 from that sector.

In order to create life cycle inventory, the economic output for each sector is first calculated, then the environmental outputs are calculated by multiplying the economic output at each stage by the environmental impact per dollar of output. The advantage of the economic input/output approach is that it quickly covers an entire economy, including all the material and energy inputs, thereby simplifying the inventory creation process. Its main disadvantage is that the data are created at high aggregate levels for an entire industry, such as steel mills, rather than particular products, such as the type of steel used to make automobiles.

“Hybrid” models which combine the economic input/output model with process models have also been proposed in order to utilize the advantages offered by both approaches.
(Hendrickson *et al* 2006)

### Step 4: Evaluate and Document the LCI Results

When writing a report to present the final results of the life-cycle inventory, it is important to thoroughly describe the methodology used in the analysis. The report should explicitly define the systems analyzed and the boundaries that were set. All assumptions made in performing the inventory should be clearly explained. The basis for comparison among systems should be given, and any equivalent usage ratios that were used should be explained.

Life-cycle inventory studies generate a great deal of information, often of a disparate nature. The analyst needs to select a presentation format and content that are consistent with the purpose of the study and that do not arbitrarily simplify the information solely for the sake of presenting it. In thinking about presentation of the results, it is useful to identify the various perspectives embodied in life-cycle inventory information. These dimensions include, but may not be limited to, the following:

- Overall product system
- Relative contribution of stages to the overall system
- Relative contribution of product components to the overall system
- Data categories within and across stages, e.g., resource use, energy consumption, and environmental releases
- Data parameter groups within a category, e.g., air emissions, waterborne wastes, and solid waste types
- Data parameters within a group, e.g., sulfur oxides, carbon dioxide, chlorine, etc.
- Geographic regionalization if relevant to the study, e.g., national versus global
- Temporal changes.

The life-cycle analyst must select among these dimensions and develop a presentation format that increases comprehension of the findings without oversimplifying them. Two main types of format for presenting results are tabular and graphical.

Sometimes it is useful to report total energy results while also breaking out the contributions to the total from process energy and energy of material resources. Solid wastes can be separated into postconsumer solid waste and industrial solid waste. Individual atmospheric and water pollutants should be reported separately. Atmospheric emissions, waterborne wastes, and industrial solid wastes can also be categorized by process emissions/wastes and fuel-related emissions/wastes. Such itemized presentations can assist in identifying and subsequently controlling certain energy consumption and environmental releases.

The results from the inventory can be presented most comprehensibly in tabular form. The choice of how the tables should be created varies, based on the purpose and scope of the study. If the inventory has been performed to help decide which type of package to use for a particular product, showing the overall system results will be the most useful way to present the data. On the other hand, when an analysis is performed to determine how a package can be changed to reduce its releases to the environment, it is important to present not only the overall results, but also the contributions made by each component of the packaging system. For example, in analyzing a liquid delivery system that uses plastic bottles, it may be necessary to show how the bottle, the cap, the label, the corrugated shipping box, and the stretch wrap around the boxes all contribute to the total results. The user can thus concentrate improvement efforts on the components that make a substantial contribution when evaluating proposed changes.

Graphical presentation of information helps to augment tabular data and can aid in interpretation. Both bar charts (either individual bars or stacked bars) and pie charts are valuable in helping the reader visualize and assimilate the information from the perspective of "gaining ownership or participation in life-cycle assessment" (Werner 1991). However, the analyst should not aggregate or sum dissimilar data when creating or simplifying a graph.

For internal industrial use by product manufacturers, pie charts showing a breakout by raw materials, process, and use/disposal have been found useful in identifying waste reduction opportunities.

For external studies, the data must be presented in a format that meets one fundamental criterion - clarity. Ensuring clarity requires that the analyst ask and answer questions about what each graph is intended to convey. It may be necessary to present a larger number of graphs and incorporate fewer data in each one. Each reader should understand the desired response after viewing the information.

Now that the data has been collected and organized into one format or another, the accuracy of the results must be verified. The accuracy must be sufficient to support the purposes for performing the LCA as defined in the goal and scope (see Chapter 2 for a discussion on goal definition).

Steps 1 and 2 of Chapter 5, Life Cycle Interpretation, describe how to efficiently assess the accuracy of the LCI results. As illustrated in Exhibit 1-2, Phases of an LCA, in Chapter 1, LCA is an iterative process. Determining the sensitivity of the LCI data collection efforts in regard to data accuracy prior to conducting the saves time and resources. Otherwise, the life cycle impact assessment effort may have to be repeated if it is later determined that the accuracy of the data is insufficient to draw conclusions.

When documenting the results of the life cycle inventory, it is important to thoroughly describe the methodology used in the analysis, define the systems analyzed and the boundaries that were set, and all assumptions made in performing the inventory analysis. Use of the worksheet (see Step 2) supports a clear process for documenting this information.

The outcome of the inventory analysis is a list containing the quantities of pollutants released to the environment and the amount of energy and materials consumed. The information can be organized by life cycle stage, media (air, water, and land), specific process, or any combination thereof that is consistent with the ground rules defined in Chapter 2, Goal Definition and Scoping, for reporting requirements.

# Chapter 4
# Life Cycle Impact Assessment

## What is a Life Cycle Impact Assessment (LCIA)?

The Life Cycle Impact Assessment (LCIA) phase of an LCA is the evaluation of potential human health and environmental impacts of the environmental resources and releases identified during the LCI. Impact assessment should address ecological and human health effects; it should also address resource depletion. A life cycle impact assessment attempts to establish a linkage between the product or process and its potential environmental impacts. For example, what are the impacts of 9,000 tons of carbon dioxide or 5,000 tons of methane emissions released into the atmosphere? Which is worse? What are their potential impacts on smog? On global warming?

### LCA versus Risk Assessment

An important distinction exists between life cycle impact assessment (LCIA) and other types of impact analysis. LCIA does not necessarily attempt to quantify any specific actual impacts associated with a product, process, or activity. Instead, it seeks to establish a linkage between a system and potential impacts. The models used within LCIA are often derived and simplified versions of more sophisticated models within each of the various impact categories. These simplified models are suitable for relative comparisons of the potential to cause human or environmental damage, but are not indicators of absolute risk or actual damage to human health or the environment. For example, risk assessments are often very narrowly focused on a single chemical at a very specific location. In the case of a traditional risk assessment, it is possible to conduct very detailed modeling of the predicted impacts of the chemical on the population exposed and even to predict the probability of the population being impacted by the emission. In the case of LCIA, hundreds of chemical emissions (and resource stressors) which are occurring at various locations are evaluated for their potential impacts in multiple impact categories. The sheer number of stressors being evaluated, the variety of locations, and the diversity of impact categories makes it impossible to conduct the assessment at the same level of rigor as a traditional risk assessment. Instead, LCIA models are based on the accepted models within each of the impact categories using assumptions and default values as necessary. The resulting models that are used within LCIA are suitable for relative comparisons, but not sufficient for absolute predictions of risk.

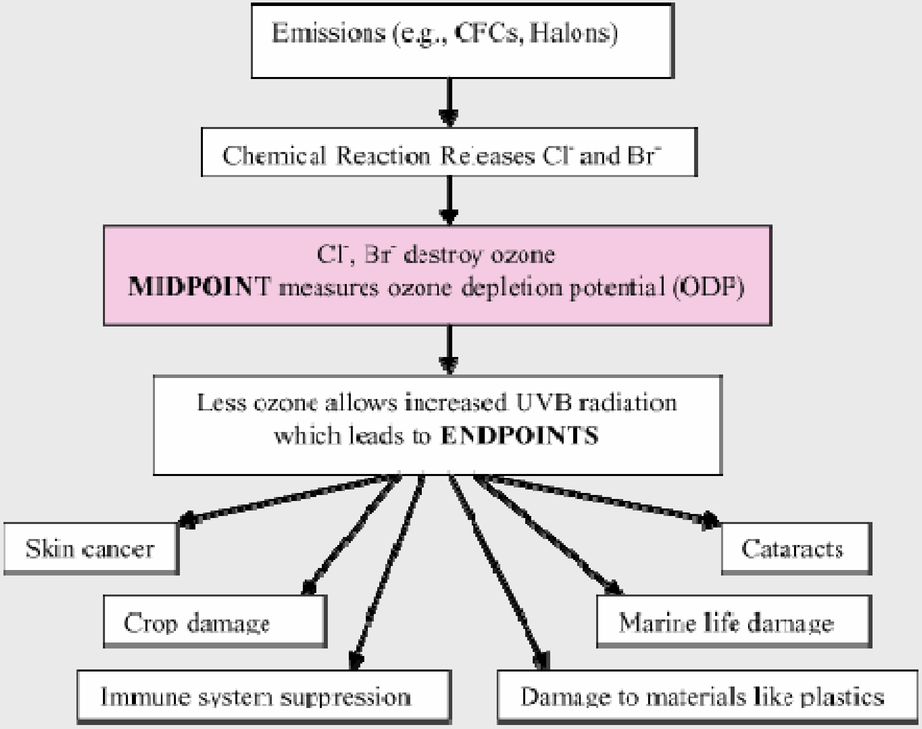
The key concept in this component is that of stressors. A stressor is a set of conditions that may lead to an impact. For example, if a product or process is emitting greenhouse gases, the increase of greenhouse gases in the atmosphere *may* contribute to global warming. Processes that result in the discharge of excess nutrients into bodies of water *may* lead to eutrophication. An LCIA provides a systematic procedure for classifying and characterizing these types of environmental effects.

## Why Conduct an LCIA?

Although much can be learned about a process by considering the life cycle inventory data, an LCIA provides a more meaningful basis to make comparisons. For example, although we know that 9,000 tons of carbon dioxide and 5,000 tons of methane released into the atmosphere are both harmful, an LCIA can determine which could have a greater potential impact. Using science-based characterization factors, an LCIA can calculate the impacts each environmental release has on problems such as smog or global warming.

**Midpoint versus Endpoint Modeling**

Midpoint impact assessment models reflect the relative potency of the stressors at a common midpoint within the cause-effect chain. Analysis at a midpoint minimizes the amount of forecasting and effect modeling incorporated into the LCIA, thereby reducing the complexity of the modeling and often simplifying communication. Midpoint modeling can minimize assumptions and value choices, reflect a higher level of societal consensus, and be more comprehensive than model coverage for endpoint estimation. (Bare *et al* 2003)



### What Do the Results of an LCIA Mean?

The results of an LCIA show the relative differences in potential environmental impacts for each option. For example, an LCIA could determine which product/process causes more global warming potential.

### Key Steps of a Life Cycle Impact Assessment

The following steps comprise a life cycle impact assessment.

1. *Selection and Definition of Impact Categories* - identifying relevant environmental impact categories (e.g., global warming, acidification, terrestrial toxicity).
2. *Classification* - assigning LCI results to the impact categories (e.g., classifying carbon dioxide emissions to global warming).
3. *Characterization* - modeling LCI impacts within impact categories using science-based conversion factors (e.g., modeling the potential impact of carbon dioxide and methane on global warming).
4. *Normalization* - expressing potential impacts in ways that can be compared (e.g. comparing the global warming impact of carbon dioxide and methane for the two options).

5. *Grouping* - sorting or ranking the indicators (e.g. sorting the indicators by location: local, regional, and global).
6. *Weighting* - emphasizing the most important potential impacts.
7. *Evaluating and Reporting LCIA Results* - gaining a better understanding of the reliability of the LCIA results.

ISO developed a standard for conducting an impact assessment entitled ISO 14042, *Life Cycle Impact Assessment* (ISO 1998), which states that the first three steps – impact category selection, classification, and characterization – are mandatory steps for an LCIA. Except for data evaluation (Step 7), the other steps are optional depending on the goal and scope of the study.

### Step 1: Select and Define Impact Categories

The first step in an LCIA is to select the impact categories that will be considered as part of the overall LCA. This step should be completed as part of the initial goal and scope definition phase to guide the LCI data collection process and requires reconsideration following the data collection phase. The items identified in the LCI have potential human health and environmental impacts. For example, an environmental release identified in the LCI may harm human health by causing cancer or sterility, or affect workplace safety. Likewise, a release identified in the LCI could also affect the environment by causing acid rain, global warming, or endangering species of animals.

For an LCIA, impacts are defined as the consequences that could be caused by the input and output streams of a system on human health, plants, and animals, or the future availability of natural resources. Typically, LCIAs focus on the potential impacts to three main categories: human health, ecological health, and resource depletion. Exhibit 4-1 shows some of the more commonly used impact categories.

### Step 2: Classification

The purpose of classification is to organize and possibly combine the LCI results into impact categories. For LCI items that contribute to only one impact category, the procedure is a straightforward assignment. For example, carbon dioxide emissions can be classified into the global warming category.
For LCI items that contribute to two or more different impact categories, a rule must be established for classification. There are two ways of assigning LCI results to multiple impact categories (ISO 1998):

- Partition a representative portion of the LCI results to the impact categories to which they contribute. This is typically allowed in cases when the effects are dependent on each other.
- Assign all LCI results to all impact categories to which they contribute. This is typically allowed when the effects are independent of each other.

For example, since nitrogen dioxide could potentially affect both ground level ozone formation and acidification (at the same time), the entire quantity of nitrogen dioxide would be assigned to both impact categories (e.g., 100 percent to ground level ozone and 100 percent to acidification). This procedure must be clearly documented.

**Exhibit 4-1. Commonly Used Life Cycle Impact Categories**

| Impact Category | Scale | Examples of LCI Data (i.e. classification) | Common Possible Characterization Factor | Description of Characterization Factor |
|---|---|---|---|---|
| Global Warming | Global | Carbon Dioxide ($CO_2$)<br>Nitrogen Dioxide ($NO_2$)<br>Methane ($CH_4$)<br>Chlorofluorocarbons (CFCs)<br>Hydrochlorofluorocarbons (HCFCs)<br>Methyl Bromide ($CH_3Br$) | Global Warming Potential | Converts LCI data to carbon dioxide ($CO_2$) equivalents<br>Note: global warming potentials can be 50, 100, or 500 year potentials. |
| Stratospheric Ozone Depletion | Global | Chlorofluorocarbons (CFCs)<br>Hydrochlorofluorocarbons (HCFCs)<br>Halons<br>Methyl Bromide ($CH_3Br$) | Ozone Depleting Potential | Converts LCI data to trichlorofluoromethane (CFC-11) equivalents. |
| Acidification | Regional<br>Local | Sulfur Oxides (SOx)<br>Nitrogen Oxides (NOx)<br>Hydrochloric Acid (HCL)<br>Hydroflouric Acid (HF)<br>Ammonia ($NH_4$) | Acidification Potential | Converts LCI data to hydrogen (H+) ion equivalents. |
| Eutrophication | Local | Phosphate ($PO_4$)<br>Nitrogen Oxide (NO)<br>Nitrogen Dioxide ($NO_2$)<br>Nitrates<br>Ammonia ($NH_4$) | Eutrophication Potential | Converts LCI data to phosphate ($PO_4$) equivalents. |
| Photochemical Smog | Local | Non-methane hydrocarbon (NMHC) | Photochemical Oxident Creation Potential | Converts LCI data to ethane ($C_2H_6$) equivalents. |
| Terrestrial Toxicity | Local | Toxic chemicals with a reported lethal concentration to rodents | $LC_{50}$ | Converts $LC_{50}$ data to equivalents; uses multi-media modeling, exposure pathways. |
| Aquatic Toxicity | Local | Toxic chemicals with a reported lethal concentration to fish | $LC_{50}$ | Converts $LC_{50}$ data to equivalents; uses multi-media modeling, exposure pathways. |
| Human Health | Global<br>Regional<br>Local | Total releases to air, water, and soil. | $LC_{50}$ | Converts $LC_{50}$ data to equivalents; uses multi-media modeling, exposure pathways. |
| Resource Depletion | Global<br>Regional<br>Local | Quantity of minerals used<br>Quantity of fossil fuels used | Resource Depletion Potential | Converts LCI data to a ratio of quantity of resource used versus quantity of resource left in reserve. |
| Land Use | Global<br>Regional<br>Local | Quantity disposed of in a landfill or other land modifications | Land Availability | Converts mass of solid waste into volume using an estimated density. |
| Water Use | Regional<br>Local | Water used or consumed | Water Shortage Potential | Converts LCI data to a ratio of quantity of water used versus quantity of resource left in reserve. |

Step 3: Characterization

Impact characterization uses science-based conversion factors, called characterization factors, to convert and combine the LCI results into representative indicators of impacts to human and ecological health. Characterization factors also are commonly referred to as equivalency factors. Characterization provides a way to directly compare the LCI results within each impact category. In other words, characterization factors translate different inventory inputs into directly comparable impact indicators. For example, characterization would provide an estimate of the relative terrestrial toxicity between lead, chromium, and zinc.

**Impact Categories and Associated Endpoints**

The following is a list of several impact categories and endpoints that identify the impacts.

**Global Impacts**

*Global Warming* - polar melt, soil moisture loss, longer seasons, forest loss/change, and change in wind and ocean patterns.
*Ozone Depletion* - increased ultraviolet radiation.
*Resource Depletion* -decreased resources for future generations.

**Regional Impacts**

*Photochemical Smog* - "smog," decreased visibility, eye irritation, respiratory tract and lung irritation, and vegetation damage.
*Acidification* - building corrosion, water body acidification, vegetation effects, and soil effects.

**Local Impacts**

*Human Health* - increased morbidity and mortality.
*Terrestrial Toxicity* - decreased production and biodiversity and decreased wildlife for hunting or viewing.
*Aquatic Toxicity* - decreased aquatic plant and insect production and biodiversity and decreased commercial or recreational fishing.
*Eutrophication* – nutrients (phosphorous and nitrogen) enter water bodies, such as lakes, estuaries and slow-moving streams, causing excessive plant growth and oxygen depletion.
*Land Use* - loss of terrestrial habitat for wildlife and decreased landfill space.
*Water Use* - loss of available water from groundwater and surface water sources.

Impact indicators are typically characterized using the following equation:

$$\text{Inventory Data} \times \text{Characterization Factor} = \text{Impact Indicators}$$

For example, all greenhouse gases can be expressed in terms of $CO_2$ equivalents by multiplying the relevant LCI results by a $CO_2$ characterization factor and then combining the resulting impact indicators to provide an overall indicator of global warming potential.

Characterization can put these different quantities of chemicals on an equal scale to determine the amount of impact each one has on global warming. The calculations show that ten pounds of methane have a larger impact on global warming than twenty pounds of chloroform.

**Characterization of Global Warming Impacts**

The following calculations demonstrate how characterization factors can be used to estimate the global warming potential (GWP) of defined quantities of greenhouse gases:

| | |
|---|---|
| Chloroform GWP Factor Value* = 9 | Quantity = 20 pounds |
| Methane GWP Factor Value* = 21 | Quantity = 10 pounds |

Chloroform GWP Impact = 20 pounds x 9 = 180
Methane GWP Impact = 10 pounds x 21 = 210

*Intergovernmental Panel on Climate Change (IPCC) Model

The key to impact characterization is using the appropriate characterization factor. For some impact categories, such as global warming and ozone depletion, there is a consensus on acceptable characterization factors. For other impact categories, such as resource depletion, a consensus is still being developed. Exhibit 4-1 describes possible characterization factors for some of the commonly used life cycle impact categories.

A properly referenced LCIA will document the source of each characterization factor to ensure that they are relevant to the goal and scope of the study. For example, many characterization factors are based on studies conducted in Europe. Therefore, the relevancy of the European characterization factors must be investigated before they can be applied to American data.

**TRACI**

EPA's Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) is an impact assessment tool that will support consistency in environmental decision making. TRACI allows the examination of the potential for impacts associated with the raw material usage and chemical releases resulting from the processes involved in producing a product. It allows the user to examine the potential for impacts for a single life cycle stage, or the whole life cycle, and to compare the results between products or processes. The purpose of TRACI is to allow a determination or a preliminary comparison of two or more options on the basis of the following environmental impact categories: ozone depletion, global warming, acidification, eutrophication, photochemical smog, human health cancer, human health noncancer, human health criteria, ecotoxicity, fossil fuel use, land use, and water use (EPA 2003).

### Step 4: Normalization

Normalization is an LCIA tool used to express impact indicator data in a way that can be compared among impact categories. This procedure normalizes the indicator results by dividing by a selected reference value.

There are numerous methods of selecting a reference value, including:

- The total emissions or resource use for a given area that may be global, regional or local

- The total emissions or resource use for a given area on a per capita basis
- The ratio of one alternative to another (i.e., the baseline)
- The highest value among all options.

The goal and scope of the LCA may influence the choice of an appropriate reference value. Note that normalized data can only be compared within an impact category. For example, the effects of acidification cannot be directly compared with those of aquatic toxicity because the characterization factors were calculated using different scientific methods.

### Step 5: Grouping

Grouping assigns impact categories into one or more sets to better facilitate the interpretation of the results into specific areas of concern. Typically, grouping involves sorting or ranking indicators. The following are two possible ways to group LCIA data (ISO 1998):

- Sort indicators by characteristics such as emissions (e.g., air and water emissions) or location (e.g., local, regional, or global).
- Sort indicators by a ranking system, such as high, low, or medium priority. Ranking is based on value choices.

### Step 6: Weighting

The weighting step (also referred to as valuation) of an LCIA assigns weights or relative values to the different impact categories based on their perceived importance or relevance. Weighting is important because the impact categories should also reflect study goals and stakeholder values. As stated earlier, harmful air emissions could be of relatively higher concern in an air non-attainment zone than the same emission level in an area with better air quality. Because weighting is not a scientific process, it is vital that the weighting methodology is clearly explained and documented.

Although weighting is widely used in LCAs, the weighting stage is the least developed of the impact assessment steps and also is the one most likely to be challenged for integrity. In general, weighting includes the following activities:

- Identifying the underlying values of stakeholders
- Determining weights to place on impacts
- Applying weights to impact indicators.

Weighted data could possibly be combined across impact categories, but the weighting procedure must be explicitly documented. The un-weighted data should be shown together with the weighted results to ensure a clear understanding of the assigned weights.

Note that in some cases, the presentation of the impact assessment results alone often provides sufficient information for decision-making, particularly when the results are straightforward or obvious. For example, when the best-performing alternative is significantly and meaningfully better than the others in at least one impact category, and equal to the alternatives in the remaining impact categories, then *one alternative is clearly better*. Therefore, any relative weighting of the impact assessment results would not change its rank as first preference. The decision can be made without the weighting step.

Several issues exist that make weighting a challenge. The first issue is subjectivity. According to ISO 14042, any judgment of preferability is a subjective judgment regarding the relative importance of one impact category over another. Additionally, these value judgments may change with location or time of year. For example, someone located in Los Angeles, CA, may place more importance on the values for photochemical smog than would a person located in Cheyenne, Wyoming. The second issue is derived from the first: how should users fairly and consistently make decisions based on environmental preferability, given the subjective nature of weighting? Developing a truly objective (or universally agreeable) set of weights or weighting methods is not feasible. However, several approaches to weighting do exist and are used successfully for decision-making, such as the Analytic Hierarchy Process, the Modified Delphi Technique, and Decision Analysis Using Multi-Attribute Theory.

### Step 7: Evaluate and Document the LCIA Results

Now that the impact potential for each selected category has been calculated, the accuracy of the results must be verified. The accuracy must be sufficient to support the purposes for performing the LCA as defined in the goal and scope. When documenting the results of the life cycle impact assessment, thoroughly describe the methodology used in the analysis, define the systems analyzed and the boundaries that were set, and all assumptions made in performing the inventory analysis.

The LCIA, like all other assessment tools, has inherent limitations. Although the LCIA process follows a systematic procedure, there are many underlying assumptions and simplifications, as well subjective value choices.

Depending on the LCIA methodology selected, and/or the inventory data on which it is based, some of the key limitations may include:

- Lack of spatial resolution – e.g., a 4,000-gallon ammonia release is worse in a small stream than in a large river.
- Lack of temporal resolution – e.g., a five-ton release of particulate matter during a one month period is worse than the same release spread through the whole year.
- Inventory speciation – e.g., broad inventory listing such as “VOC” or “metals” do not provide enough information to accurately assess environmental impacts.
- Threshold and non-threshold impact – e.g., ten tons of contamination is not necessarily ten times worse than one ton of contamination.

The selection of more complex or site-specific impact models can help reduce the limitations of the impact assessment’s accuracy. It is important to document these limitations and to include a comprehensive description of the LCIA methodology, as well as a discussion of the underlying assumptions, value choices, and known uncertainties in the impact models with the numerical results of the LCIA to be used in interpreting the results of the LCA.

# Chapter 5
# Life Cycle Interpretation

## What is Life Cycle Interpretation?

Life cycle interpretation is a systematic technique to identify, quantify, check, and evaluate information from the results of the LCI and the LCIA, and communicate them effectively. Life cycle interpretation is the last phase of the LCA process.

ISO has defined the following two objectives of life cycle interpretation:

1. Analyze results, reach conclusions, explain limitations, and provide recommendations based on the findings of the preceding phases of the LCA, and to report the results of the life cycle interpretation in a transparent manner.
2. Provide a readily understandable, complete, and consistent presentation of the results of an LCA study, in accordance with the goal and scope of the study. (ISO 1998b)

## Comparing Alternatives Using Life Cycle Interpretation

Interpreting the results of an LCA is not as simple as two is better then three, therefore Alternative A is the best choice! While conducting the LCI and LCIA it is necessary to make assumptions, engineering estimates, and decisions based on your values and the values of involved stakeholders. Each of these decisions must be included and communicated within the final results to clearly and comprehensively explain conclusions drawn from the data. In some cases, it may not be possible to state that one alternative is better than the others because of the uncertainty in the final results. This does not imply that efforts have been wasted. The LCA process will still provide decision-makers with a better understanding of the environmental and health impacts associated with each alternative, where they occur (locally, regionally, or globally), and the relative magnitude of each type of impact in comparison to each of the proposed alternatives included in the study. This information more fully reveals the pros and cons of each alternative.

## Can I Select an Alternative Based Only on the Results of the LCA?

The purpose of conducting an LCA is to better inform decision-makers by providing a particular type of information (often unconsidered), with a life cycle perspective of environmental and human health impacts associated with each product or process. However, LCA does not take into account technical performance, cost, or political and social acceptance. Therefore, it is recommended that LCA be used in conjunction with these other parameters.

## Key Steps to Interpreting the Results of the LCA

The guidance provided in this chapter is a summary of the information provided on life cycle interpretation from the ISO standard entitled "*Environmental Management - Life Cycle Assessment - Life Cycle Interpretation*," ISO 14043 (ISO 1998b). Within the ISO standard, the following steps to conducting a life cycle interpretation are identified and discussed:

1. Identification of the Significant Issues Based on the LCI and LCIA.
2. Evaluation which Considers Completeness, Sensitivity, and Consistency Checks.
3. Conclusions, Recommendations, and reporting.

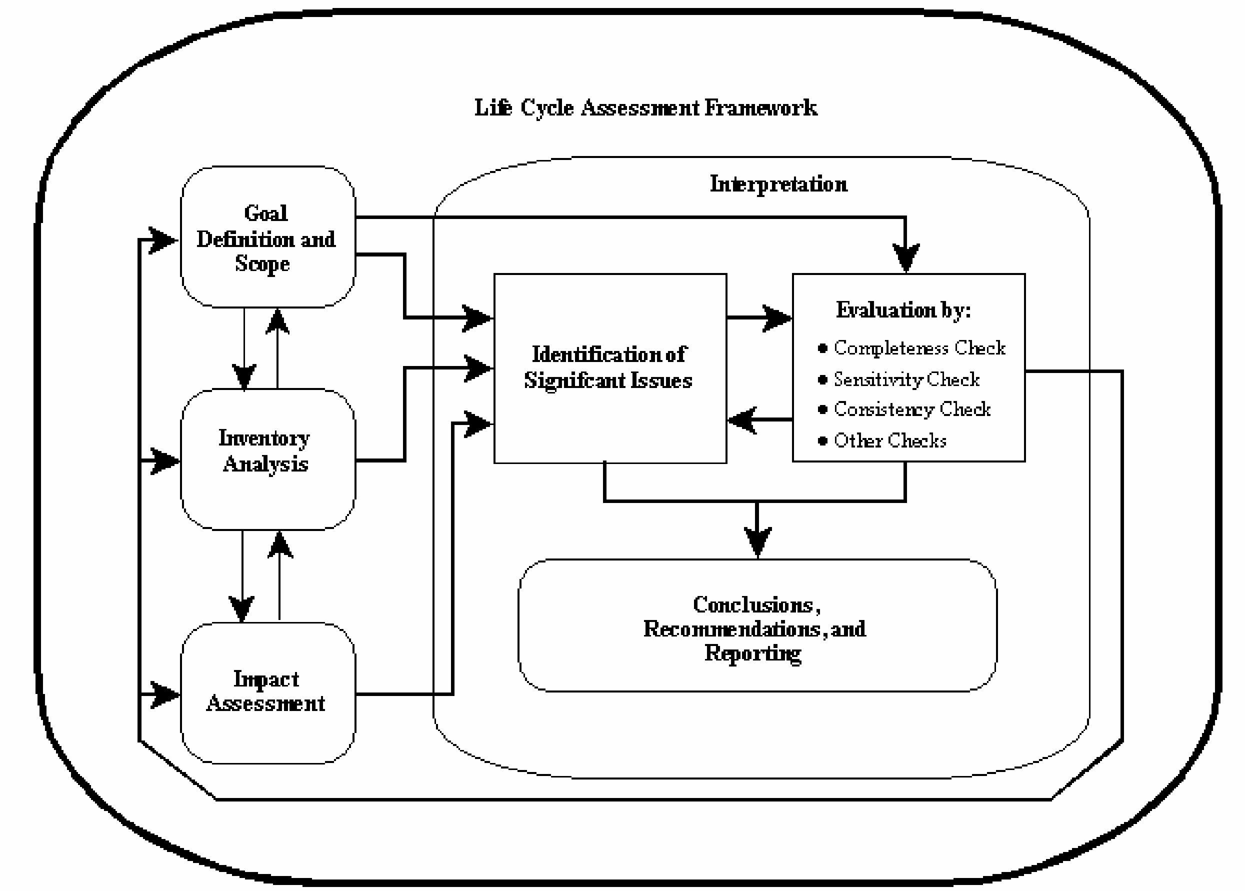


**Exhibit 5-1. Relationship of Interpretation Steps with other Phases of LCA** (Source: ISO, 1998b)

Exhibit 5-1 illustrates the steps of the life cycle interpretation process in relation to the other phases of the LCA process. Each step is summarized below.

Step 1: Identify Significant Issues
The first step of the life cycle interpretation phase involves reviewing information from the first three phases of the LCA process in order to identify the data elements that contribute most to the results of both the LCI and LCIA for each product, process, or service, otherwise known as "significant issues."

The results of this effort are used to evaluate the completeness, sensitivity, and consistency of the LCA study (Step 2). The identification of significant issues guides the evaluation step. Because of the extensive amount of data collected, it is only feasible within reasonable time and resources to assess the data elements that contribute significantly to the outcome of the results.

Before determining which parts of the LCI and LCIA have the greatest influence on the results for each alternative, the previous phases of the LCA should be reviewed in a comprehensive manner (e.g., study goals, ground rules, impact category weights, results, external involvement, etc.).

Review the information collected and the presentations of results developed to determine if the goal and scope of the LCA study have been met. If they have, the significance of the results can then be determined.

Determining significant issues of a product system may be simple or complex. For assistance in identifying environmental issues and determining their significance, the following approaches are recommended:

- *Contribution Analysis* - the contribution of the life cycle stages or groups of processes are compared to the total result and examined for relevance.
- *Dominance Analysis* - statistical tools or other techniques, such as quantitative or qualitative ranking (e.g., ABC Analysis), are used to identify significant contributions to be examined for relevance.
- *Anomaly Assessment* - based on previous experience, unusual or surprising deviations from expected or normal results are observed and examined for relevance.

Significant issues can include:

- Inventory parameters like energy use, emissions, waste, etc.
- Impact category indicators like resource use, emissions, waste, etc.
- Essential contributions for life cycle stages to LCI or LCIA results such as individual unit processes or groups of processes (e.g., transportation, energy production).

Step 2: Evaluate the Completeness, Sensitivity, and Consistency of the Data

The evaluation step of the interpretation phase establishes the confidence in and reliability of the results of the LCA. This is accomplished by completing the following tasks to ensure that products/processes are fairly compared:

1. Completeness Check - examining the completeness of the study.
2. Sensitivity Check - assessing the sensitivity of the significant data elements that influence the results most greatly.
3. Consistency Check - evaluating the consistency used to set system boundaries, collect data, make assumptions, and allocate data to impact categories for each alternative.

Each technique is summarized below.

*Completeness Check* - The completeness check ensures that all relevant information and data needed for the interpretation are available and complete. A checklist should be developed to indicate each significant area represented in the results. Data can be organized by life cycle stage, different processes or unit operations, or type of data represented (raw materials, energy, transportation, environmental release to air, land, or water). Using the established checklist, it is possible to verify that the data comprising each area of the results are consistent with the system boundaries (e.g., all life cycle stages are included) and that the data is representative of the specified area (e.g., accounting for 90 percent of all raw materials and environmental releases). The result of this effort will be a checklist indicating that the results for each product/process are complete and reflective of the stated goals and scope of the LCA study. If deficiencies are noted, then a fair comparison cannot be performed and additional efforts are required to fill the gaps. In some cases, data may not be available to fill the data gaps; under these circumstances, it is necessary to report the differences in the data with the final results and estimate the impact to the comparison either quantitatively (percent uncertainty) or qualitatively (Alternative A’s reported result may be higher because “X” is not included in its assessment).

*Sensitivity Check* - The objective of the sensitivity check is to evaluate the reliability of the results by determining whether the uncertainty in the significant issues identified in Step 1 affect the decision-maker’s ability to confidently draw comparative conclusions.  A sensitivity check can be performed on the significant issues using the following three common techniques for data quality analysis:

1. Contribution Analysis – Identifies the data that has the greatest contribution on the impact indicator results.

2. Uncertainty Analysis – Describes the variability of the LCIA data to determine the significance of the impact indicator results.

3. Sensitivity Analysis – Measures the extent that changes in the LCI results and characterization models affect the impact indicator results.

Additional guidance on how to conduct a contribution, uncertainty, or sensitivity analysis can be found in the EPA document entitled “Guidelines for Assessing the Quality of Life Cycle Inventory Analysis,” April 1995, EPA 530-R-95-010.  As part of the LCI and LCIA phases, a sensitivity, uncertainty, and/or contribution analysis may have been conducted.  These results can be used as the sensitivity check.  As part of the goal, scope, and definition phase of the LCA process, the data quality and accuracy goals were defined.  Verify that these goals have been met with the sensitivity check.  If deficiencies exist, then the accuracy of the results may not be sufficient to support the decisions to be made and additional efforts are required to improve the accuracy of the LCI data collected and/or impact models used in the LCIA.  In some cases, better data or impact models may not be available.  Under these circumstances, report the deficiencies for each relevant significant issue and estimate the impact to the comparison either quantitatively or qualitatively.

*Consistency Check* - The consistency check determines whether the assumptions, methods, and data used throughout the LCA process are consistent with the goal and scope of the study, and for each product/process evaluated.  Verifying and documenting that the study was completed as intended at the conclusion increases confidence in the final results.

A formal checklist should be developed to communicate the results of the consistency check.  Exhibit 5-2 provides examples of the types of information to be included in the checklist.  The goal and scope of the LCA determines which categories should be used.

Depending upon the goal and scope of the LCA, some inconsistency may be acceptable.  If any inconsistency is detected, document the role it played in the overall consistency evaluation.

After completing steps 1 and 2, it has been determined that the results of the impact assessment and the underlying inventory data are complete, comparable, and acceptable to draw conclusions and make recommendations.  If this is not true, stop!  Repeat steps 1 and 2 until the results will be able to support the original goals for performing the LCA.

**Exhibit 5-2. Examples of Checklist Categories and Potential Inconsistencies**

| Category | Example of Inconsistency |
|---|---|
| Data Source | Alternative A is based on literature and Alternative B is based on measured data. |
| Data Accuracy | For Alternative A, a detailed process flow diagram is used to develop the LCI data. For Alternative B, limited process information was available and the LCI data developed was for a process that was not described or analyzed in detail. |
| Data Age | Alternative A uses 1980's era raw materials manufacturing data. Alternative B used a one year-old study. |
| Technological Representation | Alternative A is bench-scale laboratory model. Alternative B is a full-scale production plant operation. |
| Temporal Representation | Data for Alternative A describe a recently developed technology. Alternate B describes a technology mix, including recently built and old plants. |
| Geographical Representation | Data for Alternative A were data from technology employed under European environmental standards. Alternative B uses the data from technology employed under U.S. environmental standards. |
| System Boundaries, Assumptions, & Models | Alternative A uses a Global Warming Potential model based on 500 year potential. Alternative B uses a Global Warming Potential model based on 100 year potential. |

Step 3: Draw Conclusions and Recommendations

The objective of this step is to interpret the results of the life cycle impact assessment (not the LCI) to determine which product/process has the overall least impact to human health and the environment, and/or to one or more specific areas of concern as defined by the goal and scope of the study.

Depending upon the scope of the LCA, the results of the impact assessment will return either a list of un-normalized and un-weighted impact indicators for each impact category for the alternatives, or it will return a single grouped, normalized, and weighted score for each alternative, or something in between, e.g., normalized but not weighted.

In the case where a score is calculated, the recommendation may be to accept the product/process with the lowest score. Or, it could be to investigate the reasons how the process could be modified to lower the score. However, do not forget the underlying assumptions that went into the analysis.

If an LCIA stops at the characterization stage, the LCIA interpretation is less clear-cut. The conclusions and recommendations rest on balancing the potential human health and environmental impacts in the light of study goals and stakeholder concerns.

A few words of caution should be noted. It is important to draw conclusions and provide recommendations based only on the facts. Understanding and communicating the uncertainties and limitations in the results is equally as important as the final recommendations. In some instances, it may not be clear which product or process is better because of the underlying uncertainties and limitations in the methods used to conduct the LCA or the availability of good data, time, or resources. In this situation, the results of the LCA are still valuable. They can be used to help inform decision-makers about the human health and environmental pros and cons, understanding the significant impacts of each, where they are occurring (locally, regionally, or globally), and the relative magnitude of each type of impact in comparison to each of the proposed alternatives included in the study.

## Reporting the Results

Now that the LCA has been completed, the materials must be assembled into a comprehensive report documenting the study in a clear and organized manner. This will help communicate the results of the assessment fairly, completely, and accurately to others interested in the results. The report presents the results, data, methods, assumptions, and limitations in sufficient detail to allow the reader to comprehend the complexities and trade-offs inherent in the LCA study.

If the results will be reported to someone who was not involved in the LCA study, i.e., third-party stakeholders, this report will serve as a reference document and should be provided to them to help prevent any misrepresentation of the results.

The reference document should consist of the following elements (ISO 1997):

1. Administrative Information
    a. Name and address of LCA practitioner (who conducted the LCA study)
    b. Date of report
    c. Other contact information or release information
2. Definition of Goal and Scope
3. Life Cycle Inventory Analysis (data collection and calculation procedures)
4. Life Cycle Impact Assessment (methodology and results of the impact assessment that was performed)
5. Life Cycle Interpretation
    a. Results
    b. Assumptions and limitations
    c. Data quality assessment
6. Critical Review (internal and external)
    a. Name and affiliation of reviewers
    b. Critical review reports
    c. Responses to recommendations

## Critical Review

The desirability of a peer review process has been a major focus of discussion in many life-cycle analysis forums. The discussion stems from concerns in four areas; lack of understanding regarding the methodology used or the scope of the study, desire to verify data and the analyst's compilations of data, questioning key assumptions and the overall results, and communication of results. For these reasons, it is recommended that a peer review process be established and implemented early in any study that will be used in a public forum.

The following discussion is not intended to be a blueprint of a specific approach. Instead, it is meant to point out issues that the practitioner or sponsor should keep in mind when establishing a peer review procedure. Overall, a peer review process should address the four areas previously identified:

- Scope/boundaries methodology
- Data acquisition/compilation
- Validity of key assumptions and results
- Communication of results.

The peer review panel should participate in all phases of the study: (1) reviewing the purpose, system boundaries, assumptions, and data collection approach; (2) reviewing the compiled data and the associated quality measures; and, (3) reviewing the draft inventory report, including the intended communication strategy.

A spreadsheet, such as the one presented in Appendix A would be useful in addressing many of the issues surrounding scope/boundaries methodology, data/compilation of data, and validity of assumptions and results. Criteria may need to be established for communication of results. These criteria could include showing how changes in key assumptions could affect the study results, and guidance on how to publish and communicate results without disclosing proprietary data.

It is generally believed that the peer review panel should consist of a diverse group of three to five individuals representing various sectors, such as federal, state, and local governments, academia, industry, environmental or consumer groups, and LCA practitioners. Not all sectors need be represented on every panel. The credentials or background of individuals should include a reputation for objectivity, experience with the technical framework or conduct of life-cycle analysis studies, and a willingness to work as part of a team. Issues for which guidelines are still under development include panel selection, number of reviews, using the same reviewers for all life-cycle studies or varying the members between studies, and having the review open to the public prior to its release. The issue of how the reviews should be performed raises a number of questions, such as these: Should a standard spreadsheet be required? Should oral as well as written comments from the reviewers be accepted? How much time should be allotted for review? Who pays for the review process?

The peer review process should be flexible to accommodate variations in the application or scope of life-cycle studies. Peer review should improve the conduct of these studies, increase the understanding of the results, and aid in further identifying and subsequently reducing any environmental consequences of products or materials. EPA supports the use of peer reviews as a mechanism to increase the quality and consistency of life-cycle inventories.

## Conclusion

Adding life cycle assessment to the decision-making process provides an understanding of the human health and environmental impacts that traditionally is not considered when selecting a product or process. This valuable information provides a way to account for the full impacts of decisions, especially those that occur outside of the site that are directly influenced by the selection of a product or process.

Remember, LCA is a tool to better inform decision-makers and should be included with other decision criteria, such as cost and performance, to make a well-balanced decision.

# References

Bare, J.C., Norris, G.A., Pennington, D.W., and McKone, T. 2003. “TRACI – The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts.” *Journal of Industrial Ecology*. 6(3-4), pp 49-78. The MIT Press. http://mitpress.mit.edu/jie

Boustead, I., and Hancock, G.F. 1979. *Handbook of Industrial Energy Analysis*. Chichester: Ellis Horwood and New York: John Wiley. ISBN 0-470-26492-6. Chapter 3, “Real Industrial Systems,” p. 76.

Goldsmith, E and R Allen. 1972. “A Blueprint for Survival.” *The Economist* 2(1).

Guinee *et al*. 2001. *An Operational Guide to the ISO Standards*. http://www.leidenuniv.nl/cml/ssp/projects/lca2/lca2.html

Curran, M.A. (ed) 1996. *Environmental Life Cycle Assessment*. ISBN 0-07-015063-X, McGraw-Hill.

Curran, M.A., Mann, M., and Norris, G. 2005. “International Workshop on Electricity Data for Life Cycle Inventories.” *J Cleaner Production.* 13(8), pp 853-862.

Environmental Protection Agency. 2003. *Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI): User’s Guide and System Documentation.* EPA 600/R-02/052. National Risk Management Research Laboratory. Cincinnati, Ohio, USA.

Environmental Protection Agency. 1995. *Guidelines for Assessing the Quality of Life Cycle Inventory Analysis*. EPA/530/R-95/010. Office of Solid Waste. Washington, DC. USA.

Environmental Protection Agency. 1993. *Life Cycle Assessment: Inventory Guidelines and Principles*. EPA/600/R-92/245. Office of Research and Development. Cincinnati, Ohio, USA.

Environmental Protection Agency. 1986. EPA Quality Assurance Management Staff. *Development of Data Quality Objectives: Description of Stages I and II.*

Hendrickson, C.T., Lave L., and Matthews, H.S. 2006. *Environmental Life Cycle Assessment of Goods and Services: An Input-Output Approach.* Resources for the Future, Washington, DC, ISBN 1-933115-23-8.

International Standards Organization. 1997. *Environmental Management - Life Cycle Assessment - Principles and Framework ISO 14040.*

International Standards Organization. 1998. *Life Cycle Assessment - Impact Assessment ISO 14042.*

International Standards Organization. 1998b. *Environmental Management - Life Cycle Assessment - Life Cycle Interpretation ISO 14043.*

Jensen, A.A. and Remmen, A. 2004. “Background Report for a UNEP Guide to Life Cycle Management - A Bridge to Sustainable Products.” Final draft 30 December 2004. UNEP/SETAC Life Cycle Initiative. Available from: http://www.uneptie.org/pc/sustain/reports/lcini/Background%20document%20Guide%20LIFE%20CYCLE%20MANAGEMENT%20rev%20final%20draft.pdf. Accessed 08 June 2005.

Meadows, D.H. et al. 1972. *The Limits to Growth: A Report for the Club of Rome's Project on the Predicament of Mankind.* Universe Books, New York. P. 205.

Society of Environmental Toxicology and Chemistry. 1991. *A Technical Framework for Life Cycle Assessment*. Fava, J., Denison, R., Jones, B., Curran, M.A., Vigon, B., Selke, S., and Barnum, J. (eds).

Society of Environmental Toxicology and Chemistry. 1993. *Guidelines for Life Cycle Assessment: A 'Code of Practice.'* Consoli, F., Allen, D., Boustead, I., Fava, J., Franklin, W., Jensen, A.A., Oude, N., Parrish, R., Perriman, R., Postlethwaite, D., Quay, B., Seguin, J., and Vigon, B. (eds).

Society of Environmental Toxicology and Chemistry. 1997. *Life Cycle Impact Assessment: The State-of-the-Art*. Barnthouse, L., Fava, J., Humphreys, K., Hunt, R., Laibson, L., Noessen, S., Owens, J.W., Todd, J.A., Vigon, B., Wietz, K., and Young, J. (eds).

Society of Environmental Toxicology and Chemistry. 2004. *Life-Cycle Management*. Hunkeler, D., Rebitzer, G., Finkbeiner, M., Schmidt W-P., Jensen, A.A., Stranddorf, H., and Christiansen, K.

Werner, A.F. 1991. *Product Lifecycle Assessment: A Strategic Approach*. Proceedings of the Global Pollution Prevention '91 Conference, Washington, D.C.

# Appendix A
# Sample Inventory Spreadsheet

(This is a fictitious example of the life cycle inventory
for a gasoline system and does not represent real data).

|  |  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|
| **PROCESS NAME:** |  |  | Fictitious Gasoline Life Cycle Inventory |  |  |  |  |  |  |  |
| **PROCESS ID:** |  |  | Gasoline |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |
| **REFERENCE FLOW:** |  |  | 1000 |  | Units: | gallons | of: | Gasoline |  |  |
|  |  |  |  |  |  |  |  |  |  |  |
| **PROCESS DESCRIPTION:** |  |  | Summary of LCI to extract, produce, and distribute 1,000 gallons of gasoline used |  |  |  |  |  |  |  |
|  |  |  | to fuel a typical passenger automobile in the US. |  |  |  |  |  |  |  |
| **BASIS OF CALCULATIONS** |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  | Summer | Winter | Average | Units | Reference |  |  |
|  | Oxygen Content |  |  | 2.1 | 1.9 | 0.02 | percent | EPA, OTAQ; MOBILE 6 |  |  |
|  |  |  |  |  |  |  |  |  |  |  |
|  | Molecular Weight |  |  |  |  | 88 | g/mol | www.chemfinder.com |  |  |
|  |  |  |  |  |  |  |  |  |  |  |
|  | Oxygenate Content by Volume |  |  |  |  | 11.05 | percent by volume |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |
|  | Oxygenate Content by Weight |  |  |  |  | 11.15 | percent by weight |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |
|  | Fuel Economy Estimated for Average Car By Fuel Type |  |  |  |  | 20.22 | miles/gal | MOBILE 6 |  |  |
|  |  |  |  |  |  |  |  |  |  |  |
|  | Petroleum Refining Process Efficiency (mass outputs/mass inputs) |  |  |  |  |  |  |  |  |  |
|  |  | Petroleum Refinery Process Efficiency (mass basis) |  |  |  | 92 | percent | EIA |  |  |
|  |  | GREET v1.6 Published Petroleum Refinery Efficiency |  |  |  | 85 | percent | Greet1.6 |  |  |
|  |  | Process Efficiency Used in Calculations |  |  |  | 85 | percent |  |  |  |
| **Process Inputs** |  |  |  |  |  |  |  |  |  |  |
|  | Material | Coal |  |  |  |  | 9.88E+01 | lb |  |  |
|  |  | Crude Oil |  |  |  |  | 5.64E+02 | gal |  |  |
|  |  | Natural Gas |  |  |  |  | 3.23E+02 | SCF |  |  |
|  |  | Uranium |  |  |  |  | 6.69E-02 | lb |  |  |
|  |  | Wood |  |  |  |  | 3.99E+00 | lb |  |  |
|  |  | Drilling Fluids |  |  |  |  | Unknown |  |  |  |
| **Process Outputs** |  |  |  |  |  |  |  |  |  |  |
|  | Product | Gasoline |  |  |  |  | 594 | gal | Calculated |  |
|  | Co-Product | N/A |  |  |  |  |  |  |  |  |
|  | **Air Emissions** |  |  |  |  |  |  |  |  |  |

|  |  |  | Mat. P&D | Fuel P&D | Fuel Use | Process | Total | Units |  |  |
|---|---|---|---|---|---|---|---|---|---|---|
|  |  | Volatile Organic Compounds (VOC) | 1.86E-01 | 1.49E-01 | 2.98E-01 | 1.36E+01 | 1.42E+01 | lb |  |  |
|  |  | Carbon Monoxide (CO) | 4.69E-01 | 4.78E-01 | 2.32E+00 | 3.00E+02 | 3.03E+02 | lb |  |  |
|  |  | Nitrogen Oxides (NOx) | 1.51E+00 | 1.64E+00 | 8.33E+00 | 2.26E+01 | 3.41E+01 | lb |  |  |
|  |  | PM10 | 6.16E-02 | 2.06E-01 | 2.45E-01 | 6.79E-01 | 1.19E+00 | lb |  |  |
|  |  | Sulfur Oxides (SOx) | 6.41E-01 | 2.17E+00 | 2.52E+00 | 1.44E+00 | 6.77E+00 | lb |  |  |
|  |  | Methane | 5.60E-01 | 1.26E+00 | 3.18E-01 | 1.70E+00 | 3.84E+00 | lb |  |  |
|  |  | Nitrous Oxide (N2O) | 3.91E-03 | 4.38E-03 | 2.85E-02 |  | 3.68E-02 | lb |  |  |
|  |  | Carbon Dioxide (CO2) | 2.20E+02 | 3.75E+02 | 1.56E+03 | 1.20E+04 | 1.41E+04 | lb |  |  |
|  |  | VOC loss: evaporation |  |  |  | 1.39E+01 | 1.39E+01 | lb |  |  |
|  |  | VOC loss: spillage | 2.70E-04 | 2.36E-03 |  |  | 2.62E-03 | lb |  |  |
|  |  | 1 1 1-Trichloroethane |  |  |  | 2.19E-05 | 2.19E-05 | lb |  |  |
|  |  | 1 2 3-Trichloropropane |  |  |  | 9.67E-06 | 9.67E-06 | lb |  |  |
|  |  | 1 2 4-Trichlorobenzene |  |  |  | 5.8E-07 | 5.8E-07 | lb |  |  |
|  |  | 1 2 4-Trimethylbenzene | 1.07E-04 | 1.02E-04 |  | 1.23E-01 | 1.23E-01 | lb |  |  |
|  |  | 1 2-Dibromoethane | 1.24E-06 | 1.19E-06 |  | 1.61E-05 | 1.86E-05 | lb |  |  |
|  |  | 1 2-Dichloroethane | 3.2E-06 | 3.06E-06 |  | 4.15E-05 | 4.78E-05 | lb |  |  |
|  |  | 1 3-Butadiene | 2.9E-05 | 2.77E-05 |  | 8.39E-02 | 8.40E-02 | lb |  |  |
|  |  | 2 2 4-TM-Pentane |  |  |  | 1.20E+00 | 1.20E+00 | lb |  |  |
|  |  | 2 2 5-TM-Hexane |  |  |  | 1.39E-01 | 1.39E-01 | lb |  |  |
|  |  | 2 3 3-TM-Pentane |  |  |  | 2.22E-01 | 2.22E-01 | lb |  |  |
|  |  | 2 3 4-TM-Pentane |  |  |  | 2.21E-01 | 2.21E-01 | lb |  |  |
|  |  | 2 3-Dimethylbutane |  |  |  | 1.39E-01 | 1.39E-01 | lb |  |  |
|  |  | 2 4-Dimethylphenol |  |  |  | 1.01E-07 | 1.01E-07 | lb |  |  |
|  |  | 2-Methyl-2-butene |  |  |  | 9.19E-02 | 9.19E-02 | lb |  |  |
|  |  | 2-Methylhexane |  |  |  | 1.57E-01 | 1.57E-01 | lb |  |  |
|  |  | 2-Methylpentane |  |  |  | 2.84E-01 | 2.84E-01 | lb |  |  |
|  |  | 3-Methylhexane |  |  |  | 1.64E-01 | 1.64E-01 | lb |  |  |
|  |  | 3-Methylpentane |  |  |  | 1.82E-01 | 1.82E-01 | lb |  |  |
|  |  | Acenaphthene |  |  |  | 9.23E-05 | 9.23E-05 | lb |  |  |
|  |  | Acenaphthylene |  |  |  | 5.20E-04 | 5.20E-04 | lb |  |  |
|  |  | Acetonitrile |  |  |  | 4.29E-06 | 4.29E-06 | lb |  |  |
|  |  | Acetophenone |  |  |  | 2.75E-06 | 2.75E-06 | lb |  |  |
|  |  | Acreolin | 4.29E-07 | 3.2E-06 | 1.57E+03 | 8.21E-03 | 8.21E-03 | lb |  |  |
|  |  | Aluminum (fume or dust) |  |  |  | 2.36E-08 | 2.36E-08 | lb |  |  |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Ammonia | 1.32E-03 | 2.43E-03 | | 2.68E+00 | 2.68E+00 | lb | | |
| | | Anthracene | 5.88E-07 | 5.62E-07 | | 1.14E-04 | 1.16E-04 | lb | | |
| | | Antimony | 2.17E-07 | 1.62E-06 | | 1.85E-06 | 3.69E-06 | lb | | |
| | | Antimony Compounds | 5.9E-07 | 5.64E-07 | | 7.65E-06 | 8.80E-06 | lb | | |
| | | Arsenic | 9.85E-07 | 7.34E-06 | | 7.60E-05 | 8.43E-05 | lb | | |
| | | Asbestos (friable) | | | | | 0.00E+00 | lb | | |
| | | Barium | | | | 8.80E-08 | 8.80E-08 | lb | | |
| | | Barium Compounds | | | | 1.05E-06 | 1.05E-06 | lb | | |
| | | Benzene | 1.60E-03 | 2.26E-03 | | 6.38E-01 | 6.42E-01 | lb | | |
| | | Benzo(a)anthracene | | | | 1.30E-05 | 1.30E-05 | lb | | |
| | | Benzo(a)pyrene | | | | 1.30E-05 | 1.30E-05 | lb | | |
| | | Benzo(b)fluoranthene | | | | 1.54E-05 | 1.54E-05 | lb | | |
| | | Benzo(g,h,i)perylene | | | | 3.24E-05 | 3.24E-05 | lb | | |
| | | Benzo(k)fluoranthene | | | | 1.54E-05 | 1.54E-05 | lb | | |
| | | Beryllium | 1.12E-07 | 8.35E-07 | | | 9.47E-07 | lb | | |
| | | Biphenyl | 2.31E-05 | 1.05E-05 | | 3.73E-04 | 4.06E-04 | lb | | |
| | | Butraldehyde | | | | 5.58E-06 | 5.58E-06 | lb | | |
| | | Cadmium | 2.14E-07 | 1.6E-06 | | 2.79E-08 | 1.84E-06 | lb | | |
| | | Carbon Disulfide | 1.89E-06 | 1.81E-06 | | 2.45E-05 | 2.83E-05 | lb | | |
| | | Carbon Tetrachloride | 2.43E-06 | 7.29E-06 | | 2.16E-05 | 3.13E-05 | lb | | |
| | | Carbonyl Sulfide | 5.23E-05 | 5.01E-05 | | 7.58E-05 | 1.78E-04 | lb | | |
| | | Certain Glycol Ethers | | | | 3.11E-05 | 3.11E-05 | lb | | |
| | | Chlorine | 4.06E-05 | 3.97E-05 | | 5.25E-04 | 6.05E-04 | lb | | |
| | | Chlorine Dioxide | | | | 4.29E-09 | 4.29E-09 | lb | | |
| | | Chlorobenzene | | | | | 0.00E+00 | lb | | |
| | | Chlorodifluoromethane | 8.34E-06 | 7.99E-06 | | 1.08E-04 | 1.25E-04 | lb | | |
| | | Chloromethane | | | | 2.97E-06 | 2.97E-06 | lb | | |
| | | Chromium | 1.28E-06 | 9.52E-06 | | 7.51E-08 | 1.09E-05 | lb | | |
| | | Chromium Compounds | 9.85E-08 | 9.42E-08 | | 1.28E-06 | 1.47E-06 | lb | | |
| | | Chromium III | | | | 7.85E-05 | 7.85E-05 | lb | | |
| | | Chromium VI | | | | 5.23E-05 | 5.23E-05 | lb | | |
| | | Chrysene | | | | 1.30E-05 | 1.30E-05 | lb | | |
| | | Cobalt | 7.22E-07 | 4.86E-06 | | 3.22E-08 | 5.62E-06 | lb | | |
| | | Cobalt Compounds | 2.48E-09 | 2.38E-09 | | 1.02E-06 | 1.03E-06 | lb | | |
| | | Copper | | | | 3.01E-08 | 3.01E-08 | lb | | |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Copper Compounds | 3.2E-07 | 3.07E-07 | | 4.16E-06 | 4.78E-06 | lb | | |
| | | Cresol (mixed Isomers) | 3.87E-06 | 3.7E-06 | | 5.02E-05 | 5.78E-05 | lb | | |
| | | Cumene | 1.42E-03 | 3.36E-03 | | 5.10E-03 | 9.88E-03 | lb | | |
| | | Cumene Hydroperoxide | | | | 1.09E-05 | 1.09E-05 | lb | | |
| | | Cyanide Compounds | | | | 8.07E-05 | 8.07E-05 | lb | | |
| | | Cyclohexane | 2.54E-04 | 2.43E-04 | | 3.30E-03 | 3.79E-03 | lb | | |
| | | Dibenz(a,h)anthracene | | | | | 0.00E+00 | lb | | |
| | | Dicyclopentadiene | | | | 3.94E-06 | 3.94E-06 | lb | | |
| | | Diethanolamine | 2.94E-05 | 2.82E-05 | | 3.82E-04 | 4.40E-04 | lb | | |
| | | Dioxins | 2.36E-12 | 1.76E-11 | | | 1.99E-11 | lb | | |
| | | Ethylbenzene | 7.00E-04 | 1.11E-03 | | 3.44E-01 | 3.46E-01 | lb | | |
| | | Ethylene | 3.62E-04 | 3.46E-04 | | 4.69E-03 | 5.40E-03 | lb | | |
| | | Ethylene Glycol | 1.89E-05 | 1.81E-05 | | 2.45E-04 | 2.82E-04 | lb | | |
| | | Ethylene Oxide | | | | 4.29E-06 | 4.29E-06 | lb | | |
| | | Formaldehyde | 2.93E-05 | 3.95E-05 | | 2.32E-01 | 2.32E-01 | lb | | |
| | | Fluoranthene | | | | 1.15E-04 | 1.15E-04 | lb | | |
| | | Fluorene | | | | 1.91E-04 | 1.91E-04 | lb | | |
| | | Hydrazine | | | | 1.63E-06 | 1.63E-06 | lb | | |
| | | Hydocarbons (non CH4) | 2.49E-02 | 1.86E-01 | | | 2.11E-01 | lb | | |
| | | Hydrochloric Acid | 2.27E-03 | 1.63E-02 | | 1.26E-03 | 1.98E-02 | lb | | |
| | | Hydrogen Cyanide | | | | 4.21E-05 | 4.21E-05 | lb | | |
| | | Hydrogen Fluoride | 3.50E-04 | 2.28E-03 | | 6.52E-04 | 3.28E-03 | lb | | |
| | | Indeno(123cd)pyrene | | | | 9.71E-06 | 9.71E-06 | lb | | |
| | | Isopentane | | 4.1E-07 | | 4.55E-01 | 4.55E-01 | lb | | |
| | | Isopropyl Alcohol | | | | 3.59E-06 | 3.59E-06 | lb | | |
| | | Kerosene | 1.09E-05 | 8.09E-05 | | | 9.18E-05 | lb | | |
| | | Lead | 1.73E-06 | 1.29E-05 | | 1.29E-08 | 1.46E-05 | lb | | |
| | | Lead Compounds | 2.08E-07 | 1.99E-07 | | 2.69E-06 | 3.10E-06 | lb | | |
| | | m-Xylene | 9.61E-04 | 1.66E-03 | | 4.01E-03 | 6.63E-03 | lb | | |
| | | Manganese | 2.97E-06 | 2.21E-05 | | 4.43E-05 | 6.94E-05 | lb | | |
| | | Manganese Compounds | | | | 2.23E-06 | 2.23E-06 | lb | | |
| | | Mercury | 8.13E-07 | 6.06E-06 | | 2.31E-05 | 3.00E-05 | lb | | |
| | | Mercury Compounds | | | | 1.29E-07 | 1.29E-07 | lb | | |
| | | Metals | 4.5E-06 | 3.35E-05 | | | 3.80E-05 | lb | | |
| | | Methanol | 1.05E-03 | 1.00E-03 | | 1.36E-02 | 1.57E-02 | lb | | |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Methyl Ethyl Ketone | 4.91E-04 | 4.70E-04 | | 6.37E-03 | 7.33E-03 | lb | | |
| | | Methyl Isobutyl Ketone | 3.37E-05 | 3.22E-05 | | 4.37E-04 | 5.03E-04 | lb | | |
| | | Methyl Tert-Butyl Ether | 3.42E-04 | 3.27E-04 | | 2.30E+00 | 2.30E+00 | lb | | |
| | | Methylene Chloride | 1.85E-06 | 1.38E-05 | | 0.00E+00 | 1.56E-05 | lb | | |
| | | Molybdenum Trioxide | 4.50E-07 | 4.31E-07 | | 5.84E-06 | 6.72E-06 | lb | | |
| | | n-Butane | | | | 1.10E-01 | 1.10E-01 | lb | | |
| | | n-Butyl Alcohol | | | | 2.45E-05 | 2.45E-05 | lb | | |
| | | n-Pentane | 7.21E-04 | 5.29E-04 | | 1.91E-01 | 1.92E-01 | lb | | |
| | | n-Hexane | 7.21E-04 | 6.90E-04 | | 4.13E-01 | 4.14E-01 | lb | | |
| | | n-Heptane | | | | 1.90E-01 | 1.90E-01 | lb | | |
| | | n-Octane | | | | 4.12E-03 | 4.12E-03 | lb | | |
| | | n-nonane | | | | 3.19E-03 | 3.19E-03 | lb | | |
| | | n-Decane | | | | 3.07E-03 | 3.07E-03 | lb | | |
| | | n-Undecane | | | | 1.75E-03 | 1.75E-03 | lb | | |
| | | n-Dodecane | | | | 2.31E-03 | 2.31E-03 | lb | | |
| | | n-Tridecane | | | | 2.74E-03 | 2.74E-03 | lb | | |
| | | n-Tetradecane | | | | 2.97E-03 | 2.97E-03 | lb | | |
| | | n-Pentadecane | | | | 2.83E-03 | 2.83E-03 | lb | | |
| | | n-Hexadecane | | | | 2.67E-03 | 2.67E-03 | lb | | |
| | | n-Heptadecane | | | | 2.62E-03 | 2.62E-03 | lb | | |
| | | n-Octadecane | | | | 1.60E-03 | 1.60E-03 | lb | | |
| | | n-Nonadecane | | | | 1.95E-03 | 1.95E-03 | lb | | |
| | | n-Icosane | | | | 1.79E-03 | 1.79E-03 | lb | | |
| | | n-Henicosane | | | | 1.66E-03 | 1.66E-03 | lb | | |
| | | n-Docosane | | | | 1.62E-03 | 1.62E-03 | lb | | |
| | | n-Methyl-2-Pyrrolidone | 3.8E-05 | 3.64E-05 | | 4.93E-04 | 5.67E-04 | lb | | |
| | | n-Nitrodimethylamine | 9.06E-08 | 6.75E-07 | | | 7.66E-07 | lb | | |
| | | Naphthalene | 7.36E-05 | 5.09E-05 | | 1.76E-02 | 1.77E-02 | lb | | |
| | | Nickel | 6.68E-06 | 4.83E-05 | | 9.81E-05 | 1.53E-04 | lb | | |
| | | Nickel Compounds | 5.81E-06 | 5.56E-06 | | 7.53E-05 | 8.67E-05 | lb | | |
| | | Nitrate Compounds | | | | | 0.00E+00 | lb | | |
| | | o-Xylene | 9.39E-04 | 1.64E-03 | | 3.73E-03 | 6.31E-03 | lb | | |
| | | Other Aldehydes | 8.17E-05 | 6.08E-04 | | | 6.90E-04 | lb | | |
| | | Other Organics | 1.24E-04 | 9.27E-04 | | | 1.05E-03 | lb | | |
| | | p-Xylene | 9.94E-04 | 1.69E-03 | | 1.61E-03 | 4.30E-03 | lb | | |

|  |  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|
|  |  | Particulates (total) | 3.61E-02 | 2.69E-01 |  | 0.00E+00 | 3.05E-01 | lb |  |  |
|  |  | Perchloroethylene | 4.10E-07 | 3.05E-06 |  | 0.00E+00 | 3.46E-06 | lb |  |  |
|  |  | Phenanthrene | 3.00E-05 | 1.31E-05 |  | 4.81E-04 | 5.24E-04 | lb |  |  |
|  |  | Phenols | 2.52E-05 | 3.15E-05 |  | 3.12E-04 | 3.69E-04 | lb |  |  |
|  |  | Polycyclic Aromatic Compounds | 7.74E-06 | 7.41E-06 |  | 1.00E-04 | 1.16E-04 | lb |  |  |
|  |  | Propionaldehyde |  |  |  | 8.97E-03 | 8.97E-03 | lb |  |  |
|  |  | Propylene | 6.65E-04 | 6.36E-04 |  | 8.63E-03 | 9.93E-03 | lb |  |  |
|  |  | Pyrene |  |  |  | 1.57E-04 | 1.57E-04 | lb |  |  |
|  |  | Quinoline |  |  |  | 1.01E-05 | 1.01E-05 | lb |  |  |
|  |  | Radionuclides (Ci) | 8.90E-06 | 6.63E-05 |  |  | 7.52E-05 | lb |  |  |
|  |  | Selenium | 3.09E-06 | 2.30E-05 |  |  | 2.61E-05 | lb |  |  |
|  |  | Selenium Compounds |  |  |  | 1.07E-07 | 1.07E-07 | lb |  |  |
|  |  | Styrene | 1.23E-06 | 1.18E-06 |  | 4.10E-02 | 4.10E-02 | lb |  |  |
|  |  | Sulfuric Acid | 1.36E-03 | 1.30E-03 |  | 1.76E-02 | 2.03E-02 | lb |  |  |
|  |  | Tert-Butyl Alcohol | 9.20E-07 | 8.81E-07 |  | 1.19E-05 | 1.37E-05 | lb |  |  |
|  |  | Tetrachloroethylene | 1.03E-05 | 9.81E-06 |  | 1.33E-04 | 1.53E-04 | lb |  |  |
|  |  | Toluene | 3.36E-03 | 4.36E-03 |  | 2.00E+00 | 2.00E+00 | lb |  |  |
|  |  | Toluene-2 6-Diisocyanate |  |  |  | 4.14E-06 | 4.14E-06 | lb |  |  |
|  |  | Trichloroethylene | 1.08E-05 | 1.30E-05 |  | 1.35E-04 | 1.59E-04 | lb |  |  |
|  |  | Vanadium |  |  |  | 5.93E-06 | 5.93E-06 | lb |  |  |
|  |  | Vinyl Acetate |  |  |  | 1.51E-05 | 1.51E-05 | lb |  |  |
|  |  | Xylene (mixed isomers) | 5.52E-04 | 5.28E-04 |  | 1.31E+00 | 1.31E+00 | lb |  |  |
|  |  | Zinc (fume or dust) | 1.09E-06 | 1.05E-06 |  | 1.42E-05 | 1.63E-05 | lb |  |  |
|  |  | Zinc Compounds | 8.05E-06 | 7.71E-06 |  | 1.04E-04 | 1.20E-04 | lb |  |  |
|  |  | Acetaldehyde | 0.00E+00 | 0.00E+00 |  | 6.72E-02 | 6.72E-02 | lb |  |  |
|  |  | Total | 2.24E+02 | 3.85E+02 | 1.57E+03 | 1.24E+04 | 1.45E+04 | lb |  |  |
|  | **Water Emissions** |  |  |  |  |  |  |  |  |  |
|  |  |  | Mat. P&D | Fuel P&D | Fuel Use | Process | Total | Units |  |  |
|  |  | 1 1 1-Trichloroethane |  |  |  |  | 0.00E+00 | lb |  |  |
|  |  | 1 2 3-Trichloropropane |  |  |  |  | 0.00E+00 | lb |  |  |
|  |  | 1 2 4-Trichlorobenzene |  |  |  |  | 0.00E+00 | lb |  |  |
|  |  | 1 2 4-Trimethylbenzene | 3.99E-07 | 1.6E-06 |  | 2.17E-01 | 2.17E-01 | lb |  |  |
|  |  | 1 2-Dibromoethane | 9.6E-10 | 9.41E-10 |  | 1.29E-08 | 1.48E-08 | lb |  |  |
|  |  | 1 2-Dichloroethane |  |  |  | 2.15E-09 | 2.15E-09 | lb |  |  |
|  |  | 1 3-Butadiene | 1.27E-07 | 1.25E-07 |  | 1.70E-06 | 1.96E-06 | lb |  |  |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 2 2 4-TM-Pentane | | | | 7.97E-01 | 7.97E-01 | lb | | |
| | | 2 2 5-TM-Hexane | | | | 2.49E-01 | 2.49E-01 | lb | | |
| | | 2 3 3-TM-Pentane | | | | 3.96E-01 | 3.96E-01 | lb | | |
| | | 2 3 4-TM-Pentane | | | | 3.95E-01 | 3.95E-01 | lb | | |
| | | 2 3-Dimethylbutane | | | | 2.49E-01 | 2.49E-01 | lb | | |
| | | 2 4-Dimethylphenol | | | | 2.25E-07 | 2.25E-07 | lb | | |
| | | 2-Methyl-2-Butene | | | | 1.64E-01 | 1.64E-01 | lb | | |
| | | 2-Methylhexane | | | | 2.80E-01 | 2.80E-01 | lb | | |
| | | 2-Methylpentane | | | | 5.07E-01 | 5.07E-01 | lb | | |
| | | 3-Methylhexane | | | | 2.93E-01 | 2.93E-01 | lb | | |
| | | 3-Methylpentane | | | | 3.25E-01 | 3.25E-01 | lb | | |
| | | Acetaldehyde | | | | 5.25E-07 | 5.25E-07 | lb | | |
| | | Acetonitrile | | | | | 0.00E+00 | lb | | |
| | | Acetophenone | | | | | 0.00E+00 | lb | | |
| | | Acid | 4.96E-10 | 3.7E-09 | | | 4.19E-09 | lb | | |
| | | Aluminum (fume or dust) | | | | | 0.00E+00 | lb | | |
| | | Ammonia | 1.02E-04 | 2.25E-04 | | 1.11E-03 | 1.44E-03 | lb | | |
| | | Anthracene | | | | 8.07E-07 | 8.07E-07 | lb | | |
| | | Antimony | | | | 9.17E-07 | 9.17E-07 | lb | | |
| | | Antimony Compounds | 1.51E-07 | 1.48E-07 | | 2.03E-06 | 2.33E-06 | lb | | |
| | | Arsenic | | | | 8.37E-08 | 8.37E-08 | lb | | |
| | | Barium | | | | 3.99E-06 | 3.99E-06 | lb | | |
| | | Barium Compounds | | | | 1.37E-05 | 1.37E-05 | lb | | |
| | | Benzene | 4.25E-04 | 1.16E-03 | | 8.58E-02 | 8.73E-02 | lb | | |
| | | Beryllium | | | | 4.94E-08 | 4.94E-08 | lb | | |
| | | Biphenyl | 0.00E+00 | 1.15E-06 | | 7.19E-07 | 1.87E-06 | lb | | |
| | | Biological Oxygen Demand (BOD) | 1.11E-03 | 8.31E-03 | | | 9.42E-03 | lb | | |
| | | Boron | 5.46E-06 | 4.07E-05 | | | 4.62E-05 | lb | | |
| | | Cadmium | 3.60E-04 | 2.83E-04 | | 1.63E-03 | 2.27E-03 | lb | | |
| | | Carbon Disulfide | | | | 8.59E-09 | 8.59E-09 | lb | | |
| | | Certain Glycol Ethers | | | | 3.33E-06 | 3.33E-06 | lb | | |
| | | Chlorine | 2.56E-06 | 2.51E-06 | | 3.43E-05 | 3.94E-05 | lb | | |
| | | Chromates | 5.46E-06 | 4.07E-05 | | | 4.62E-05 | lb | | |
| | | Chromium | | | | 5.65E-07 | 5.65E-07 | lb | | |
| | | Chromium Compounds | 9.24E-07 | 9.05E-07 | | 1.24E-05 | 1.42E-05 | lb | | |

|  |  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|
|  |  | Cobalt |  |  |  | 4.81E-06 | 4.81E-06 | lb |  |  |
|  |  | Cobalt Compounds |  |  |  | 3.18E-06 | 3.18E-06 | lb |  |  |
|  |  | Copper |  |  |  | 1.07E-08 | 1.07E-08 | lb |  |  |
|  |  | Copper Compounds | 3.42E-07 | 3.35E-07 |  | 4.59E-06 | 5.27E-06 | lb |  |  |
|  |  | Cresol (mixed isomers) | 3.43E-07 | 3.36E-07 |  | 4.60E-06 | 5.28E-06 | lb |  |  |
|  |  | Cumene | 7.80E-04 | 4.13E-03 |  | 1.92E-03 | 6.83E-03 | lb |  |  |
|  |  | Cyclohexane | 3.15E-07 | 3.09E-07 |  | 4.23E-06 | 4.85E-06 | lb |  |  |
|  |  | Diethanolamine | 1.21E-01 | 9.00E-01 |  | 2.55E-05 | 1.02E+00 | lb |  |  |
|  |  | Ethylbenzene | 2.26E-04 | 7.83E-04 |  | 1.40E-01 | 1.41E-01 | lb |  |  |
|  |  | Ethylene |  |  |  | 1.42E-06 | 1.42E-06 | lb |  |  |
|  |  | Ethylene Glycol | 4.48E-05 | 3.24E-04 |  | 2.02E-05 | 3.89E-04 | lb |  |  |
|  |  | Fluorine |  |  |  | 5.71E-05 | 5.71E-05 | lb |  |  |
|  |  | Hydrogen Fluoride |  |  |  | 1.52E-07 | 1.52E-07 | lb |  |  |
|  |  | Iron | 6.62E-01 | 4.03E-01 |  | 3.08E+00 | 4.14E+00 | lb |  |  |
|  |  | Isopentane |  |  |  | 9.86E-01 | 9.86E-01 | lb |  |  |
|  |  | Lead |  |  |  | 1.42E-07 | 1.42E-07 | lb |  |  |
|  |  | Lead Compounds | 1.40E-07 | 1.37E-07 |  | 1.87E-06 | 2.15E-06 | lb |  |  |
|  |  | m-Xylene |  |  |  | 1.41E-03 | 1.41E-03 | lb |  |  |
|  |  | Manganese | 2.64E-02 | 1.61E-02 |  | 1.23E-01 | 1.65E-01 | lb |  |  |
|  |  | Manganese Compounds |  |  |  | 3.41E-06 | 3.41E-06 | lb |  |  |
|  |  | Mercury | 4.65E-05 | 9.99E-05 |  | 1.68E-04 | 3.14E-04 | lb |  |  |
|  |  | Methanol | 3.15E-04 | 1.95E-04 |  | 1.55E-03 | 2.06E-03 | lb |  |  |
|  |  | Methyl Ethyl Ketone | 1.32E-06 | 1.29E-06 |  | 1.77E-05 | 2.03E-05 | lb |  |  |
|  |  | Methyl Isobutyl Ketone | 4.96E-09 | 4.86E-09 |  | 6.65E-08 | 7.64E-08 | lb |  |  |
|  |  | Methyl Tert-Butyl Ether | 1.88E-05 | 2.57E-05 |  | 1.32E+00 | 1.32E+00 | lb |  |  |
|  |  | Molybdenum Trioxide | 5.99E-07 | 5.87E-07 |  | 8.03E-06 | 9.22E-06 | lb |  |  |
|  |  | n-Butane |  |  |  | 1.96E-01 | 1.96E-01 | lb |  |  |
|  |  | n-Butyl Alcohol |  |  |  | 2.58E-08 | 2.58E-08 | lb |  |  |
|  |  | n-Pentane |  |  |  | 3.75E-01 | 3.75E-01 | lb |  |  |
|  |  | n-Hexane | 3.38E-07 | 2.07E-06 |  | 3.14E-01 | 3.14E-01 | lb |  |  |
|  |  | n-Heptane |  |  |  | 1.74E-01 | 1.74E-01 | lb |  |  |
|  |  | n-Methyl-2-Pyrrolidone |  |  |  | 6.72E-05 | 6.72E-05 | lb |  |  |
|  |  | n-Octane |  |  |  | 1.65E-02 | 1.65E-02 | lb |  |  |
|  |  | n-Nonane |  |  |  | 1.28E-02 | 1.28E-02 | lb |  |  |
|  |  | n-Decane |  |  |  | 1.23E-02 | 1.23E-02 | lb |  |  |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | n-undecane | | | | 7.00E-03 | 7.00E-03 | lb | | |
| | | n-Dodecane | | | | 9.24E-03 | 9.24E-03 | lb | | |
| | | n-Tridecane | | | | 1.10E-02 | 1.10E-02 | lb | | |
| | | n-Tetradecane | | | | 1.19E-02 | 1.19E-02 | lb | | |
| | | n-Pentadecane | | | | 1.13E-02 | 1.13E-02 | lb | | |
| | | n-Hexadecane | | | | 1.07E-02 | 1.07E-02 | lb | | |
| | | n-Heptadecane | | | | 1.05E-02 | 1.05E-02 | lb | | |
| | | n-Octadecane | | | | 6.39E-03 | 6.39E-03 | lb | | |
| | | n-Nonadecane | | | | 7.80E-03 | 7.80E-03 | lb | | |
| | | n-Icosane | | | | 7.16E-03 | 7.16E-03 | lb | | |
| | | n-Henicosane | | | | 6.63E-03 | 6.63E-03 | lb | | |
| | | n-Docosane | | | | 6.46E-03 | 6.46E-03 | lb | | |
| | | Naphthalene | 1.47E-04 | 4.13E-04 | | 6.59E-04 | 1.22E-03 | lb | | |
| | | Nickel | | | | 4.06E-07 | 4.06E-07 | lb | | |
| | | Nickel Compounds | 5.53E-06 | 3.18E-05 | | 1.95E-05 | 5.69E-05 | lb | | |
| | | Nitrates | 2.73E-03 | 2.68E-03 | | 3.67E-02 | 4.21E-02 | lb | | |
| | | o-Xylene | | | | 1.41E-03 | 1.41E-03 | lb | | |
| | | Oil | 5.58E-04 | 4.16E-03 | | 0.00E+00 | 4.72E-03 | lb | | |
| | | p-Cresol | | | | 7.83E-07 | 7.83E-07 | lb | | |
| | | p-Xylene | | | | 1.41E-03 | 1.41E-03 | lb | | |
| | | Phenanthrene | | | | 9.23E-08 | 9.23E-08 | lb | | |
| | | Phenol | 1.35E-04 | 1.00E-03 | | 2.07E-05 | 1.16E-03 | lb | | |
| | | Polycyclic Aromatic Compounds | 4.98E-08 | 4.88E-08 | | 6.68E-07 | 7.66E-07 | lb | | |
| | | Propylene | | | | 1.43E-06 | 1.43E-06 | lb | | |
| | | Selenium | | | | 6.12E-07 | 6.12E-07 | lb | | |
| | | Selenium Compounds | | | | 4.94E-06 | 4.94E-06 | lb | | |
| | | Sodium Nitrite | | | | 6.01E-05 | 6.01E-05 | lb | | |
| | | Styrene | | | | 1.01E-07 | 1.01E-07 | lb | | |
| | | Sulfates | 2.68E-04 | 2.00E-03 | | 0.00E+00 | 2.27E-03 | lb | | |
| | | Sulfuric Acid | 2.04E-02 | 1.52E-01 | | 0.00E+00 | 1.73E-01 | lb | | |
| | | Tert-Butyl Alcohol | | | | 1.76E-05 | 1.76E-05 | lb | | |
| | | Tetrachloroethylene | | | | 1.07E-06 | 1.07E-06 | lb | | |
| | | Toluene | 9.15E-04 | 2.65E-03 | | 6.30E-01 | 6.33E-01 | lb | | |
| | | Vanadium | | | | 7.08E-08 | 7.08E-08 | lb | | |
| | | Xylene (mixed Isomers) | 3.84E-06 | 1.94E-05 | | 6.22E-01 | 6.22E-01 | lb | | |

|  |  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|
|  |  | Zinc Compounds | 1.32E-01 | 8.05E-02 |  | 6.15E-01 | 8.27E-01 | lb |  |  |
|  |  | Volatile Organic Compounds (VOC) |  | 5.05E-07 |  | 9.08E-02 | 9.09E-02 | lb |  |  |
|  |  | Total | 9.70E-01 | 1.58E+00 |  | 1.28E+01 | 1.54E+01 | lb |  |  |
|  | **Solid Waste** |  |  |  |  |  |  |  |  |  |
|  |  |  | Mat. P&D | Fuel P&D | Fuel Use | Process | Total | Units |  |  |
|  |  | Sludge | 2.52E+01 | 1.54E+01 |  | 1.17E+02 | 1.58E+02 | lb |  |  |
|  |  | Solid Waste #1 | 5.50E+00 | 4.08E+01 |  |  | 4.63E+01 | lb |  |  |
|  |  | Disposal Off-site, Subtitle D Landfill | 7.73E-03 | 5.78E-03 |  | 1.70E-02 | 3.05E-02 | lb |  |  |
|  |  | Disposal Off-site, Subtitle C Landfill | 3.04E-03 | 2.27E-03 |  | 6.68E-03 | 1.20E-02 | lb |  |  |
|  |  | Disposal On-site, Subtitle D Landfill | 1.34E-03 | 1.00E-03 |  | 2.94E-03 | 5.28E-03 | lb |  |  |
|  |  | Disposal On-site, Subtitle C landfill | 3.41E-04 | 2.55E-04 |  | 7.50E-04 | 1.35E-03 | lb |  |  |
|  |  | Total: | 3.08E+01 | 5.61E+01 |  | 1.17E+02 | 2.04E+02 | lb |  |  |
| **Raw Materials Extracted** |  |  |  |  |  |  |  |  |  |  |
|  | Fossil Fuel |  | Mat. P&D | Fuel P&D | Fuel Use | Process | Total | Units |  |  |
|  |  | Coal | 1.08E+05 | 8.06E+05 |  |  | 9.14E+05 | Btu |  |  |
|  |  | Crude Oil | 1.19E+07 | 4.73E+06 |  | 5.67E+07 | 7.33E+07 | Btu |  |  |
|  |  | Natural Gas | 3.54E+04 | 2.64E+05 |  |  | 3.00E+05 | Btu |  |  |
|  | Non-Fossil Fuel |  |  |  |  |  |  |  |  |  |
|  |  | Uranium | 4.72E-05 | 6.69E-02 |  |  | 6.69E-02 | lb |  |  |
|  |  | Wood | 3.79E-01 | 3.61E+00 |  |  | 3.99E+00 | lb |  |  |
|  | **Water Consumption** |  |  |  |  |  |  |  |  |  |
|  |  |  | Mat. P&D | Fuel P&D | Fuel Use | Process | Total | Units |  |  |
|  |  | Public Supply |  |  |  |  | 0.00E+00 | gal |  |  |
|  |  | River/Canal |  |  |  |  | 0.00E+00 | gal |  |  |
|  |  | Sea |  |  |  |  | 0.00E+00 | gal |  |  |
|  |  | Unspecified |  |  |  | 2.27E+02 | 2.27E+02 | gal |  |  |
|  |  | Well |  |  |  |  | 0.00E+00 | gal |  |  |
|  |  | Total: |  |  |  | 2.27E+02 | 2.27E+02 | gal |  |  |
| **Land Use** |  |  |  |  |  |  |  |  |  |  |
|  |  |  | Mat. P&D | Fuel P&D | Fuel Use | Process | Total | Units |  |  |
|  |  | Unknown |  |  |  |  |  | acres |  |  |

# Appendix B
# LCA and LCI Software Tools

| Tool | Vendor | URL |
|---|---|---|
| BEES 3.0 | NIST Building and Fire Research Laboratory | http://www.bfrl.nist.gov/oae/software/bees.html |
| Boustead Model 5.0 | Boustead Consulting | http://www.boustead-consulting.co.uk/products.htm |
| CMLCA 4.2 | Centre of Environmental Science | http://www.leidenuniv.nl/cml/ssp/software/cmlca/index.html |
| Dubo-Calc | Netherlands Ministry of Transport, Public Works and Water Management | http://www.rws.nl/rws/bwd/home/www/cgi-bin/index.cgi?site=1&doc=1785 |
| Ecoinvent 1.2 | Swiss Centre for Life Cycle Inventories | http://www.ecoinvent.ch |
| Eco-Quantum | IVAM | http://www.ivam.uva.nl/uk/producten/product7.htm |
| EDIP PC-Tool | Danish LCA Center | http://www.lca-center.dk |
| eiolca.net | Carnegie Mellon University | http://www.eiolca.net |
| Environmental Impact Indicator | ATHENA™ Sustainable Materials Institute | http://www.athenaSMI.ca |
| EPS 2000 Design System | Assess Ecostrategy Scandinavia AB | http://www.assess.se/ |
| GaBi 4 | PE Europe GmbH and IKP University of Stuttgart | http://www.gabi-software.com/software.html |
| GEMIS | Öko-Institut | http://www.oeko.de/service/gemis/en/index.htm |
| GREET 1.7 | DOE's Office of Transportation | http://www.transportation.anl.gov/software/GREET/index.html |
| IDEMAT 2005 | Delft University of Technology | http://www.io.tudelft.nl/research/dfs/idemat/index.htm |
| KCL-ECO 4.0 | KCL | http://www1.kcl.fi/eco/softw.html |
| LCAIT 4.1 | CIT Ekologik | http://www.lcait.com/01_1.html |
| LCAPIX v1.1 | KM Limited | http://www.kmlmtd.com/pas/index.html |
| MIET 3.0 | Centre of Environmental Science | http://www.leidenuniv.nl/cml/ssp/software/miet/index.html |
| REGIS | Sinum AG | http://www.sinum.com/htdocs/e_software_regis.shtml |
| SimaPro 6.0 | PRé Consultants | http://www.pre.nl/simapro.html |
| SPINE@CPM | Chalmers | http://www.globalspine.com |
| SPOLD | The Society for Promotion of Life-Cycle Assessment | http://lca-net.com/spold/ |
| TEAM™ 4.0 | Ecobalance | http://www.ecobalance.com/uk_lcatool.php |
| Umberto | ifu Hamburg GmbH | http://www.ifu.com/en/products/umberto |
| US LCI Data | National Renewable Energy Lab | http://www.nrel.gov/lci |

**BEES 3.0.** Created by the National Institute for Standards and Technology (NIST) Building and Fire Research Laboratory, the BEES (Building for Environmental and Economic Sustainability) software can be used for balancing the environmental and economic performance of building products. Version 3.0 of the Windows™-based decision support software, aimed at designers, builders, and product

manufacturers, includes actual environmental and economic performance data for 200 building products. BEES 3.0 can be downloaded free of charge from the NIST website.

**Boustead Model 5.0.** Created by Boustead Consulting, the Boustead Model is an extensive database in which data such as fuels and energy use, raw materials requirements, and solid, liquid, and gaseous emissions are stored. It also includes software which enables the user to manipulate data in the database and to select a suitable data presentation method from a host of options.

**CMLCA 4.2.** Created by the Centre of Environmental Science (CML) at Leiden University, Chain Management by Life Cycle Assessment (CMLCA) is a software tool that is intended to support the technical steps of the LCA procedure. The program can be downloaded from the CML website.

**Dubo-Calc.** The Netherlands Ministry of Transport, Public Works, and Water Management has created a database containing LCI data of construction materials which are used in civil works. Data included are secondary data, derived from other databases, brought together in a set to use with their software for designers.

**Ecoinvent Database v1.2.** The ecoinvent data v1.2 comprises more than 2700 datasets with global/European/Swiss coverage. About 1000 elementary flows are reported for each dataset, including emissions to air, water, and soil, mineral and fossil resources, and land use. Several actual and widespread impact assessment methods, namely the cumulative energy demand, climate change, CML 2001, Eco-indicator 99, the ecological scarcity method 1997, EDIP 1997, EPS 2000, and Impact 2002+ are implemented. The ecoinvent data are available through EMIS, GaBi, Regis, SimaPro, and Umberto and are importable into CMLCA, KCL-eco, and TEAM.

**Eco-Quantum.** Eco-Quantum is a calculating tool on the basis of LCA which serves actors in the building sector with quantitative information on the environmental impact of buildings as a whole. The added value of Eco-Quantum in this context is the database with composition data of about 1000 building components. Eco-Quantum is available only in Dutch.

**EDIP PC-Tool.** Developed for the Danish EPA, the EDIP PC-Tool is a user friendly Windows application and database that supports the LCA process carried out according to the EDIP method. To carry out an LCA, detailed information on all the processes and materials included in the life cycle of the product is needed. Therefore, the tool has been equipped with a relational database, close in structure to the internationally recognized SPOLD format.

**eiolca.net.** Created by the Green Design Institute of Carnegie Mellon, this web site allows users to estimate the overall environmental impacts from producing a certain dollar amount of a commodity or service in the United States. The database first was made publicly available in 1999; since then two major and several minor updates have been conducted. The web-based model provides rough guidance on the relative impacts of different types of products, materials, services, or industries with respect to resource use and emissions. The latest version is based on the 1997 industry benchmark input-output accounts compiled by the Bureau of Economic Analysis of the U.S. Department of Commerce. It incorporates emissions and resource use factors estimated for all 491 sectors of the U.S economy, using publicly available electricity and fuel consumption data compiled by the U.S. Census Bureau, the U.S. Departments of Energy and Transportation, and environmental databases created by the U.S. EPA.

**Environmental Impact Indicator.** Developed by the Athena Institute, the Estimator was prepared for architects, engineers, and researchers to get LCA answers about conceptual designs of new buildings or renovations to existing buildings. The Estimator assesses the environmental implications of industrial, institutional, office, or both multi-unit and single-family residential designs. The Estimator incorporates the Institute’s inventory databases that cover more than 90 structural and envelope materials. Released in 2002, it simulates over 1,000 different assembly combinations and is capable of modeling 95 percent of the building stock in North America. Athena has also developed databases for energy use and related air emissions for on-site construction of building assemblies; maintenance, repair and replacement effects though the operating life; and, demolition and disposal.

**EPS 2000 Design System.** Created by Assess Ecostrategy Scandinavia AB, EPS (Environmental Priority Strategies) is a life cycle impact assessment software for sustainable product development. A demo version can be ordered from the website.

**GaBi 4 Software System and Database**. GaBi is supported jointly by PE Europe GmbH and IKP University of Stuttgart. Different versions are available from educational to professional use of Life Cycle Analysis to evaluate life cycle environmental, cost, and social profiles of products, processes and technologies. GaBi offers databases with worldwide coverage as well as Ecoinvent data. A demo version is available for download.

**GEMIS (Global Emission Model for Integrated Systems)**. The Öko-Institut’s GEMIS is a life cycle analysis program and database for energy, material, and transport systems. The GEMIS database offers information on fossil fuels, renewables, processes for electricity and heat, raw materials, and transports. The GEMIS database can be downloaded for free from the website.

**GREET 1.7.** The U.S. Department of Energy's Office of Transportation Technologies fuel-cycle model called GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) allows researchers to evaluate various engine and fuel combinations on a consistent fuel-cycle basis.

**IDEMAT 2005.** Created by Delft University of Technology, IDEMAT is a tool for material selections in the design process. It provides a database with technical information about materials, processes and components and allows the user to compare information. A demo version can be downloaded from the DTU website.

**KCL-ECO 4.0.** KCL-ECO can be used to apply LCA to complicated systems with many modules and flows. It includes allocation, impact assessment (characterization, normalization, and weighting), and graphing features. A demo version can be downloaded from the KCL website.

**LCAIT 4.1**. Offered by CIT Ekologik since 1992, LCAit has been used for the environmental assessment of products and processes. It includes an impact assessment database, including characterization factors and weighting factors. A demo version can be downloaded from the CIT website.

**LCAPIX**. Offered by KM Limited, the LCAPIX v1.1 software combines LCA and Activity Based Costing (ABC) to help businesses assure environmental compliance while assuring sustained profitability. It allows for a quantitative measurement which can indicate the potential burden of any product. A licensing fee is required, but a demo version can be downloaded from the KM Ltd. website.

**MIET 3.0. – Missing Inventory Estimation Tool.** Created by the Centre of Environmental Science (CML), MIET is a Microsoft Excel spreadsheet that enables LCA practitioners to estimate LCI of missing flows that were truncated. MIET is based on the most up-to-date U.S. input-output table and environmental data. MIET covers about 1,200 different environmental interventions including air, water, industrial and agricultural soil emissions, and resource use by various industrial sectors. MIET can be downloaded for free from the CML website after filling out a short questionnaire.

**REGIS.** Developed by Sinum AG, REGIS is a software tool for creating corporate ecobalances and improving corporate environmental performance according to ISO14031. A demo version can be downloaded from the Sinum website.

**SimaPro 6.0.** Created by PRé Consultants, SimaPro is a professional LCA software tool that contains several impact assessment methods and several inventory databases, which can be edited and expanded without limitation. It can compare and analyze complex products with complex life cycles. A demo version can be downloaded from the web site link provided above.

**SPINE@CPM.** Maintained by IMI, Industrial Environmental Informatics at Chalmers University of Technology, LCI@CPM is a web portal for LCI information. The portal provides the possibility to: search for specific LCI-data in the database; purchase LCI-data sets; and convert SPINE data sets into ISO/TS 14048 automatically. The database contains more than 500 data sets. SPINE@CPM is the ISO/TS 14048 version of the Swedish national database. Some of the data sets in the database are reported as full flow-charts where each included process or transport is separately stored in the database. The data published in LCI@CPM are reviewed in order to ensure that the quality requirements according to ISO/TS 14048 have been fulfilled.

**SPOLD Data Exchange Software.** The Society for Promotion of Life Cycle Development, a now defunct group, lives on in memory through this software that can be used to create, edit, import, and export data in the SPOLD '99 format. It can be downloaded from the 2.-0 LCA consultants website.

**TEAM™ 4.0**. Offered by Pricewaterhouse Coopers Ecobilan Group (also known as Ecobalance), TEAM™ 3.0 is a professional tool for evaluating the life cycle environmental and cost profiles of products and technologies. It contains comprehensive database of over 600 modules with worldwide coverage. An online demo is available from the website.

**Umberto.** Created by the Institute for Environmental Informatics (ifeu) in Hamburg, Germany, Umberto serves to visualize material and energy flow systems. Data are taken from external information systems or are newly modeled and calculated.

**US LCI Data.** In May 2001, NREL and its partners created the U.S. Life-Cycle Inventory (LCI) Database to provide support to public, private, and non-profit sector efforts in developing product life cycle assessments and environmentally-oriented decision support systems and tools. The objective of the U.S. LCI Database Project is to provide LCI data for commonly used materials, products and processes following a single data development protocol consistent with international standards. Since the goal is to make the creation of LCIs easier, rather than to carry out full product LCIs, database modules provide data on many of the processes needed by others for conducting LCIs. However, the modules do not contain data characterizing the full life cycles of specific products. The data protocol is based on ISO 14048 and is compatible with the EcoSpold format. The LCI data are available in several formats: a streamlined spreadsheet, an EcoSpold format spreadsheet, an EcoSpold XML file, and a detailed spreadsheet with all the calculation details.

# Glossary

| | |
|---|---|
| **Accidental Emission** | An unintended environmental release. |
| **Allocation** | Partitioning the input or output flows of a unit process to the product of interest. |
| **Attributional LCA** | An LCA that accounts for flows/impacts of pollutants, resources, and exchanges among processes within a chosen temporal window. |
| **Background Data** | The background data include energy and materials that are delivered to the foreground system as aggregated data sets in which individual plants and operations are not identified. |
| **Brines (oilfield)** | Wastewater produced along with crude oil and natural gas from oilfield operations. |
| **By-Products** | an incidental product deriving from a manufacturing process or chemical reaction, and not the primary product or service being produced. A by-product can be useful and marketable, or it can have negative ecological consequences. |
| **Characterization** | Characterization is the second step of an impact assessment and characterizes the magnitude of the potential impacts of each inventory flow to its corresponding environmental impact. |
| **Characterization Factor** | Factor derived from a characterization model which is applied to convert the assigned LCI results to the common unit of the category indicator. |
| **Classification** | Classification if the first step of an impact assessment and is the process of assigning inventory outputs into specific environmental impact categories. |
| **Composite Data** | Data from multiple facilities performing the same operation that have been combined or averaged in some manner. |
| **Consequential LCA** | An LCA that attempts to account for flows/impacts that are caused beyond the immediate system in response to a change to the system. |
| **Co-Product** | A product produced together with another product. |
| **Environmental Aspects** | Elements of a business’ products, actions, or activities that may interact with the environment. |
| **Environmental Loadings** | Releases of pollutants to the environment, such as atmospheric and waterborne emissions and solid wastes. |

| | |
|---|---|
| **Equivalency Factor** | An indicator of the potential of each chemical to impact the given environmental impact category in comparison to the reference chemical used. |
| **Equivalent Usage Ratio** | A basis for comparing two or more products that fulfill the same function. For example, comparing two containers based on a set volume of beverage to be delivered to the customer. |
| **Facility-Specific Data** | Data from a particular operation within a given facility that are not combined in any way. |
| **Foreground Data** | Data from the foreground system that is the system of primary concern to the analyst. |
| **Fuel P&D** | Activities involved in the processing and delivery of fuel used to run a process; also called Precombustion Energy. |
| **Functional Unit** | The unit of comparison that assures that the products being compared provide an equivalent level of function or service. |
| **Green Technology** | A technology that offers a more environmentally benign approach compared to an existing technology. |
| **Impact Assessment** | The assessment of the environmental consequences of energy and natural resource consumption and waste releases associated with an actual or proposed action. |
| **Impact Categories** | Classifications of human health and environmental effects caused by a product throughout its life cycle. |
| **Impact Indicators** | Impact indicators measure the potential for an impact to occur rather than directly quantifying the actual impact. |
| **Industrial System** | A collection of operations that together perform some defined function. |
| **Inventory Analysis** | The identification and quantification of energy, resource usage, and environmental emissions for a particular product, process, or activity. |
| **Interpretation** | The evaluation of the results of the inventory analysis and impact assessment to reduce environmental releases and resource use with a clear understanding of the uncertainty and the assumptions used to generate the results. |
| **Life Cycle Assessment** | A cradle-to-grave approach for assessing industrial systems that evaluates all stages of a product's life. It provides a comprehensive view of the environmental aspects of the product or process. |
| **Material P&D** | Activities involved in the processing and delivery of materials to a process. |

| | |
|---|---|
| **Normalization** | Normalization is a technique for changing impact indicator values with differing units into a common, unitless format by dividing the value(s) by a selected reference quantity. This process increases the comparability of data among various impact categories. |
| **Precombustion Energy** | The extraction, transportation, and processing of fuels used for power generation, including adjusting for inefficiencies in power generation and transmission losses. |
| **Product Life Cycle** | The life cycle of a product system begins with the acquisition of raw materials and includes bulk material processing, engineered materials production, manufacture and assembly, use, retirement, and disposal of residuals produced in each stage. |
| **Routine emissions** | Those releases that normally occur from a process, as opposed to accidental releases that proceed from abnormal process conditions. |
| **Sensitivity Analysis** | A systematic evaluation process for describing the effect of variations of inputs to a system on the output. |
| **Specific data** | Data that are characteristic of a particular subsystem, or process. |
| **Stressors** | A set of conditions that may lead to an environmental impact. For example, an increase in greenhouse gases may lead to global warming. |
| **System Flow Diagram** | A depiction of the inputs and outputs of a system and how they are connected. |
| **Weighting** | The act of assigning subjective, value-based weighting factors to the different impact categories based on their perceived importance or relevance. |