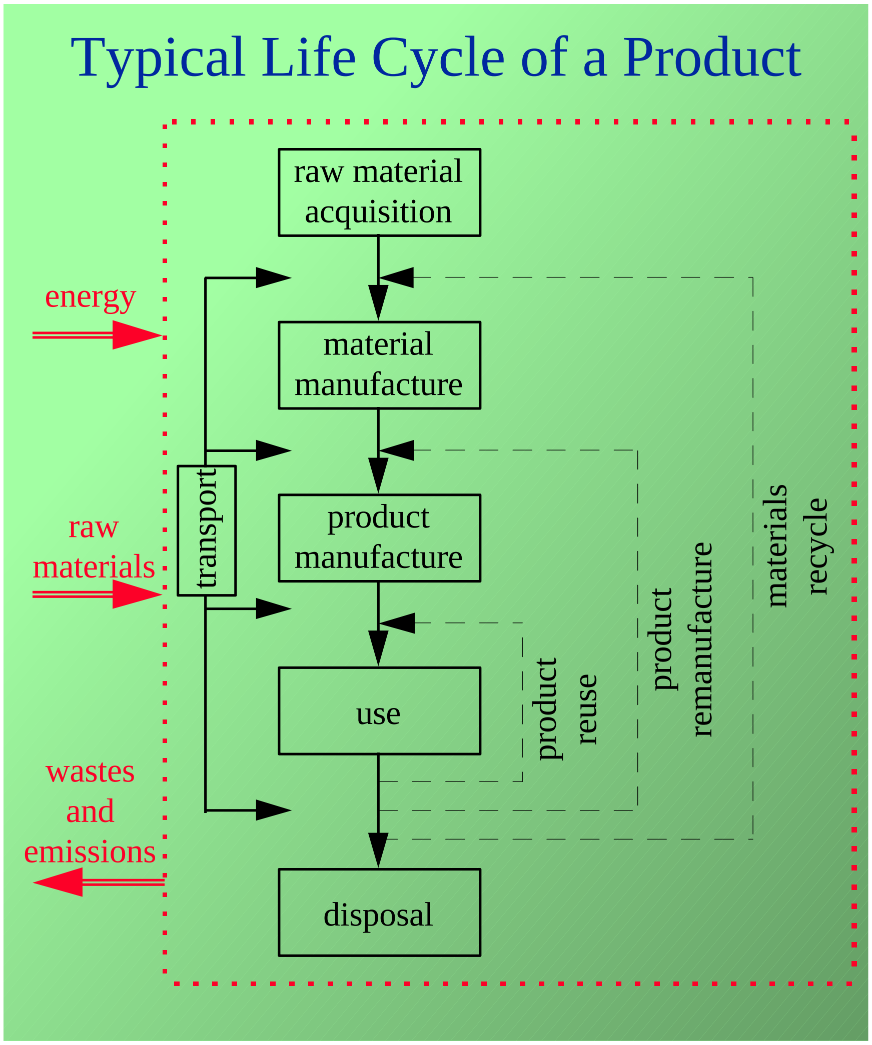
Life-Cycle Assessment
Lesson 2

Life-Cycle Inventories

This begins the second lesson on life-cycle assessment: a deeper look at life-cycle inventories.

A life-cycle inventory consists of data collection and calculations to quantify the inputs and outputs of a product life-cycle. This inventory is the heart of the LCA method.



This is the same life-cycle framework that was shown in Lesson 1. Remember that besides the manufacturing stages, the life cycle of a product includes distribution, use, and final disposal. The raw-material acquisition life-cycle stage would include such activities as mining, crude oil extraction, and timber harvesting. Examples of material manufacture are the production of pigments from minerals or the production of plastics and solvents from petroleum feedstocks. Product manufacture includes activities like turning steel into car bodies, or pigments and solvents into paints. Product use emissions, such as those from car exhaust during driving or electricity consumption during use of a power tool, are included in a life-cycle inventory. Finally, in the disposal life-cycle stage the inventory of wastes, energy, and emissions that occur when products are sent to disposal are quantified.

The LCA framework shown here is simplified in order to clarify the life cycle stages. In a life-cycle inventory, the inputs and outputs of each life-cycle stage are quantified. Process inputs can be divided into two kinds: 1) inputs of raw materials and energy resources (environmental input), and 2) inputs of products, semi-finished products or energy, which are outputs from other processes that must themselves be inventoried (economic input). Similarly, there are two kinds of output: 1) outputs of emissions (environmental output), and 2) output of a product, a semi-finished product or energy (economic output).

Allocation of Inputs and Outputs

Many choices for allocation methods.

Difficulties in conducting an inventory arise when processes that generate more than one product are studied. For example, in the electrolysis of salt in water to produce molecular chlorine and caustic soda, where the chemical equation is

$$2H_20 + 2NaCl \rightarrow 2NaOH + Cl_2 + H_2,$$

the environmental effects of the electrolysis process cannot be attributed entirely to either caustic soda, chlorine, or hydrogen. A suitable allocation rule is needed here, for instance allocation on the basis of mass or on the economic value of the products.

Recycle Loops

- product recycle
- product remanufacture
- material recycle

Recycle loops in the life-cycle of a product add another layer of complexity to completing a life-cycle inventory. As discussed in Lesson 1, products can be recycled in a number of different ways. If an item is reused for its original purpose, such as when glass bottles are cleaned and refilled, it is called product recycle. Product remanufacture occurs when an item is put to a different use after its original purpose has been fulfilled, such as when newspapers are shredded and used for packaging. Another type of recycling is material recycle, where the materials in an item are used as feedstock in material production. An example of material recycle is the production of steel ingots from junked cars.

Avoided Emissions and Energy Consumption

rationale must be clearly stated

When a disposal process generates a certain output (e.g. energy generated by the incineration of material or recycling of the product or its materials) this not only causes emissions, but also saves emissions (it is no longer necessary to produce the energy or the material). To allow for this, avoided emissions (or waste or energy consumption) are introduced. These are equivalent to the emissions that would have occurred in actual production of the material or energy. The avoided impacts of a process are deducted from the emissions caused by other processes.

Inputs and Outputs for Production of 1 kg Ethylene

Energy Content	Category	Unit Average
Fuels, MJ	Coal	0.94
	Oil	1.8
	Gas	6.1
	Hydro	0.12
	Nuclear	0.32
	Other	<0.01
	Total	9.2
Feedstock, MJ	Coal	<0.01
	Oil	31
	Gas	29
	Total	60
Total Fuel + Feedstock		69

Intense material tracking is required for a comprehensive life-cycle inventory, even for a simple product made of a single raw material in one or two manufacturing steps. For a complicated product that is itself composed of many diverse products and whose processes produce co-products, it becomes even more challenging.

This table (which stretches over the next few pages) shows the inputs and outputs of production for a simple product: ethylene. The data for the production of this commodity chemical are presented here so that the level of detail that is pursued in inventorying products might be better understood.

The portion of the table that is on this page gives the fuel and feedstock requirements for the production of 1 kg of ethylene. The main raw materials of ethylene production, oil and gas, are also fuels. The energy content of this feedstock for ethylene production is reported here instead of its mass so that it can be combined with the energy that was required in the production process.

These data are from a report authored by Ian Boustead for the European Centre for Plastics in the Environment (PWMI) in Brussels.

Inputs and Outputs for Production of 1 kg Ethylene

	Category	Unit Average
Raw materials, mg	Iron ore	200
	Limestone	100
	Water	1,900,000
	Bauxite	300
	Sodium chloride	5,400
	Clay	20
	Ferromanganese	<1

This portion of the inventory data for ethylene production gives the raw materials required (other than fossil fuel feedstock, which was grouped with energy requirements on the previous page).

Inputs and Outputs for Production of 1 kg Ethylene

	Category	Unit Average
Air emissions, mg	Dust	1,000
	Carbon monoxide	600
	Carbon dioxide	530,000
	Sulfur oxides	4,000
	Nitrogen oxides	6,000
	Hydrogen sulfide	10
	Hydrogen chloride	20
	Hydrocarbons	7,000
	Other organics	1
	Metals	1

These are the air emissions associated with the production of 1 kg of ethylene. As you can see, these emissions are listed for individual compounds or classes of compounds. As will be discussed in more detail later, obtaining individually speciated emission data in the inventory stage of an LCA is important for the impact assessment portion. In this inventory, all hydrocarbons are lumped together, and all metals together, which is unfortunate because individual hydrocarbons have very different environmental effects, as to individual metals. However, compiling an inventory of even the production of a simple commodity chemical with all the emissions speciated would be a daunting, if not impossible, task.

Inputs and Outputs for Production of 1 kg Ethylene

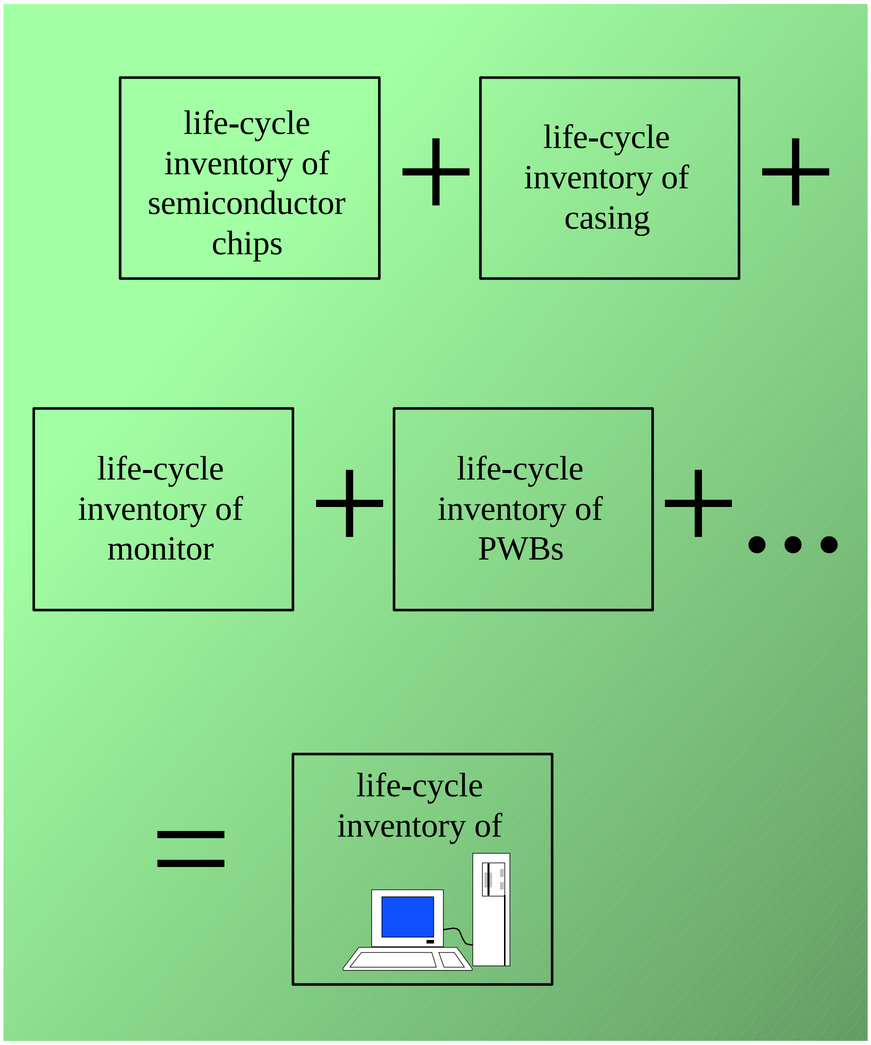
	Category	Unit Average
Water emissions, mg	COD	200
	BOD	40
	Acid as H+	60
	Metals	300
	Chloride ions	50
	Dissolved organics	20
	Suspended solids	200
	Oil	200
	Phenol	1
	Dissolved solids	500
	Other nitrogen	10

These are the water emissions associated with the production of 1 kg of ethylene. Again, emissions are grouped by compound or class of compound.

Inputs and Outputs for Production of 1 kg Ethylene

	Category	Unit Average
Solid waste, mg	Industrial waste	1,400
	Mineral waste	8,000
	Slags and ash	3,000
	Nontoxic chemicals	400
	Toxic chemicals	1

Finally, this last page of the table on ethylene production gives the solid waste associated with the production of 1 kg of ethylene.



For a product produced from many materials, life-cycle inventories become extremely complex. The wastes, emissions, and raw-material and energy use of each significant component must be inventoried. Consider a life-cycle inventory for a personal computer as an example. Semiconductor chips, printed circuit boards, a casing, and a display monitor would all have vastly different emissions and energy and raw material usage in different stages of their life cycle.

System Boundaries

Processes are excluded in order to keep the life-cycle inventory manageable.

So while the inventory process seems simple enough in principle, in practice, it is subject to a number of practical limitations. As discussed in Lesson 1, an important part of the planning phase of an LCA is to choose system boundaries that make completion of the life-cycle assessment possible, give the resources devoted to it. When setting system boundaries, it is not always clear which process should be included in the inventory. In the production of ethylene, for example, oil has to be extracted; this oil is transported in a tanker; steel is needed to construct the tanker, and the raw materials needed to produce this steel have to be extracted. For practical reasons a limit must be set. Usually, the production of capital goods (such as tankers for transport) is excluded. This would be a bad approximation if the capital goods were not used for mass production or mass transport. Items like satellites, for example, are never mass-produced. Sometimes special equipment must be constructed to move an item only once.

Inventory Data Must Be Combined with Effect Data before Conclusions Can Be Drawn

Selected Air Emissions from the Production of 1 kg Polyethylene and 1 kg Glass

Emissions (kg)	Polyethylene	Glass
CO_2	1.8	0.49
NO_x	0.0011	16
SO_2	0.00099	0.0027
CO	0.00067	0.000057

Because a great deal of effort is expended in compiling a life-cycle inventory, it is tempting to draw conclusions from the results. However, the inventory itself does not provide all the information necessary for improvement analysis. Instead, the data are used to conduct an impact assessment, which is used in the improvement analysis.

Inventory data, for example, cannot be used to determine which of two products has better environmental characteristics. This table displays the results of a small part of an inventory of the production of two materials, polyethylene and glass, and is shown here to illustrate that inventory data do not in themselves provide enough information to determine whether 1 kg of polyethylene is more or less environmentally friendly than 1 kg of glass. As shown, carbon dioxide emissions are higher for polyethylene than for glass, while emissions of nitrogen oxides are much higher for glass than for polyethylene.

These two compounds have very different effects on the environment. Nitrogen oxides participate in the smog cycle and are associated with acid precipitation and acid deposition, while carbon dioxide emissions are a concern because of the role they may play in global warming.

The relative importance of the different emissions must be determined in the impact assessment stage of LCA to bring meaning to the values obtained in the inventory stage.

Speciated Emissions are Necessary for Impact Assessment

Air Emissions for Grocery Sacks
(0% Recycling), pounds

	20,000 Polyethylene Sacks	10,000 Paper Sacks
TOTAL	2.4	64
Particulates	1.6	24.6
Hydrocarbons	12	4.9

(from Franklin Associates, Ltd., “Energy and Environmental Profile Analysis of Polyethylene and Unbleached Paper Sacks,” Prairie Village, KS, June 1990)

This table shows selected air emissions for paper and plastic grocery sacks, which illustrates the importance of obtaining speciated emissions data during a life-cycle inventory. In this life-cycle inventory, Franklin Associates found that paper grocery sacks have higher total air emissions than plastic sacks. There are qualitative differences in the air emissions, however, with paper sacks having higher emissions of particulates, nitrogen oxides, and sulfur oxides and lower emissions of hydrocarbons than plastic sacks. Qualitative differences in hydrocarbons exist so that it is possible that 12 pounds of hydrocarbons emitted during the life cycle of 20,000 polyethylene sacks do less environmental damage than 4.9 pounds of hydrocarbons emitted during the life cycle of 10,000 paper sacks. Because the hydrocarbons are lumped together, it is impossible to assess their impacts and compare the two grocery sack systems.

Uncertainty in Life-Cycle Inventories

- incomplete or inaccurate data
- obsolete data/poor choice of technology

Life-cycle inventory data are often incomplete or inaccurate, largely because the resources necessary to gather high-quality data are not available. Sometimes inventory data cannot be obtained because they are proprietary. Sometimes the inventory data that is available is aggregated so that air and waterborne emissions are quantified as totals rather than given as quantities for individual constituents, making a thorough impact assessment impossible. Moreover, the data are subject to obsolescence; there are many cases where processing industries have cut emissions by substantial amounts during the last ten years. The use of obsolete data can therefore cause distortions. Connected to this subject is the matter of choice of technology. A distinction can be made between worst, average, and best (or modern) technology. Before starting to collect data it is important to be aware of which type of technology you are interested in.

Energy Flows

- hydroelectric power
- fossil fuel power

Another source of uncertainty in life-cycle inventories is the use of "average" or "typical' values instead of values specific to a facility or region. For example, when evaluating the energy requirements of a product, both the raw materials and the inputs and outputs from the generation and use of the energy flow must be included. Note that the inputs and outputs of energy generation vary widely among the different methods of power generation. Even among coal-fired power plants, there is a difference in wastes and emissions for different grades of coal.

Uncertainties in Life-Cycle Inventories

Mass per 10,000 Hot Drink Containers, lb

	Paper Cup		Plastic Cup	
	Study #1	Study #2	Study #1	Study #2
Air Emissions	18.1	3.5-5.8	11.8	1.5-1.9
Wastes in Water	2.9	9-16	2.1	0.7
Solid Waste	270	720-970	140	71

Study #1: Franklin Associates, Ltd., "Resource and Environmental Profile Analysis of Polystyrene and Bleached Paperboard Containers," Prairie Village, KS, 1990.

Study #2: M. B. Hocking, "Paper versus Polystyrene," *Science*, **251**, 504-505, Feb. 1991.

Sometimes life-cycle inventories conducted by different practitioners for the same products provide insight into the accuracy of the inventories. As an example, consider the life-cycle inventories of polystyrene and paperboard cups from two different practitioners, as shown in this table. Air emissions for paperboard cups were estimated to be 3.5 to 5.8 lb per 10,000 cups by Hocking and 18 lb per 10,000 cups by Franklin. Franklin's values are three to five times higher than Hocking's. For polystyrene cups, Hocking estimated air emissions of 1.5 to 1.9 lb per 10,000 cups while Franklin reported emissions of 12 lb per 10,000 cups so that Franklin's values are six to eight times higher than Hocking's. Hocking did not report some of the high mass emissions, which could account for this discrepancy. Both practitioners, however, report a larger quantity of air emissions for paper cups than for plastic cups. Both practitioners also found lower total waterborne emissions for paper cups, and both practitioners estimated larger quantities of solid waste from paperboard cups, but not by similar amounts. The postconsumer solid waste for polystyrene cups reported by Hocking was about one third of the postconsumer solid waste reported in the Franklin study, which suggests that the capacities or construction of the polystyrene cups for the two studies were not similar.

So some of the differences in the inventory values these two practitioners obtained can be rationalized, but the disagreement between their values lends insight into the accuracy of the data. Some LCA practitioners report that their inventory values are accurate to within 10%, but this is unlikely given the uncertainties inherent in the inventory process. In general, differences in inventory values are not meaningful unless they are large.

Uncertainties and Product Comparisons

Uncertainties and assumptions in life-cycle inventories create skepticism about the results of life-cycle studies performed to compare products.

There is disagreement among experts about the utility of life-cycle concepts in comparing products. Often, life-cycle inventories are commissioned by a group that has a vested interest in the results. For example, a group of plastics manufacturers might pay for a study comparing paper and plastic products. Whichever product is determined to be environmentally preferable will have an edge in marketing. But because the assumptions and choices made by the life-cycle practitioner during the study influence the results, objectivity is crucial to their validity.

Summary of Lesson 2

- Even for simple products, life-cycle inventories are a lot of work.
- Allocation of co-products and avoided inputs and outputs adds complexity.
- Inventory data must be combined with environmental effect information to be useful.
- Inventoried emissions should be speciated if possible so that impact assessment can be carried out properly.
- A certain amount of error is inherent in even a carefully performed life-cycle inventory.

This concludes the second lesson on life-cycle assessment in this module. There are several important points that should be taken from this lesson. For one, a life-cycle inventory of even a simple product requires a great deal of data gathering and analysis, and must be restricted in scope in order to keep the inventory process manageable. Allocation of inputs and outputs for co-products is an issue that must be addressed in an inventory, along with inputs and outputs that are avoided due to recycling or recovery of products.

While a great deal of effort is required to create a life-cycle inventory, life-cycle inventory data alone are not sufficient for making an improvement analysis. For example, a life-cycle inventory cannot by itself show which of two products is environmentally superior. An impact assessment of the inputs and outputs of the products are needed first. Inventoried emissions should be speciated so that the difference in effects between compounds can be taken into account when the impact assessment is conducted.

No matter how much care is taken in preparing an inventory, the results obtained have a great deal of uncertainty. Because of this, when LCAs are used to compare products, the differences between products have to be substantial to be meaningful. Clearly, errors and assumptions in the inventory stage of life-cycle assessment are brought into the subsequent stages of life-cycle assessment (impact assessment and improvement analysis). Life-cycle inventory factors such as the choice of technology and system boundaries, data quality, etc. have to be taken into account when interpreting the results of LCAs.

Despite the level of uncertainty, life-cycle assessments are a uniquely useful tool, and as discussed in Lesson 1 are used in industry and the public sector for a variety of purposes.