LCA 101 - INTRODUCTION TO LCA

The following document provides an introductory overview of Life Cycle Assessment (LCA). The uses of and major components of LCA are discussed. 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 into their decision-making processes.

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Chapter 1 - What is Life Cycle Assessment?

What is Life Cycle Assessment (LCA)?

As environmental awareness increases, industries and businesses have started to assess 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 called life cycle assessment (LCA). This concept considers the entire life cycle of a product.

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 selection.

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 you make a more informed decision.

LCA is a technique for assessing all the inputs and outputs of a product, process, or service (Life Cycle Inventory); assessing the associated wastes, human health and ecological burdens (Impact Assessment); and interpreting and communicating the results of the assessment (Life Cycle Interpretation) throughout the life cycle of the products or processes under review. The term "life cycle" refers to the major activities in the course of the product's life-span from its manufacture, use, maintenance, and 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.

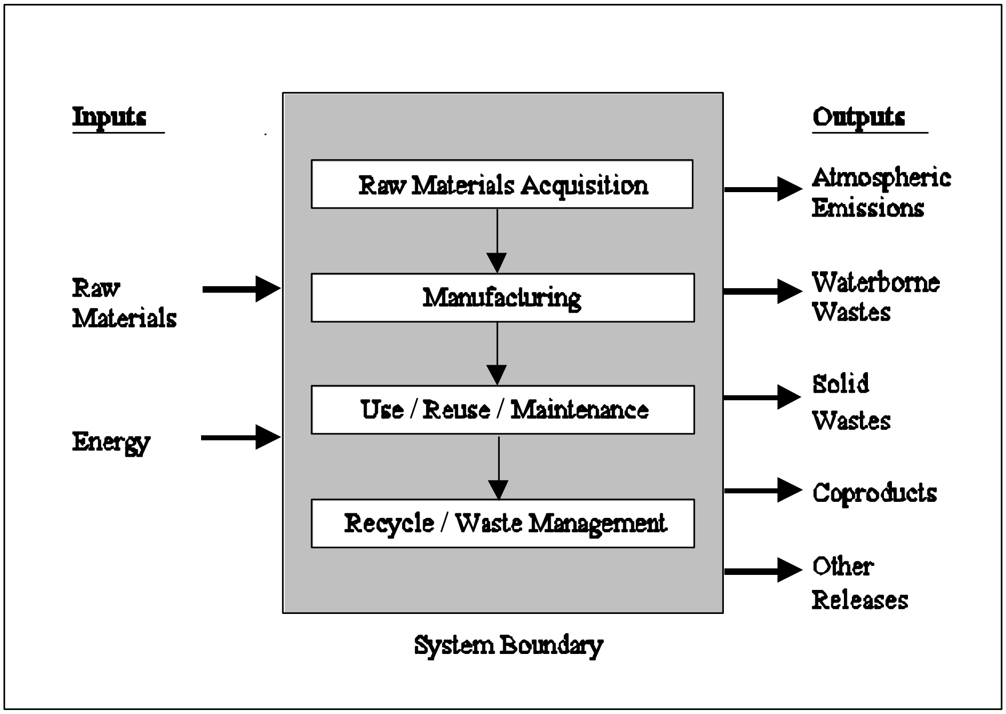

Exhibit 1-1. Life Cycle Stages (Source: EPA, 1993)

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, wastewater discharge).

3. *Impact Assessment* - Assess the 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.

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 alternatives, LCA can help decision-makers compare all major environmental impacts caused by both products, processes, or services.

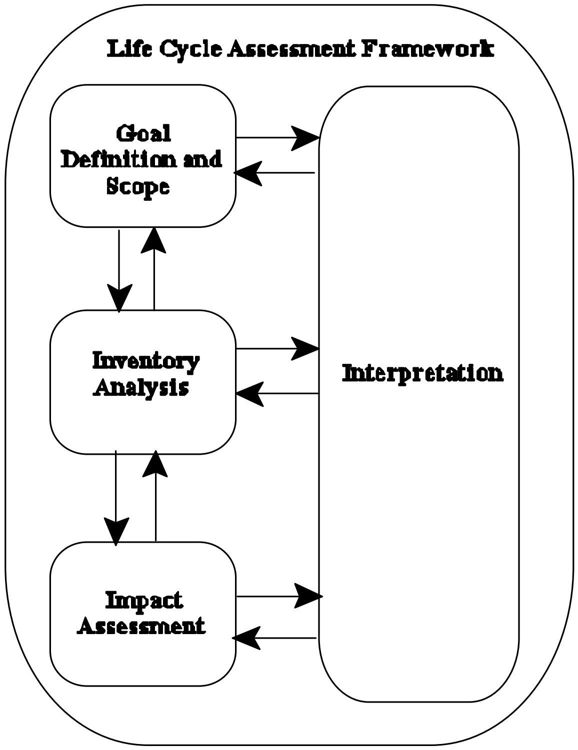

Exhibit 1-2. Phases of an LCA (Source: ISO, 1997)

What Are the Benefits of Conducting an LCA?

An LCA will 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 was 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.

> 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 actually produce 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, researchers 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.

Limitations of Conducting an LCA

Performing an LCA can be resource and time intensive. Depending upon how thorough an LCA the users wish 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.

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 How the Data Should Be Organized and the Results Displayed
4. Determine What Will or Will Not Be Included in the LCA
5. Determine the Required Accuracy of Data
6. Determine Ground Rules for Performing the Work

Each decision and its associated impact on the LCA process is 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. There may also be secondary goals for performing an LCA, which would vary depending on the type of project.

Examples of Secondary Goals:

- To prove one product is environmentally superior to a competitive product.
- To identify stages within the life cycle of a product or process where a reduction in resource use and emissions might be achieved.
- To determine the impacts to particular stakeholders or affected parties.
- To establish a baseline of information on a system's overall resource use, energy consumption, and environmental loadings.
- To help guide the development of new products, processes, or 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.

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/process being studied. Comparisons between products/processes must be made on the basis of the same function, quantified by the same functional unit. This ensures that the products/processes being compared are true substitutes for each other. 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.

> 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 4-inch thick insulation Type A is not necessarily the same as six square feet of 4-inch thick insulation Type B. Insulation type A may have an R factor equal to 10, 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%, you must determine how thick Type B must be to also decrease heat flow by 80%.

Determine What Will or Will Not Be Included in the LCA

As Chapter 1 explained, an inventory analysis identifies and quantifies the environmental releases of a product or process throughout its entire life cycle. Ideally, 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.

The four life cycle stages are explained in more detail below.

<u>Raw Materials Acquisition</u>

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 (EPA 1993).

<u>Manufacturing</u>

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 (EPA 1993).

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 (EPA 1993). 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 (EPA 1993).

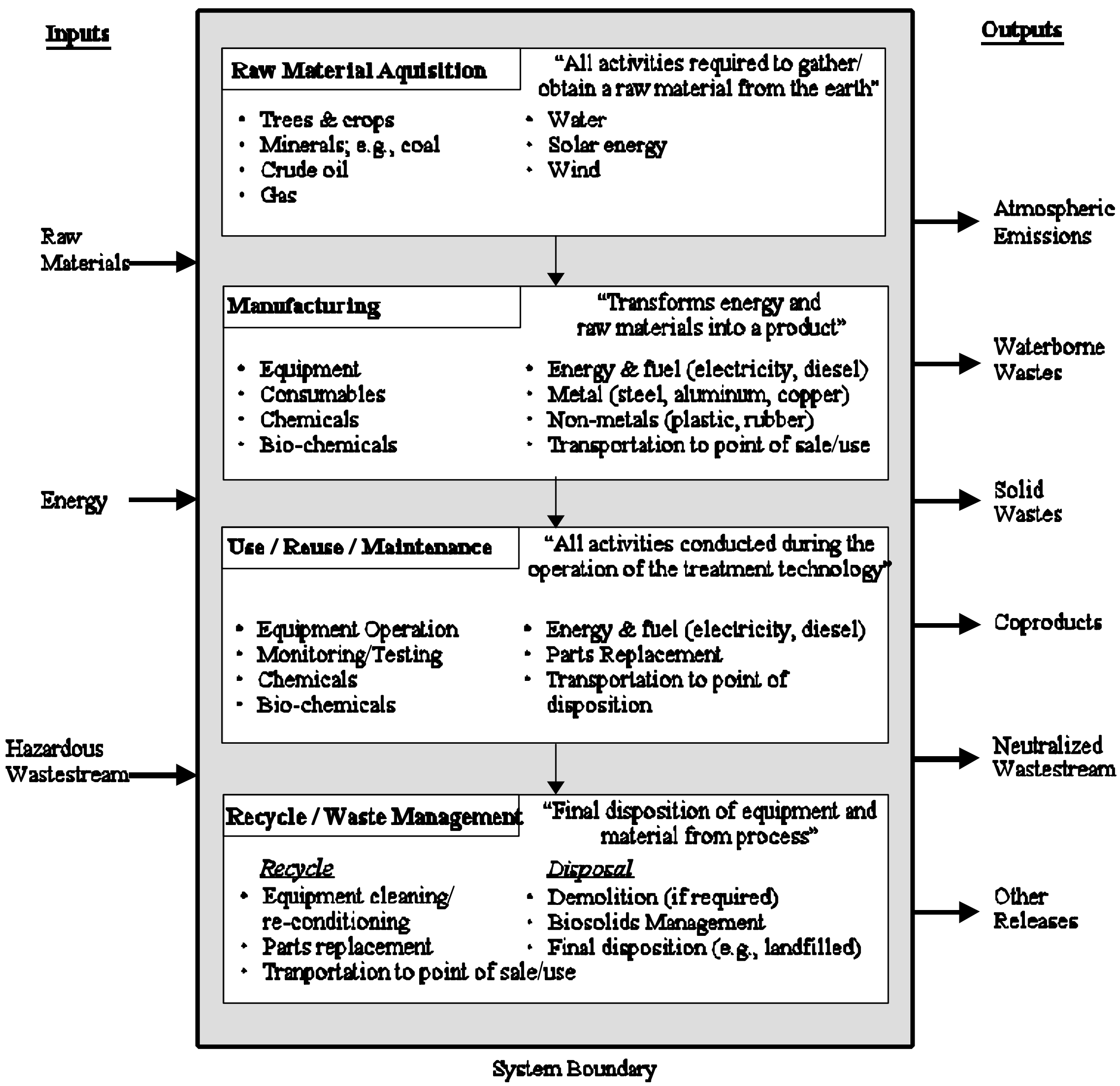

Exhibit 2-1. Sample Life Cycle Stages for a Treatment Project

Determine the Required Accuracy of Data

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 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 judgement 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 judgement 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.

Determine 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 (EPA 1993).

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, by media (air, water, land), by specific processes, or any combination thereof.

Key Steps of a Life Cycle Inventory
In 1993, EPA published a guidance document entitled *Life-Cycle Assessment: Inventory Guidelines and Principles.* In 1995, EPA published *Guidelines for Assessing the Quality of Life-Cycle Inventory Analysis*. The combination of these two guidance documents provides the framework for performing an inventory analysis and assessing the quality of the data used and the results. The two documents define the following steps of a life cycle inventory:

- develop a flow diagram of the processes being evaluated
- develop a data collection plan
- collect data
- evaluate and report results

Each step is summarized below.

<u>Step 1: Develop a Flow Diagram</u>
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.

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.

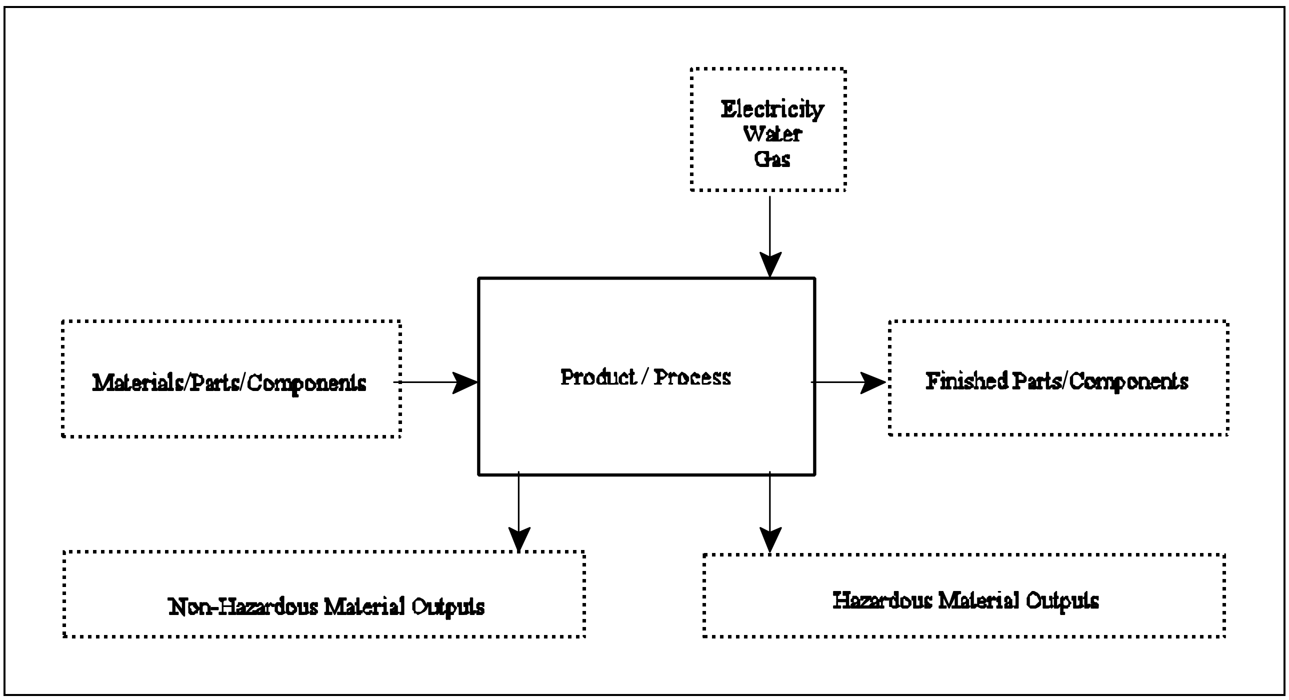

Exhibit 3-1. Unit Process Input/Output Template

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, and
- 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; and
- 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 necessarily depends on the level of accuracy required to inform the decision-makers involved in the process.

> 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% 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 judgement.

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 a 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.

Develop a Data Collection Worksheet and Checklist - The next step is to develop a life cycle inventory checklist that covers most of the decision areas in the performance of an inventory (*see Appendix A*). A checklist 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 on the inventory checklist:

- purpose of the inventory
- system boundaries
- geographic scope
- types of data used
- data collection procedures
- data quality measures
- computational model construction
- presentation of results.

An accompanying data worksheet (*see Appendix A*) should be used to record the inputs and outputs for each process modeled in the flow diagram.

The checklist and worksheet are valuable tools for ensuring completeness, accuracy, and consistency. They are especially important for large projects when several people collect data from multiple sources. The checklist and worksheet should be tailored to meet the needs of a specific LCI.

<u>Step 3: Collect Data</u>

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.

Data collection efforts involve a combination of research, site-visits and direct contact with experts which generate large quantities of data. An electronic database or spreadsheet can be useful to hold and manipulate the data. As an alternative to developing a computer model from scratch, 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.

<u>Step 4: Evaluate and Document the LCI Results</u>
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.

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 regards to data accuracy prior to conducting the life cycle impact assessment (LCIA) saves time and resources. Otherwise, the LCIA 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 checklist and 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, by media (air, water, land), by 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 life cycle inventory

(LCI). Impact assessment should address ecological and human health effects; it can 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?

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 precise basis to make comparisons. For example, although we know that 9,000 tons of CO_2 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. An impact assessment can also incorporate value judgements. In an air non-attainment zone, for example, air emissions could be of relatively higher concern than the same emission level in a region with better air quality.

What Do the Results of an LCIA Mean?

The results of an LCIA provide a checklist showing the relative differences in potential environmental impacts for each option. For example, an LCIA could determine which product/process causes more greenhouse gases, or could potentially kill more fish.

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 CO_2 emissions to global warming).
3. *Characterization* - modeling LCI impacts within impact categories using science-based conversion factors. (e.g., modeling the potential impact of CO_2 and methane on global warming).
4. *Normalization* - expressing potential impacts in ways that can be compared (e.g. comparing the global warming impact of CO_2 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.

The International Organization of Standardization (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 fishkills in a local lake.

For an LCIA, impacts are defined as the consequences 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.

Exhibit 4-1. Commonly Used Life Cycle Impact Categories

Impact Category	Scale	Relevant LCI Data (i.e., classification)	Common Characterization Factor	Description of Characterization Factor
Global Warming	Global	Carbon Dioxide (CO_2) Nitrogen Dioxide (NO_2) Methane (CH_4) Chlorofluorocarbons (CFCs) Hydrochlorofluorocarbons (HCFCs) Methyl Bromide (CH_3Br)	Global Warming Potential	Converts LCI data to carbon dioxide (CO_2) equivalents Note: global warming potentials can be 50, 100, or 500 year potentials.
Stratospheric Ozone Depletion	Global	Chlorofluorocarbons (CFCs) Hydrochlorofluorocarbons (HCFCs) Halons Methyl Bromide (CH_3Br)	Ozone Depleting Potential	Converts LCI data to trichlorofluoromethane (CFC-11) equivalents.
Acidification	Regional Local	Sulfur Oxides (SOx) Nitrogen Oxides (NOx) Hydrochloric Acid (HCL) Hydroflouric Acid (HF) Ammonia (NH_4)	Acidification Potential	Converts LCI data to hydrogen (H+) ion equivalents.
Eutrophication	Local	Phosphate (PO_4) Nitrogen Oxide (NO) Nitrogen Dioxide (NO_2) Nitrates Ammonia (NH_4)	Eutrophication Potential	Converts LCI data to phosphate (PO_4) equivalents.

Impact Category	**Scale**	**Relevant LCI Data (i.e., classification)**	**Common Characterization Factor**	**Description of Characterization Factor**
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.
Aquatic Toxicity	Local	Toxic chemicals with a reported lethal concentration to fish	LC_{50}	Converts LC_{50} data to equivalents.
Human Health	Global Regional Local	Total releases to air, water, and soil.	LC_{50}	Converts LC_{50} data to equivalents.
Resource Depletion	Global Regional Local	Quantity of minerals used 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 Regional Local	Quantity disposed of in a landfill	Solid Waste	Converts mass of solid waste into volume using an estimated density.

<u>Step 2: Classification</u>

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 (CO_2) 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):

- Allocate 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 one SO_2 molecule could stay at ground level or travel up into the atmosphere, it can affect either human health or acidification (but not both at the same time). Therefore, SO_2 emissions would typically be divided between those two impact categories (e.g. 50% allocated to human health and 50% allocated to acidification). On the other hand, since nitrogen dioxide (NO_2) could potentially affect both ground level ozone formation and acidification (at the same time), the entire quantity of NO_2 would be allocated to both impact categories (e.g., 100% to ground level ozone and 100% to acidification). The allocation procedure must be clearly documented.

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

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 ociean 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.
Land Use - loss of terrestrial habitat for wildlife and decreased landfill space.

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 carbon dioxide (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 of Global Warming Impacts

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

GWP = Global Warming Potential
*Intergovernmental Panel on Climate Change (IPCC) Model

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 10 pounds of methane have a larger impact on global warming than 20 pounds of chloroform.

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.

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 judgement of preferability is a subjective judgement regarding the relative importance of one impact category over another. Additionally, these value judgements 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, WY. 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 (AHP), the Modified Delphi Technique, and Decision Analysis Using Multi-Attribute Theory (MAUT).

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. When documenting the results of the life cycle impact assessment, thoroughly describe the methodology used in the analysis and all assumptions made in performing the LCIA.

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.

Some of the key limitations 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 5 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 life cycle inventory (LCI) and the life cycle impact assessment (LCIA), and communicate them effectively. Life cycle interpretation is the last phase of the LCA process.

The International Organization for Standardization (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 2 is better then 3, 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's draft standard entitled "*Environmental Management - Life Cycle Assessment - Life Cycle Interpretation*," ISO/DIS 14043 (ISO 1998b). Within the ISO draft standard the following steps to conducting a life cycle interpretation are identified and discussed:

1. Identify Significant Issues
2. Evaluate the Completeness, Sensitivity, and Consistency of the Data

3. Draw Conclusions and Recommendations

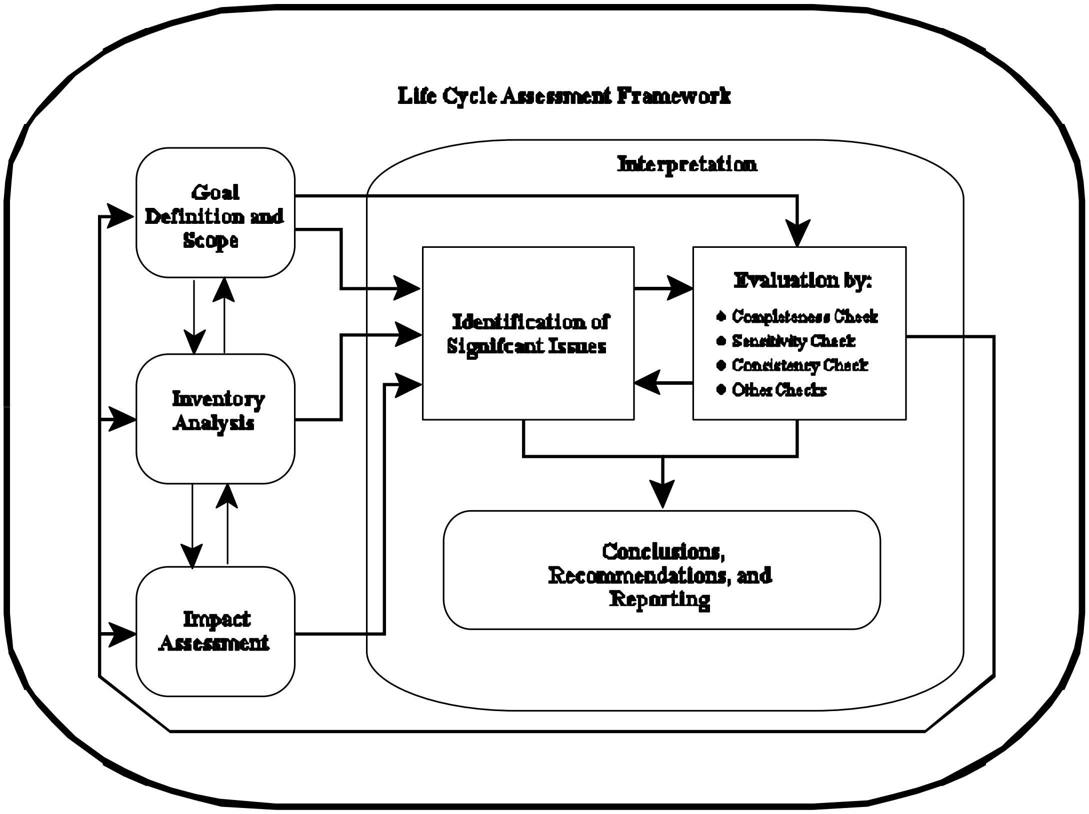

Exhibit 5-1. Relationship of Interpretation Steps with other Phases of LCA (Source: ISO, 1998b)

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.

<u>Step 1: Identify Significant Issues</u>
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, and 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).

<u>Step 2: Evaluate the Completeness, Sensitivity, and Consistency of the Data</u>
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% 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. Gravity 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 gravity, 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 gravity 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 (percent uncertainty) or qualitatively (Alternative A's reported result may be higher or lower because the uncertainty in "X" is greater than recommended in the goal and scope of the study).

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.

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.

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.

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.

In the latter case, the recommendation may simply be to accept the product/process with the lowest 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, 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

Conclusion

Adding life cycle assessment to the decision-making process provides an understanding of the human health and environmental impacts that is not considered traditionally 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.

Glossary

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.

Classification Classification if the first step of an impact assessment and is the process of assigning inventory outputs into specific environmental impact categories.

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.

Facility-specific data Data from a particular operation within a given facility that are not combined in any way.

Functional unit The unit of comparison that assures that the products being compared provide an equivalent level of function or service.

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.

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.

Life cycle inventory The identification and quantification of energy, resource usage, and environmental emissions for a particular product, process, or activity.

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.

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.

Sensitivity analysis A systematic evaluation process for describing the effect of variations of inputs to a system on the output.

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.

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Appendix A

Sample Inventory Checklist and Worksheet

LIFE-CYCLE INVENTORY CHECKLIST PART I–SCOPE AND PROCEDURES
INVENTORY OF:________________________________

Purpose of Inventory: (check all that apply)

Private Sector Use

Internal Evaluation and Decision Making

- 9 Comparison of Materials, Products, or Activities
- 9 Resource Use and Release Comparison with Other Manufacturer's Data
- 9 Personnel Training for Product and Process Design
- 9 Baseline Information for Full LCA

External Evaluation and Decision Making

- 9 Provide Information on Resource Use and Releases
- 9 Substantiate Statements of Reductions in Resource Use and Releases

Public Sector Use

Evaluation and Policy-making

- 9 Support Information for Policy and Regulatory Evaluation
- 9 Information Gap Identification
- 9 Help Evaluate Statements of Reductions in Resource Use and Releases

Public Education

- 9 Develop Support Materials for Public Education
- 9 Assist in Curriculum Design

Systems Analyzed

List the product/process systems analyzed in this inventory: ________________________________

____

Key Assumptions: (list and describe)

____

____

____

Define the Boundaries

For each system analyzed, define the boundaries by life-cycle stage, geographic scope, primary processes, and ancillary inputs included in the system boundaries.

Post Consumer Solid Waste Management Options: Mark and describe the options analyzed for each system.

- 9 Landfill ________________________
- 9 Combustion ________________________
- 9 Composting ________________________
- 9 Open-loop Recycling ________________________
- 9 Closed-loop Recycling ________________________
- 9 Other ________________________

Basis for Comparison

- 9 This is not a comparative study
- 9 This is a comparative study.

State basis for comparison between systems: (Example: 1000 units, 1,000 uses) ________________________

____

If products or processes are not normally used on a one-to-one basis, state how equivalent function was established.

____

Computational Model Construction

- 9 System calculations are made using computer spreadsheets that relate each system component to the total system.
- 9 System calculations are made using another technique. Describe: ________________________

____

Describe how inputs to and outputs from postconsumer solid waste management are handled. ________________________

____

____

Quality Assurance: (state specific activities and initials of reviewer)

Review performed on:

- 9 Data Gathering Techniques ________________
- 9 Coproduct Allocation ________________
- 9 Input Data ________________
- 9 Model Calculations and Formulas ________________
- 9 Results and Reporting ________________

Peer Review: (state specific activities and initials of reviewer)

Review performed on:

- 9 Scope and Boundary ________________
- 9 Data Gathering Techniques ________________
- 9 Coproduct Allocation ________________
- 9 Input Data ________________
- 9 Model Calculations and Formulas ________________
- 9 Results and Reporting ________________

Results Presentation

- 9 Methodology is fully described.
- 9 Individual pollutants are reported.
- 9 Emissions are reported as aggregated totals only.
  Explain why: ______________________________
  ____
- 9 Report is sufficiently detailed for its defined purpose.
- 9 Report may need more detail for additional use beyond defined purpose.
- 9 Sensitivity analyses are included in this report.
  List: ______________________________
- 9 Sensitivity analyses have been performed but are not included in the report. List: ______________________________
  ____

LIFE-CYCLE INVENTORY CHECKLIST PART II–MODULE WORKSHEET

Inventory of: ____________________ Preparer: ____________________
Life-Cycle Stage Description: ____________________
Date: ____________________ Quality Assurance Approval: ____________________
MODULE DESCRIPTION: ____________________

	Data Value [a]	Type [b]	Data [c] Age/Scope	Quality Measures [d]
MODULE INPUTS				
Materials				
Process				
Other [e]				
Energy				
Process				
Precombustion				
Water Usage				
Process				
Fuel-related				
MODULE OUTPUTS				
Product				
Coproducts [f]				
Air Emissions				
Process				
Fuel-related				
Water Effluents				
Process				
Fuel-related				
Solid Waste				
Process				
Fuel-related				
Capital Repl.				
Transportation				
Personnel				

a. Include units.

b. Indicate whether data are actual measures, engineering estimates, or theoretical or published values and whether the numbers are from a specific manufacturer or facility, or whether they represent industry-average values. List a specific source if pertinent, e.g., “obtained from Atlanta facility wastewater permit monitoring data.”

c. Indicates whether emissions are all available, regulated only, or selected. Designate data as to geographic specificity, e.g., North America, and indicate the period covered, e.g., average of monthly for 1991.

d. List measures of data quality available for the data item, e.g., accuracy, precision, representativeness, consistency-checked, other, or none.

e. Include nontraditional inputs, e.g., land use, when appropriate and necessary.

f. If coproduct allocation method was applied, indicate basis in quality measures column, e.g., weight.

Appendix B

LCA and LCI Software Tools

Name	Vendor	URL
1. ECO-it 1.0	PRé Consulting	http://www.pre.nl/eco-it.html
2. EcoManager 1.0	Franklin Associates, Ltd.	http://www.fal.com/software/ecoman.html
3. EcoPro 1.5	EMPA	http://www.sinum.com/
4. GaBi 3.0	IPTS	http://www.pe-product.de/englisch/main/software.htm
5. IDEMAT	Delft Univ. of Technology	http://www.io.tudelft.nl/research/mpo/idemat/idemat.htm
6. LCAD	Battelle/DOE	http://www.estd.battelle.org/sehsm/lca/LCAdvantage.html
7. LCAiT 2.0	CIT EkoLogik	http://www.ekologik.cit.chalmers.se/lcait.htm
8. REPAQ 2.0	Franklin Associates, Ltd.	http://www.fal.com/software/repaq.html
9. SimaPro 4	PRé Consulting	http://www.pre.nl/simapro.html
10. TEAM 2.0	Ecobalance	http://www.ecobalance.com/software/team/team_ovr.htm
11. Umberto 3.0	IFEU	http://www.ifu.com/software/umberto-e/

1. ECO-it 1.0 – PRé Consulting

ECO-it is a database tool used to assist an LCI and LCIA. ECO-it comes with over 100 indicator values for commonly used materials such as metals, plastics, paper, board and glass, as well as production, transport, energy and waste treatment processes.

2. EcoManager™ – Franklin Associates, Ltd

EcoManager ™ is life cycle inventory tool designed to be used as an internal planning, screening, and evaluation tool. The software is designed for use by persons who have or who gain a working knowledge of the LCI methodology.

EcoManager™ uses a software program developed by Pira International of the U.K., in combination with U.S. life cycle inventory data from the Franklin Associates, Ltd. (FAL) database. Developed for use with Microsoft Excel™, EcoManager™ utilizes spreadsheets and program codes called "macros" to guide the user through the construction of a life cycle inventory, access data from the databases, perform file management functions, edit existing and produce graphics and reports. The system provides on-line help at every stage of operation. The system also provides graphic and report features. And because the program has been created in Excel™, all of the power of Excel™ for graphics, exporting, and file management is available for customized outputs.

3. EcoPro1.5 – EMPA

EcoPro is a life-cycle-assessment (LCA) tool. It models product life cycles with flow chart diagrams. EcoPro is a Windows-based application with an online help, a toolbar and icons and includes a large database is included.

4. GaBi – IPTS

GaBi is a Life Cycle Engineering or Life Cycle Assessment tool that uses many predefined data objects from industry and literature. Users can link data sets supplied with the GaBi database to own data in order to calculate both Life Cycle

Inventories and Impact Assessments. It allows clear weak point analyses of inventories and valuated balances. The structure is open to alterations and extensions.

5. IDEMAT – Delft Univ. of Technology

Idemat is a computer database of over 365 materials developed by the Environmental Product Development of the faculty of Industrial Design Engineering at the Delft University of Technology. It provides technical information about materials and processes in words, numbers and graphics, and puts emphasis on environmental information. The program has been developed to be used by students of technically oriented academic disciplines like Industrial Design Engineering, Civil Engineering, Material Science and Aerospace Engineering. For satisfactory use the user must be quite familiar with the principles of Life Cycle Assessment and the methods for characterization and evaluation of the environmental impacts as published by SETAC and CML and used in Simapro.

6. LCAD – Battelle/DOE

Life-Cycle Advantage(TM) is a life cycle modeling tool that has a graphical user interface and database structure. LCAD can model process flow diagrams with material and energy balances, and labor and revenue inputs. LCAD also can assess the data reliability. The LCAD system includes a basic commodity database for the U.S. covering fuels production and distribution, power generation, and cradle-to-gate operations for selected forest products, paper, metals, cement, and basic chemicals and plastics.

7. LCAiT – CIT EkoLogik

LCAiT is a life cycle inventory tool that aids in generating an energy and materials balance. LCAiT also contains a cradle-to-gate information regarding certain materials.

8. REPAQ – Franklin Associates, Ltd.

REPAQ™ is a life cycle inventory (LCI) software program. These studies examine energy and environmental emissions for the entire life cycle of a product, beginning with raw material extraction, and continuing through refining and processing, material manufacture, product fabrication, and disposal. Products, processes and packaging can be evaluated with REPAQ™. Users may use the REPAQ™ database and enter their own data through the Custom Materials feature. This feature allows entry of data for any process for which LCI data can be gathered.

9. SimaPro 4 – PRé Consulting

SimaPro™ is a full-featured LCA software tool. Complex products with complex life cycles can be compared and analyzed. The process databases and the impact assessment databases can be edited and expanded without limitation. SimaPro™ can trace the origin of any result has been implemented. Special features include: multiple impact assessment methods, multiple process databases, automatic unit conversion. SimaPro™ comes with several well known impact assessment methods, like CML 1992 and 1996, Eco-points and the Eco-indicator 95 method developed by PRé. All impact assessment data can be edited and expanded.

10. TEAM – Ecobalance

TEAM™ is a life cycle assessment software program that TEAM™ allows the user to build and use a database and model any system representing the operations associated with products, processes and activities (waste management options, means of transportation, etc.). It is designed to describe and model complex industrial systems and to calculate the associated life cycle inventories, life cycle potential environmental impacts, and process-oriented life cycle costs.

11. Umberto 3.0 – IFEU

Umberto is a life cycle assessment tool that uses a graphical interface to model material flow networks to enter and track material and energy flows. Umberto also has a valuation system editor to assist with impact assessment.