Chapter 4
Life Cycle Impact Assessment

What is a Life Cycle Impact Assessment (LCIA)?

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

LCA versus Risk Assessment

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

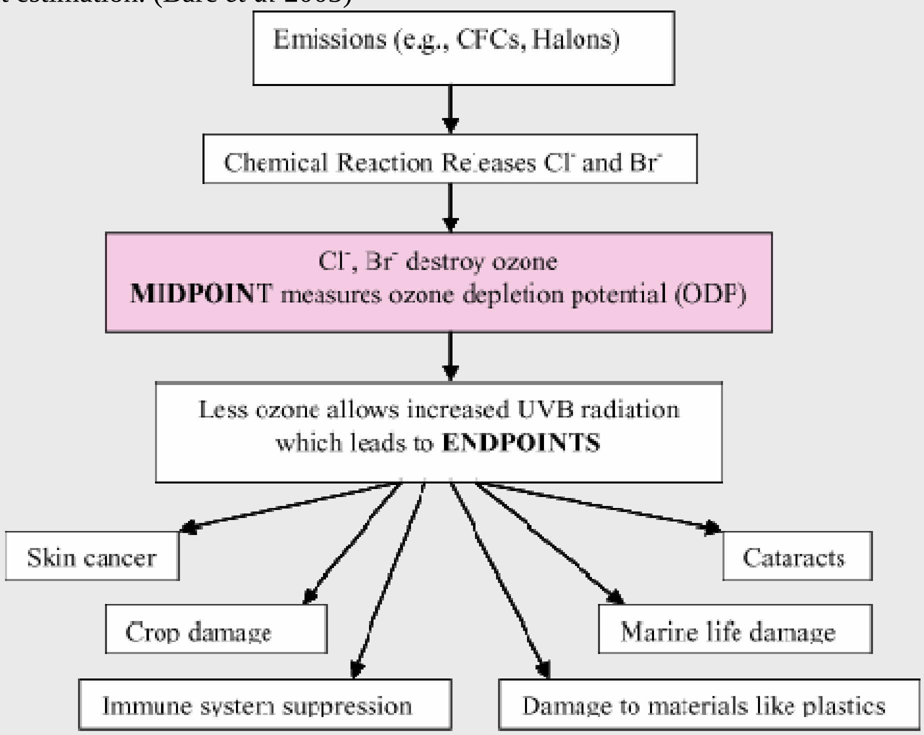
The key concept in this component is that of stressors. A stressor is a set of conditions that may lead to an impact. For example, if a product or process is emitting greenhouse gases, the increase of greenhouse gases in the atmosphere *may* contribute to global warming. Processes that result in the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

Why Conduct an LCIA?

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

Midpoint versus Endpoint Modeling

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



What Do the Results of an LCIA Mean?

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

Key Steps of a Life Cycle Impact Assessment

The following steps comprise a life cycle impact assessment.

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

5. *Grouping* - sorting or ranking the indicators (e.g. sorting the indicators by location: local, regional, and global).

6. *Weighting* - emphasizing the most important potential impacts.

7. *Evaluating and Reporting LCIA Results* - gaining a better understanding of the reliability of the LCIA results.

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

Step 1: Select and Define Impact Categories

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

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

Step 2: Classification

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

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

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

Exhibit 4-1. Commonly Used Life Cycle Impact Categories

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

Step 3: Characterization

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

Impact Categories and Associated Endpoints

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

Global Impacts

Global Warming - polar melt, soil moisture loss, longer seasons, forest loss/change, and change in wind and ocean patterns.

Ozone Depletion - increased ultraviolet radiation.

Resource Depletion -decreased resources for future generations.

Regional Impacts

Photochemical Smog - "smog," decreased visibility, eye irritation, respiratory tract and lung irritation, and vegetation damage.

Acidification - building corrosion, water body acidification, vegetation effects, and soil effects.

Local Impacts

Human Health - increased morbidity and mortality.

Terrestrial Toxicity - decreased production and biodiversity and decreased wildlife for hunting or viewing.

Aquatic Toxicity - decreased aquatic plant and insect production and biodiversity and decreased commercial or recreational fishing.

Eutrophication – nutrients (phosphorous and nitrogen) enter water bodies, such as lakes, estuaries and slow-moving streams, causing excessive plant growth and oxygen depletion.

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

Water Use - loss of available water from groundwater and surface water sources.

Impact indicators are typically characterized using the following equation:

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

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

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

Characterization of Global Warming Impacts

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

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

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

*Intergovernmental Panel on Climate Change (IPCC) Model

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

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

TRACI

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

Step 4: Normalization

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

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

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

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

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

Step 5: Grouping

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

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

Step 6: Weighting

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

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

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

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

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

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

<u>Step 7: Evaluate and Document the LCIA Results</u>
Now that the impact potential for each selected category has been calculated, the accuracy of the results must be verified. The accuracy must be sufficient to support the purposes for performing the LCA as defined in the goal and scope. When documenting the results of the life cycle impact assessment, thoroughly describe the methodology used in the analysis, define the systems analyzed and the boundaries that were set, and all assumptions made in performing the inventory analysis.

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

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

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

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