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.

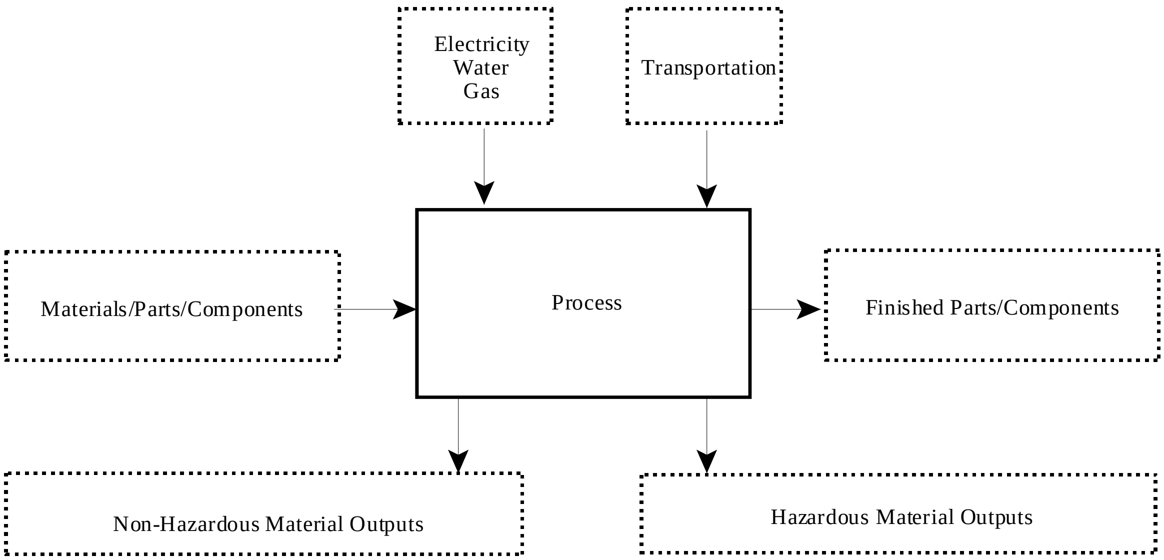
Key Steps of a Life Cycle Inventory
EPA's 1993 document, "Life-Cycle Assessment: Inventory Guidelines and Principles," and 1995 document, "Guidelines for Assessing the Quality of Life Cycle Inventory Analysis," provide the framework for performing an inventory analysis and assessing the quality of the 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.

<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.

Exhibit 3-1. Generic Unit Process



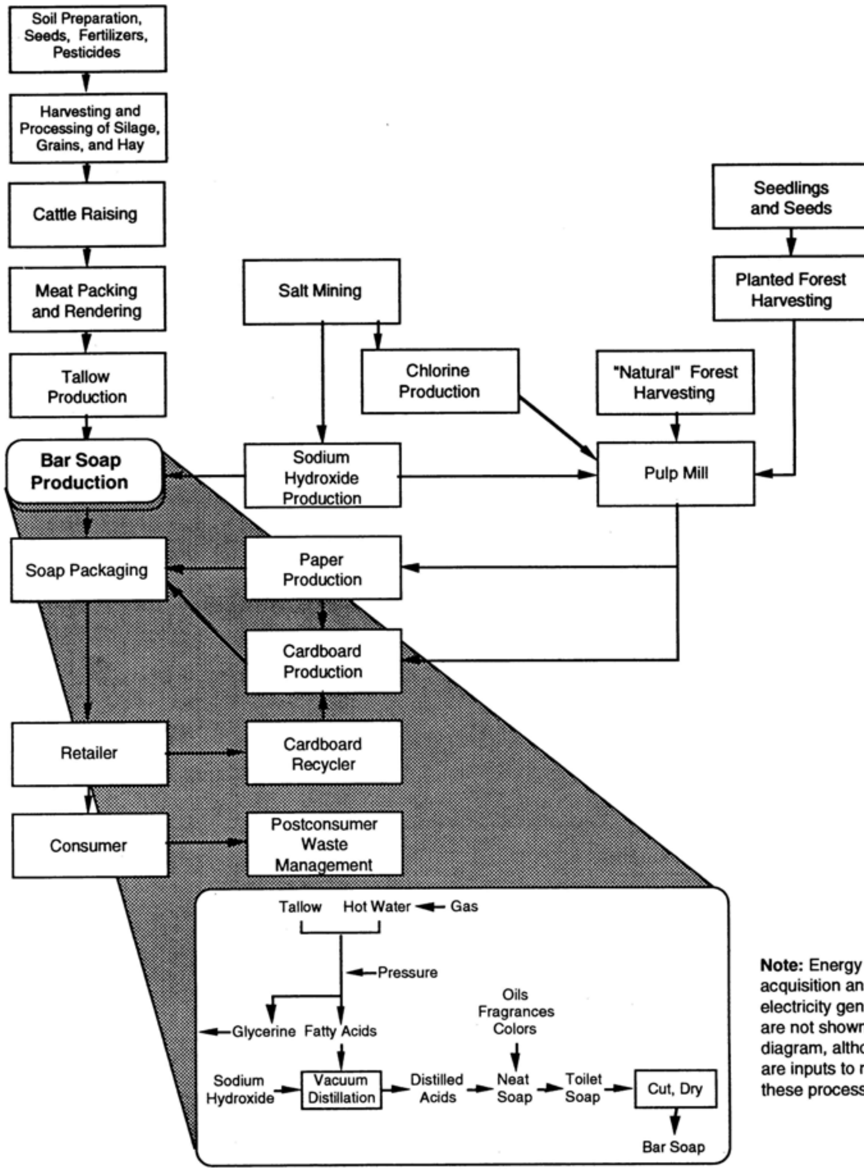
The more complex the flow diagram, the greater the accuracy and utility of the results. Unfortunately, increased complexity also means more time and resources must be devoted to this step, as well as the data collecting and analyzing steps.

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 $\pm$ 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.

<u>Products</u>
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.

<u>Transportation</u>
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.

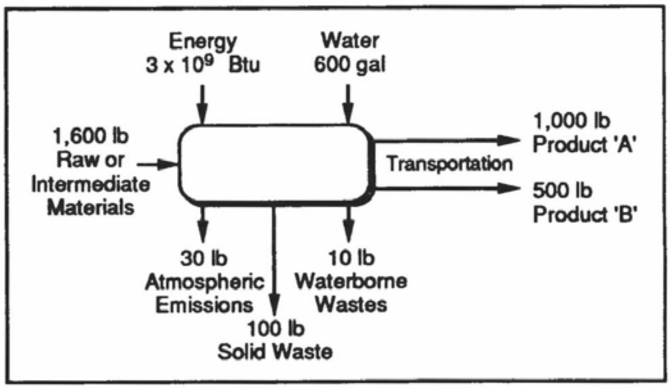
Backhauling may be a situation where there is some overlap between the transportation associated with product distribution and the transportation associated with recycling of the product or a different product after consumer use. A backhaul has been described as occurring when a truck or rail carrier 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

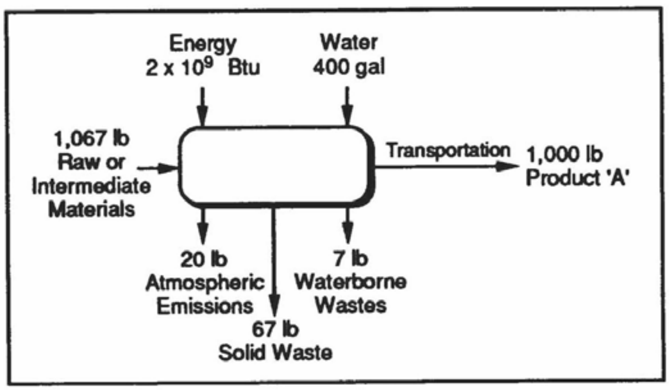
Most industrial processes are physical and/or chemical processes. The fundamentals of life-cycle inventory are based on modeling a system in such a way that calculated values reasonably represent actual (measurable) occurrences. Some processes generate multiple output streams in addition to waste streams. 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)

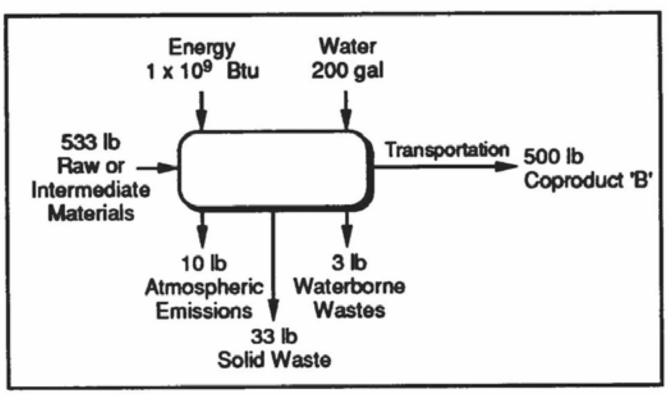
Co-Product Allocation for Product "A" and Product "B"



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.

<u>Industrial Scrap</u>

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.