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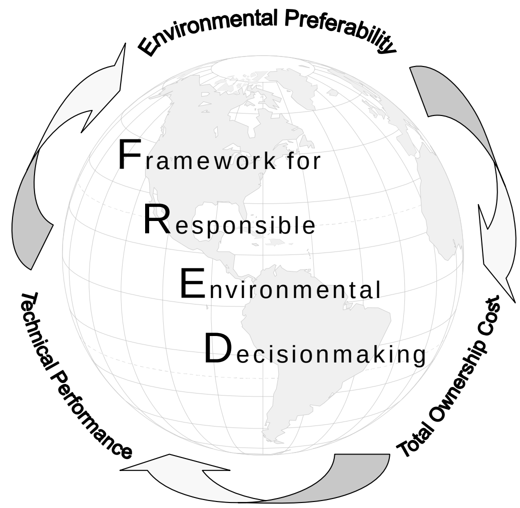
Framework for Responsible Environmental Decision-Making (FRED): Using Life Cycle Assessment to Evaluate Preferability of Products



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Framework for Responsible Environmental Decision-Making (FRED): Using Life Cycle Assessment to Evaluate Preferability of Products

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Notice

This report has been subjected to U.S. Environmental Protection Agency internal peer and administrative review and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the U.S. Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use. This document is intended as a reference guide on how to determine environmental preferability for products purchased by the federal government.

Users are encouraged to duplicate portions of this publication as needed to implement an environmental preferability-based procurement program. Organizations interested in reprinting and distributing the entire report should contact the Life Cycle Assessment Team, National Risk Management Research Laboratory, U.S. Environmental Protection Agency, Cincinnati, Ohio, 45268, to obtain a reproducible master.

Foreword

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

The National Risk Management Research Laboratory is the Agency's center for investigation of technological and management approaches for reducing risks from threats to human health and the environment. The focus of the Laboratory's research program is on methods for the prevention and control of pollution to air, land, water and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites and groundwater; and prevention and control of indoor air pollution. The goal of this research effort is to catalyze development and implementation of innovative, cost-effective environmental technologies; develop scientific and engineering information needed by EPA to support regulatory and policy decisions; and provide technical support and information transfer to ensure effective implementation of environmental regulations and strategies.

The approach outlined in this document, called the Framework for Responsible Environmental Decision-Making (FRED), was developed in support of the EPA's Office of Pollution Prevention and Toxics as they establish the Environmental Preferable Purchasing (EPP) program. EPP is in response to Executive Order 13101 which requires EPA to develop guidelines on environmentally preferable purchasing by the federal government. The goal of the program is to make the environmental aspects of products a factor in purchasing decisions, along with the traditional factors of technical performance and cost. FRED provides the basis for an approach that may be used to consistently compare the environmental profiles of products on the basis of their impacts to human health and the environment from raw material acquisition through ultimate disposal.

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

E. Timothy Oppelt, Director
National Risk Management Research Laboratory

Abstract

Historically, purchase price and technical performance have been the two primary criteria in the product selection process. In September 1998, President Clinton signed Executive Order 13101, "Greening the Government through Waste Prevention, Recycling, and Federal Acquisition" which defines the federal government's preference for "environmentally preferable" products and services. The U.S. Environmental Protection Agency (U.S. EPA) developed the *Framework for Responsible Environmental Decision- Making (FRED): Using Life Cycle Assessment to Evaluate Preferability of Products* to assist the Agency's Office of Pollution Prevention and Toxics in their development of guidelines for procurement officials in meeting the intent of this Executive Order.

The FRED decision-making methodology introduced herein demonstrates how the life-cycle concept can be used to quantify competing products' environmental performance so that this information may be integrated with considerations of total ownership cost and technical performance. Specifically, this report describes how life cycle assessment (referred to as the FRED LCA approach) can be applied to determine and compare the environmental and human health impacts of competing products.

This report provides guidance on how to conduct a relative comparison between product types to determine environmental preferability. It identifies data collection needs and issues; and describes how to calculate numeric impact indicators for a given product or service across eight human health and environmental impact categories. The eight categories were selected specifically to meet the goal of the effort and include the following: Global Climate Change, Stratospheric Ozone Depletion, Acidification, Photochemical Smog Formation, Eutrophication, Human Health, Ecological Health, and Resource Depletion.

Case studies were conducted on three product categories (motor oil, wall insulation, and asphalt coating) to evaluate the process as well as the output. It was concluded that the FRED LCA approach can be performed in a much shorter time period than is typical for a more detailed LCA. This more practical duration for procurement decisions is achieved though the focusing of data collection and a simplified impact assessment procedure.

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Acknowledgments

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Life Cycle Inventory data for the pilot projects used in developing this reference guide were graciously provided to the authors. Barbara C. Lippiatt, of the National Institute of Standards and Technology (NIST), manages the BEES (Building for Economic and Environmental Sustainability) program. We recognize her generous support in time and in sharing the BEES database, specifically wall insulation and motor oil data. Jose Garcia, of the National Highway Administration, was instrumental in providing information for the asphalt pilot project, as was Jay Walters of Asphalt Systems, Inc. Their support is also gratefully appreciated.

Chapter 1 - Introduction

Choosing among competing products in the marketplace can be a difficult process for the federal procurement official. Although purchase price and technical performance have historically been the two primary criteria in product selection process, as the result of Executive Orders 12873 and 13101(see box), and subsequent changes to the Federal Acquisition Regulations (FAR), the environmental performance of products has also become an important selection criterion.

> In October 1993, President Clinton signed Executive Order 12873, "Federal Acquisition, Recycling, and Waste Prevention," which directs Executive Agencies to evaluate the environmental attributes of the $200 billion in products and services purchased by the Federal government each year. Executive Order 13101 entitled "Greening the Government through Waste Prevention, Recycling, and Federal Acquisition," signed September 14, 1998, further defines the Federal government's preference for "environmentally preferable" products and services.

In response to these new directives, the EPA's Office of Research & Development conducted a project to develop a practical methodology to guide environmentally preferable purchasing. The overall approach is called FRED, the Framework for Responsible Environmental Decision-Making and involves integrating price, technical performance and environmental information based on LCA into purchasing decisions. This document focuses on the approach for conducting the LCA component.

Exhibit 1-1. FRED Methodology

Life Cycle Assessment (LCA) is a cradle-to-grave evaluation of the environmental effects of products and services. It provides a holistic view of the environmental aspects of products and services. The FRED LCA model specifies many of the choices to be taken in performing an LCA for environmental preferability, thus reducing the variability between studies. In addition, FRED provides baseline models for performing the impact assessment phase of LCA for environmental preferability. These models were chosen as a balance among scientific accuracy, simplicity of use and conformance with the international standards on LCA. As the science of LCA improves, other models may prove to be more environmentally relevant without losing their ease of use. For example, on-going research within the Office of Research & Development includes the development of more sophisticated impact modeling called TRACI (Tool for the Reduction and Assessment of Chemical and Other Impacts). The results of the TRACI model as it develops will be incorporated into the FRED model as appropriate.

To the greatest extent feasible, FRED follows the requirements of the International Standards Organization (ISO) 14040 series of standards.

It should be noted that the analysis will only be as good as the data that go into it. Hence, there may be cases where FRED will not be able to draw a conclusion on environmental preferability, because the data are incomplete or uncertain, or the results of the impact assessment do not clearly point to a preferable system. In these cases, the decision-maker will need to consider other factors such as product costs (i.e. total cost of ownership) and technical performance. Weighting across impact categories may also be needed. The process of assigning numeric values to impacts is based on value judgments (usually made by the decision maker or decision-making group) and tends to be a controversial part of LCA applications. However, several approaches to weighting exist and can be applied to LCA results. These are explored in detail in Chapter 4.

Some of the guidance provided by FRED includes:

- A list of eight core environmental impact categories
- Indicators and models for each impact category
- Data quality requirements for different types of products
- Minimum indicator reporting requirements

Executive Order 13101 places primary requirements on federal purchasing agents based on single characteristics such as percent recycled content. However, it is recognized that in some circumstances, a life cycle review of the multiple environmental attributes of a product or service may identify environmentally preferable products which do not meet single attribute criteria. FRED provides guidance for demonstrating the overall environmental preferability of products as a possible alternative approach to single attribute requirements. In the absence of product-specific life cycle assessments based on FRED, purchasing agents must comply with the requirements of the executive order and the associated FAR (Federal Acquisition Regulation), interpreting them as appropriate for their uses.

LCA is a systematic approach to evaluating the environmental effects associated with any given activity from the initial gathering of raw materials from the earth to the point at which all materials are returned to the earth. This evaluation includes the use of resources and releases to the air, water, and soil. LCA provides a holistic review of the potential impacts associated with particular products and services, providing indicators of the relevant environmental impacts. Studies have been conducted since the 1960s, with many organizations using LCA to holistically identify and evaluate environmental effects of the products and services they offer and/or procure.

In its application of LCA, FRED further defines specifically for the user what types of engineering and environmental data to collect. This is an important aspect of the FRED LCA system because it reduces the time and resources required to perform the LCA while ensuring that products are being compared in a fair and consistent manner.

Benefits of FRED

The FRED LCA methodology has been designed to provide the ability for procurement officials and vendors to apply a greater degree of specificity, complexity, and/or completeness to the evaluation of competing products or services. Key benefits of using FRED in choosing among competing products include:

- Simplification of data collection and impact assessment, making the approach easier to conduct and more helpful to procurement officials and vendors.
- Generation of results that can be integrated with information on product technical performance via the functional analysis step of LCA.
- Facilitated comparative assertions that will be more consistent and scientifically-based using indicators on environmental performance.
- Meeting the needs of the federal government to assess environmental benefits of competing products and services (per E.O. 13101).

Appropriate Use of FRED

FRED is designed to compare two or more product types performing the same function (e.g., R-15 fiberglass wall insulation, R-15 blown cellulose wall insulation, etc). As in any LCA study, one of the first activities in FRED is a functional analysis which integrates product technical performance into environmental performance. While an analysis of a single product may be interesting, at the minimum, products must be compared against industry average data in order to evaluate whether they represent an environmentally superior product.

Since it is based on LCA, the FRED LCA system is limited by the data availability and assumptions of the LCA technique. Comparisons must be made on an indicator by indicator basis (without combining the different environmental indicators to provide a single score). Because of the uncertainty of the data, differences between products should be at least an order of magnitude to be considered. See more discussion on data uncertainty and variability in the following section, "Data Quality."

It may be that an LCA identifies no true "winner" in terms of environmental preferability, either because the differences between the two product types are too small, or because one product is better in some areas and worse in others. In this case, the procurement officer can either fall back on price and performance to make the purchasing decision or can utilize a stakeholder analysis and a weighting methodology that is described in Chapter 4.

FRED does not consider criteria of concern such as socioeconomic issues, or occupational safety. To the extent that these criteria are relevant to the procurement process, additional analysis may be necessary.

The application of FRED discussed in this guidance document has been targeted to promoting the inclusion of holistic environmental performance evaluation in the federal agency purchasing decision-making process. The FRED methodology has been designed to provide the ability for procurement/purchasing officials and/or vendors to apply a greater degree of specificity, complexity and/or completeness to the evaluation of competing products. These applications of FRED along with guidance on the use of more sophisticated indicator models of human health and environmental impacts will be discussed in future EPA research efforts.

Roadmap to the Remainder of this Document

This reference guide focuses on the approach used to apply the FRED LCA system to develop an approach for both federal procurement officials and product vendors on how to determine holistic environmental preferability in a practical, cost-effective method by comparing products from a life cycle perspective. Chapter 2 provides guidance on the first two steps in the FRED methodology, defining the product comparison's goal and scope and identifying/collecting the necessary data for the analysis and performing error analysis to ensure that the conclusions of the FRED LCA system will be valid. Chapter 3 describes how to calculate numeric impact indicators for a given product or services in each of the eight human health and environmental impact categories modeled by FRED, step three (impact assessment)in the methodology. Issues related to total cost of ownership and technical performance are covered briefly in Chapter 4. Chapter 4 also provides guidance on how to present the results to compare the environmental preferability of products using FRED. Chapter 5 provides conclusions and future steps. Information about pilot projects, which were used to test and refine the FRED LCA system, are found in the appendices.

Chapter 2 - Framework for Responsible Environmental Decision-Making

Overview

The Framework for Responsible Environmental Decision-Making (FRED) provides a fair and consistent method for comparing the holistic environmental performance of products on the basis of their impacts to human health and the environment from raw material acquisition through ultimate disposal. As described in Chapter 1, FRED uses life cycle assessment (LCA) to achieve this objective. The steps of LCA include goal and scope definition, inventory analysis, impact assessment, and interpretation. Exhibit 2-1 illustrates the life cycle assessment framework as defined by the International Standards Organization (ISO). The key to the FRED LCA system for providing a fair and consistent method to compare products is through the use of uniform system boundaries, data quality requirements, and selection of impact categories and associated indicator models. By defining the majority of the decision points in the LCA process, the result is a consistent, practical, and user-friendly method for evaluating the human health and environmental effects of products.

The remainder of this document highlights the LCA process defined for use in FRED to evaluate environmental preferability. Specifically, guidance on *Goal and Scope Definition* and *Inventory Analysis* are provided in this Chapter. The *Impact Assessment* process is outlined in detail in Chapter 3. Chapter 4 provides guidance on *Interpretation* of the results to determine environmental preferability.

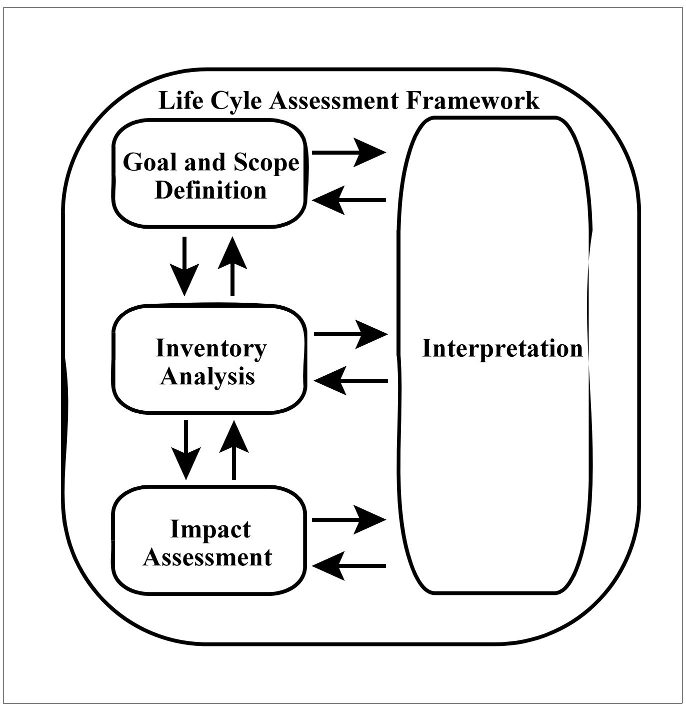


Exhibit 2-1. Life Cycle Assessment Framework
(Source: ISO 14040)

Step 1: Goal and Scope Definition

The goal and scope definition phase of the FRED LCA system helps the user define what data must be collected (boundary definition), the functional unit by which data are going to be collected, and the quality of the data required to make an accurate decision (accurately reflecting the goal of the project).

Scope

As stated earlier in Chapter 1, the FRED LCA system is based on the principle of evaluating environmental impacts across the life cycle of a product or service; i.e., raw materials acquisition, manufacturing, use/reuse/ maintenance, and recycle/waste management. These life cycle stages are illustrated in Exhibit 2-2. To consistently and fairly compare the environmental impacts from competing products, it is important that material, energy, and environmental release data, also referred to as life cycle inventory (LCI) data, are collected for all life cycle stages. The scope of each product's LCI must be verified for similarity prior to evaluating environmental preferability.

All products or services shall consider the environmental impacts from raw materials acquisition, production, manufacturing, packaging, distribution, reuse, operation, maintenance, and disposal to the greatest extent feasible.

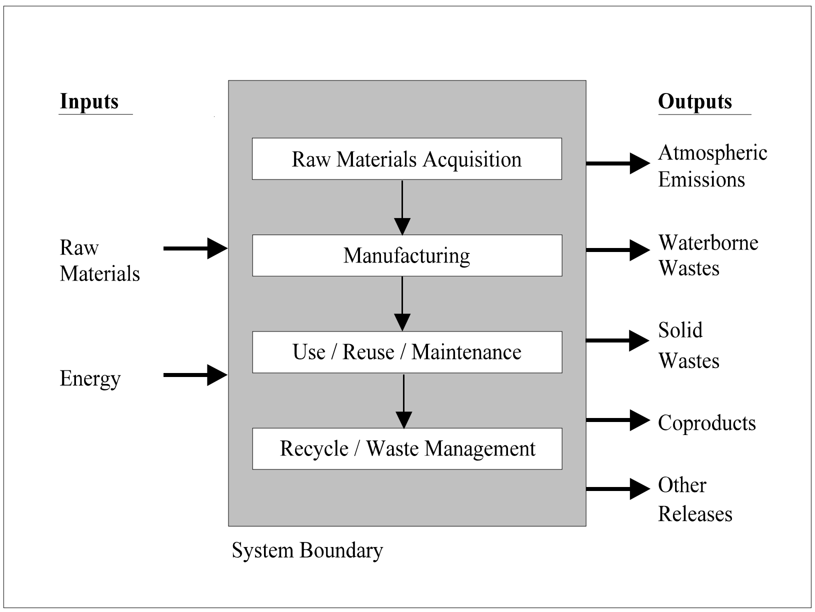


Exhibit 2-2. Life Cycle Stages (Source: EPA 1993)

System Function and Functional Unit

As a first step in performing an LCA, an analysis of the function performed by the different product systems must be performed. It is this first step which assures that the technical performance of products is taken into account in evaluating the environmental performance of competing products. Sometimes, this analysis is a straightforward exercise, but sometimes it is quite complex. For example, in comparing two different motor oils, one might take into account the miles of protection provided (e.g., 3,000 miles) without viscosity breakdown. On the other hand, one might compare the use of wall insulation with different insulating factors. Here one must include the area to be covered, the building construction, the average outside temperature (winter and summer), and the temperature maintained and life-span of the product.

Comparisons between products or services shall be made on the basis of the same system function, quantified by each products functional unit (i.e., the amount of product required to fulfill the function).

At a minimum, one must consider the following aspects of a system function in order to make a legitimate comparison of two products:

- What is the intended function of the product? (Why does one wish to purchase a product or service)
- What are the spatial characteristics of the function? (Area, volume, linear characteristics)
- What are the temporal characteristics of the function? (How long must it last, is the use intermittent?)
- What are the specific technical performance requirements for this function? (Often spelled out in technical requirements)

LCA practitioners define how data should be reported in terms of a *functional unit.* The functional unit quantifies the amount of product required to fulfill the function. Comparisons between products for environmental preferability must be made on the basis of the same function, and the LCI data must be collected on the basis of each products functional unit. Exhibit 2-3 provides examples of system functions and functional units for the 3 pilot projects used in generating this reference guide.

Exhibit 2-3. Examples of System Function and Functional Units

Product	System Function	Functional Unit
Motor Oil (petroleum based)	10W30 motor oil that provides 3,000 mile protection without viscosity breakdown to an automobile engine.	1 quart of 10W30 Motor Oil
Motor Oil (vegetable oil based)	10W30 motor oil that provides 3,000 mile protection without viscosity breakdown to an automobile engine.	1 quart of 10W30 Motor Oil
Asphalt (thin-layer)	Provide usable road surface (at least a quality rating of 5 on a scale of 10) for one lane mile of asphalt cement road for 20 years.	2 applications of 1.5 inches of asphalt cement and tack coat.
Asphalt (emulsion)	Provide usable road surface (at least a quality rating of 5 on a scale of 10) for one lane mile of asphalt cement road for 20 years.	5 applications of asphalt emulsion

Product	System Function	Functional Unit
Wall Insulation (R-13 Cellulose)	Provide a 70° F environment for a 9,600 ft^3 (1,200 ft^2 x 8 ft. ceilings) wood-frame residential house with an avg. outside temp. of 55° F, avg. winter temp. of 32° F, and an avg summer temp. of 85° F. 50 year life-span.	1,200 ft^2
Wall Insulation (R-11 Fiberglass)	Provide a 70° F environment for a 9,600 ft^3 (1,200 ft^2 x 8 ft. ceilings) wood-frame residential house with an avg. outside temp. of 55° F, avg. winter temp. of 32° F, and an avg summer temp. of 85° F. 50 year life-span.	1,200 ft^2

Comparisons between products or systems must be made on the basis of the same system function, quantified by each products' functional unit. If they are not based equally, environmental preferability can not be determined from the results.

Boundaries

Comparisons between products or services shall be of equal breadth and depth.

The system boundaries define which unit process should be included in the life cycle inventory (LCI) data collection to accurately inform the decision making process. The fundamental approach to collecting LCI data relies on the identification and quantification of material, energy, and environmental release data using the engineering principle of a mass and energy balance. Pre-defined boundaries are used to guide the LCI data collection process to direct the amount of time and resources required to complete the mass and energy balance while maintaining the study's ability to judge environmental preferability. Refer to EPA, LCI guidance "Life-Cycle Assessment: Inventory Guidelines and Principles," EPA/600/R-92/245.

Since completing a full mass and energy balance can be quite time-consuming, certain simplifying rules can be applied to data collection (as long as the goal of the study is not compromised). For example, the following can be considered when setting boundaries for data collection:

- *Mass* - include all inputs that cumulatively contribute more than one percent (1%) to the total mass input of the product system being evaluated.
- *Energy* - include all inputs that cumulatively contribute more than one percent (1%) to the total energy input of the product system being evaluated.

- *Environmental Contribution* - include all inputs that cumulatively contribute more than one percent (1%) to the estimated quantity of each type of environmental release or impact assessment category.

The 1% cut-off may be disregarded if a critical emission (such as a chemical that is toxic in small quantities) is known to be part of the system and its omissions would not accurately reflect the results of the impact modeling. The above guidelines for setting the required percent contribution are to be investigated for accuracy and practicality for determining environmental preferability during future pilot projects. Regardless of where the boundary lines are drawn for data collection, it is important to ensure that equal boundaries (same breadth and depth) are used when comparing products for environmental preferability to prevent misrepresentation of the final results.

Data Quality

> *Comparison between products and services shall be made with data of equal quality and caliber to judge environmental preferability in a public forum.*

The quality of data used to determine environmental preferability can significantly influence the results. The FRED LCA system compares products to guide environmentally preferable purchasing. As such, the quality of data used must be sufficient to support such a public decision. In addition, the quality of data collected for both products must be appropriate.

The reason why data quality is important for any comparative LCA application is that unless there are meaningful and discernable differences among the data values of the products being compared, the results of the comparison will be inconclusive. Error analysis determines mathematically and statistically whether any differences in data values are indeed sufficient to rank the data values in a meaningful manner, and thus facilitate conclusive results of the comparison.

As a general rule, the closer together the values of the LCI data are, the higher the data quality needs to be. This simply translates as a need for smaller “error bars” as performance of products is closer together. For example, if the difference between CO_2 emissions of two products is two orders of magnitude, then conclusive results may be derived even if data quality is not very good, or data sources for the two values are incomparable. On the other hand, improvement in precision of measurements may not result in conclusive results if production process variability is greater than the difference among the measured values. Therefore, careful attention must be given to the quality of the data collected to ensure that a determination of environmental preferability can be reached at the conclusion of the study.

Data quality characteristics include data uncertainty (based on data source), completeness, comparability and variability. Completeness of a data set is evaluated by identifying data gaps. All data gaps that exceed the system boundary thresholds noted above should be filled, either through additional data collection, or through the use of industry average data or surrogate data or professional judgement.

Error Analysis

Error analysis is applied to a dataset to determine the range of possible overlap of inventory emissions numbers. Without error analysis, inventory values that may seemingly appear different enough to base a decision of environmental preferability, may prove to be too close to characterize one alternative as preferable to another.

Once the error ranges have been determined, the analyst can identify which differences among product alternatives are large enough and meaningful as to the performance of the product to justify an EPP characterization of a product with the FRED LCA system.

In the following sections we will discuss variability, precision, confidence, and data source uncertainty. These data quality characteristics should help the user arrive at scientifically defensible results, in the process of applying the FRED LCA framework to compare products. In those instances when the datasets collected cannot support a defensible comparison, the error analysis will be able to point this out in a clear and straightforward manner. The following is a reference discussion intended to describe *what* are the implications of error analysis to comparisons of the environmental performance of alternative products, but not *how* to perform it. (Additional information on how to conduct an uncertainty analysis to verify the quality of life cycle inventory data can be found in the EPA document, "Guidelines for Assessing the Quality of Life-Cycle Inventory Analysis," EPA530-R-95-010.)

Variability Analysis

The variability of the actual inventory data values may be related to different production methods available to produce the same components or ingredients. Variability may also arise by use of variable grade input materials, differences in process performance based on ambient temperature variations, scrap-rate of the process, ambient air humidity, and numerous other variables that may affect process efficiency and effectiveness.

That variation may produce a variability spread (range) for the outputs of a data category for the production stage such

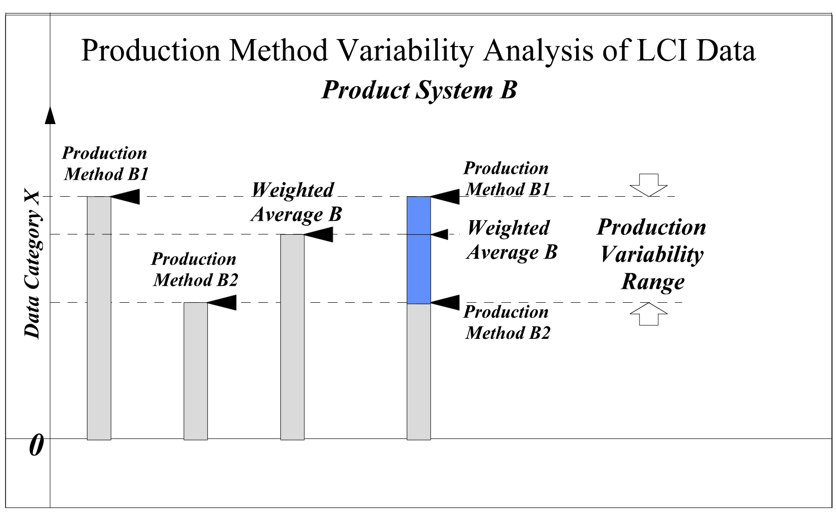


Exhibit 2-4. Production Method Variability Analysis of LCI Data

as those shown in Exhibit 2-4. These should be discussed and analyzed. This approach is appropriate in a public assertion LCA.

Precision, Validity, and Data Source Uncertainty

Different data types that are used in a life-cycle inventory have different validity. Site-specific data are collected by a practitioner at individual sites where the specific unit processes are situated and are operating. Non-site-specific data come from other available sources. Surrogate data is collected from different but reasonably similar processes which may be used in absence of Primary data. Estimated data represent the Life Cycle Inventory practitioner's best judgment as to what the unit operation's environmental releases may be like in reality. The different levels of data source uncertainty associated with values of different data types will affect the assurance one has in the conclusions that can be derived from any given data set. An error analysis performed for the specific data set used in a study will determine the uncertainty ranges for any two values based on the data type of these specific values. The approach is similar to that of variability analysis, with the added complexity of determining the validity corresponding to each data type, stemming from possible lack of consistency in the data collection/generation, unequal resolution/significant digits of the data values used, limits to detection, etc.

Exhibit 2-5 conceptually shows the error associated with different data (for products A and B, with B produced two ways), and how these may be represented graphically.

Combining the data source uncertainty, process data variability and production variability ranges will provide one with the overall uncertainty/variability range for the data point, that determines the overall "fuzziness" of the data point. Exhibit 2-6 illustrates how the overall uncertainty/ variability range may be conceptually represented graphically.

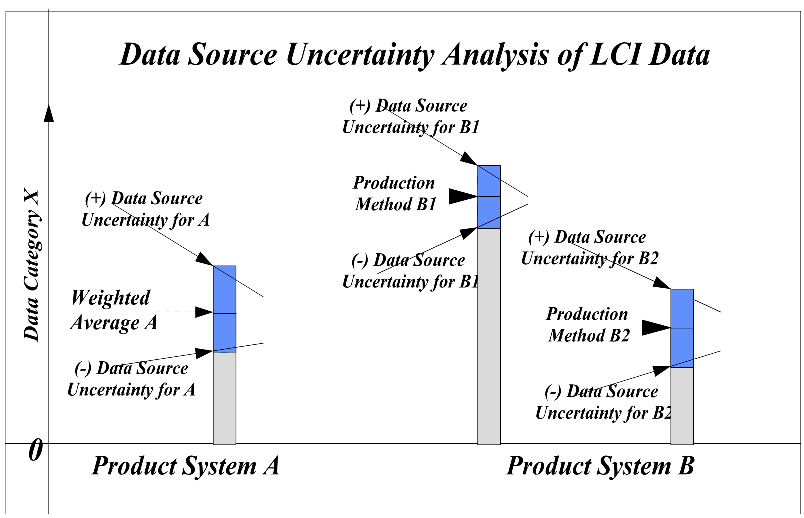


Exhibit 2-5. Data Source Uncertainty Analysis of LCI Data

Exhibit 2-7 demonstrates how the inclusion of the variability ranges could affect the resulting conclusions in any of the categories where a mass or energy difference is identified by introducing overlap of the value ranges where there had been differences before.

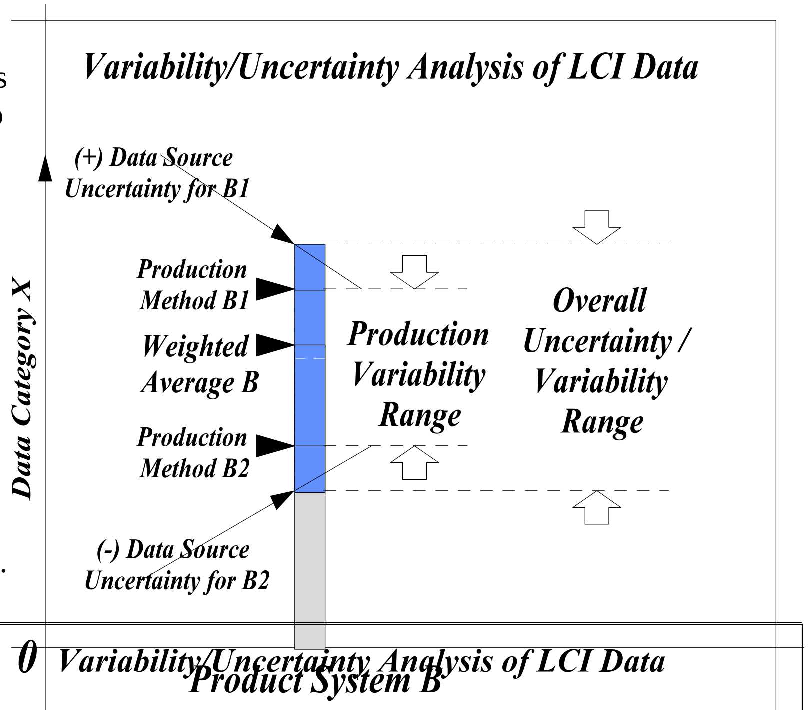


Exhibit 2-6. Variability/Uncertainty Analysis of LCI Data

Mathematical methods, such as *error analysis*, should be used to verify that the difference in the values used to determine environmental preferability is appropriate to interpret the results of the study. Variability of environmental data commonly falls into the 0 to 100 percent range. This natural variability is one reason why comparison between systems may not distinguish between systems that are less than an order of magnitude.

Data Sources

The following is intended to provide broad guidance on the selection and use of data sources with the FRED LCA system.

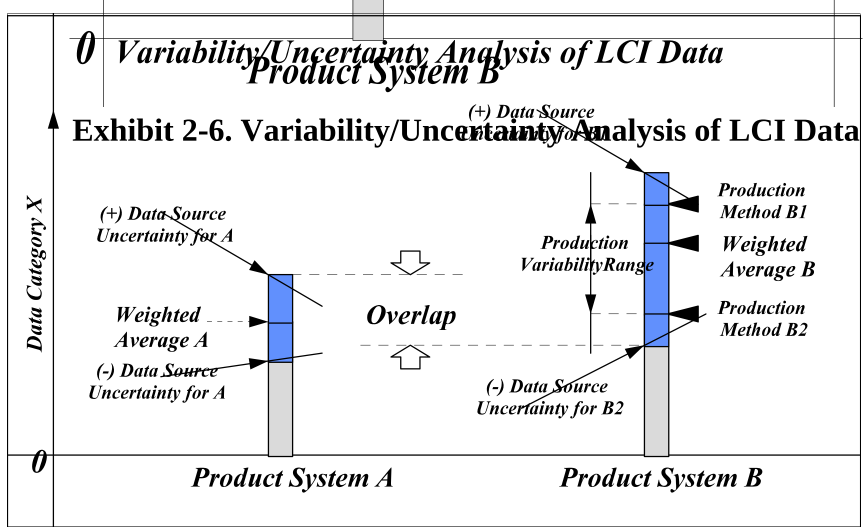


Exhibit 2-7. Variability/Uncertainty Analysis of LCI Data

The data sources used in the FRED LCA system will be a mix of site-specific and non-site-specific data (i.e. data that is based on an industry or national average, or from surrogate or estimated sources). For product comparison it is preferable that site-specific data be collected for unit processes that contribute the majority of either mass, energy, or environmental relevance to the overall study because the extent of data precision, completeness and representativeness can be determined. Exhibits 2-8 and 2-9 provide additional guidance on prioritizing the need for site-specific versus non-site-specific data for different product types by life-cycle stage. The guidance provided below is intended to reduce the time and resources required to collect LCI data for different product types by focusing data collection efforts on life-cycle stages with the greatest suspected impact. Exhibit 2-8 can be used to classify a product based on its durability, energy consumption in the use stage, and dispersion by use. Then, Exhibit 2-9 can be utilized to receive guidance on what data sources should be used for the inventory portion of data collection.

Exhibit 2-8. Classification of Product Types

Product Type	Energy Characteristic[1,2]	Examples
Durable *Products that have a long life-span (i.e., greater than 1 year).*	Energy Intensive (in Use stage)	• Vehicles • Computers • Buildings • Appliances
	Non-Energy Intensive (in Use stage)	• Roads • Paint • Furniture • Books
Non-Durable, Dispersed *Products that have a short life-span (i.e., less than 1 year), and are dispersed in the environment and can not be recovered or reused.*	Energy Intensive (in Use stage)	• Cryogenic paint stripping • Fertilizer, commercial application (i.e., dispensed from motorized vehicle) • Pesticide, commercial application (i.e., dispensed from motorized vehicle or aircraft)
	Non-Energy Intensive (in Use stage)	• Detergents • Cleaners • Cosmetics • Solvents • Hair spray • Soap
Non-Durable, Non-Dispersed *Products that have a short life-span (i.e., less than 1 year), and can be collected for disposal at the end of their life-span.*	Energy Intensive (in Use stage)	• Light bulbs • Disposable watch • Dry-cell non-rechargeable batteries
	Non-Energy Intensive (in Use stage)	• Razor blades • Engine oil • Printer paper • Paper cups • Pencils • Toothbrush

Note: 1. <u>Energy Intensive</u> - Products that require energy to perform their intended function.
2. <u>Non-Energy Intensive</u> - Products that require minimal energy to perform their intended function.

Exhibit 2-9. Data Collection Requirements

Life Cycle Stage	Site-Specific Data	Non-site-specific Data
Raw Materials Acquisition	• None	• All Product Categories
Manufacture	• All Product Categories	
Use/Reuse/ Maintenance	• Durable, Energy Intensive (in Use stage) • Non-Durable, Dispersed, Energy Intensive (in Use stage) • Non-Durable, Dispersed, Non-Energy Intensive (in Use stage)	• Durable, Non-Energy Intensive (in Use stage) • Non-Durable, Non-Dispersed, Energy Intensive (in Use stage) • Non-Durable, Non-Dispersed, Non-Energy Intensive (in Use stage)
Recycle/Waste Management	• Durable, Non-Energy Intensive (in Use stage) • Non-Durable, Non-Dispersed, Energy Intensive (in Use stage) • Non-Durable, Non-Dispersed, Non-Energy Intensive (in Use stage)	• Durable, Energy Intensive (in Use stage) • Non-Durable, Dispersed, Energy Intensive (in Use stage) • Non-Durable, Dispersed, Non-Energy Intensive (in Use stage)
Transportation (all LC stages)	• None	• All Product Categories

Impact Categories and Indicator Models

All products or services shall be compared using a minimum "core" group of eight impact categories using prescribed indicator models.

Environmental preferability is determined by comparing the potential impacts to human health and environment of products, and selecting the product with the least potential impact. How one measures the potential effects on human health and the environment from a product is a point of great controversy in society and a source of significant inconsistency in developing product comparisons. While there are many other models and systems available for use to model environmental impact (see Chapter 4 for further discussion), the FRED LCA system attempts to resolve issues of inconsistency by defining a group of eight "core" impact categories (and associated indicator models) that model a product's human health and environmental effects to promote a fair and consistent system for comparison. Exhibit 2-10 identifies the impact categories, indicator models, and the underlying data needed to assess the different categories.

Collected LCI data may contribute to one or more impact category. For example, chlorofluorocarbons (CFC's) released to the air may cause both global warming and stratospheric ozone depletion. The FRED LCA system applies the total amount of CFC's released (100%) to both impact categories to estimate the *maximum* potential impact to each category. This assignment is appropriate because CFC's participate at full potency in both environmental mechanisms simultaneously.

Step 2: Life Cycle Inventory - Identification and Collection of Appropriate Product Life-Cycle Data

The second step in the FRED LCA system is to identify and collect all product life-cycle data that will be used to estimate indicators of impacts to human health and the environment. To support the calculation of impact indicators, data must be gathered describing the inputs (e.g., energy, materials, water) and outputs (e.g., environmental releases, by-products, co-products) from all of a product's life-cycle stages identified during Step 1, Goal and Scope Definition. A procedural framework for life cycle inventory data collection can be found in the US EPA document, "Life Cycle Assessment: Inventory Guidelines and Principles," (EPA/600/R-92/245). This work has been updated through the development of the ISO 14041 document, "LCA Principles and Framework" finalized in September 1998.

As stated in the previous section, this data collection exercise can involve collecting both site-specific data as well as the use of non-site-specific data in describing the impacts from each life cycle stage of a given product. Both site-specific and non-site-specific data should be collected according to life cycle stages and by environmental media in order to facilitate an increased interpretation and presentation of results. Following the completion of the data collection process (LCI) the next step is to transfer the data quantities of environmental releases and resources used into corresponding impact categories.

Exhibit 2-10. Impact Categories and Indicator Models for the FRED LCA System

Impact Category	Impact Indicator Model	Indicator	LCI Data Needed for Model[1]
Global Warming	Intergovern-mental Panel on Climate Control (IPCC)	CO_2 Equivalents (kg)	Carbon Dioxide (CO_2) Nitrogen Dioxide (NO_2) Methane (CH_4) Chlorofluorocarbons (CFC's) Hydrochlorofluorocarbons (HCFC's) Methyl Bromide (CH_3Br)
Stratospheric Ozone Depletion	World Meteorological Organization (WMO)	CFC-11 Equivalents (kg)	Chlorofluorocarbons (CFC's) Hydrochlorofluorocarbons (HCFC's) Halons Methyl Bromide (CH_3Br)
Acidification	Chemical Equivalents	Acidification Potential	Sulfur Oxides (SOx) Nitrogen Oxides (NOx) Hydrochloric Acid (HCL) Hydrofluoric Acid (HF) Ammonia (NH_4)
Photochemical Smog	Empirical Kinetic Modeling Approach (EKMA)	Maximum Incremental Reactivity	Non-Methane Hydrocarbons (NMHC's)
Eutrophication	Redfield Ratio	PO_4 Equivalents (kg)	Phosphate (PO_4) Nitrogen Oxide (NO) Nitrogen Dioxide (NO_2) Nitrates Ammonia (NH_4)
Human Health	University of California - Berkeley TEP's	Benzene, Toluene, TEP's	Toxic Chemicals
Ecological Health	Research Triangle Institute's LCIA Expert Version 1	----	Toxic Chemicals
Resource Depletion	Life Cycle Stressor Environmental Assessment (LCSEA) Model	----	Quantity of Minerals Used Quantity of Fossil fuels Used Quantity of Precious Metals

Note: 1. The following are a sample of typical LCI items for each model. There are other LCI items that may fall under one category or another that are not listed.

Chapter 3 - FRED Impact Categories and Indicator Models

A variety of environmental impact categories and associated indicators have been developed and more continue to be identified as the science evolves. The categories range from global impacts, such as global warming, to local impacts, such as photochemical smog. After completing a review of the most common categories, eight impact categories were selected for use in the FRED LCA system. These categories were selected based on the goals of the effort, the breadth of the project's scope, and the level of acceptance within the impact assessment community.

Step 3: Life Cycle Impact Assessment

A life cycle impact assessment (LCIA) can be used to evaluate a product's potential effect on human health and environment. To accomplish this goal, the LCA principles of impact categories and impact indicator models are used.

Impact categories are defined classifications of human health and environmental effects caused by a product through out its life cycle. The FRED LCA system defines the following "core" group of eight impact categories.

- Global Warming
- Stratospheric Ozone Depletion
- Acidification
- Photochemical Smog
- Eutrophication
- Human Toxicity
- Ecological Toxicity
- Resource Depletion

Impact indicators measure the potential for the impact to occur, rather than attempting to directly quantify the actual impact. This approach works well in the FRED LCA system, because it is a comparative method using relative magnitude to determine which product has less of a potential impact, as opposed to a measure of a single product's absolute environmental impact. An impact indicator is generally an intermediate node (i.e. a mid-point) on the environmental mechanism for which there is a science-based correlation to the environmental impact. For example, one of the ways global warming potential is quantified is to evaluate the radiative forcing potential of the greenhouse gases in the atmosphere, because this measure integrates the forcing function on the earth's climate:

GHGs	➡	Radiative Forcing	➡	Global Climate Change (increasing temperature, etc.)	➡	Environmental Damage

The ISO 14042 guidelines for impact assessment describe the need for environmentally relevant indicators and that the indicator results should be clearly stated in terms of the following criteria:

a) The ability of the category indicator to reflect the consequences of the LCI results on the category endpoint(s), at least qualitatively; and

b) The addition of environmental data or information to the characterization model, with respect to the category endpoint(s), including:

   - the condition of the category endpoint(s),
   - the relative magnitude of the assessed change in the category endpoint(s),
   - the spatial aspects, such as area and scale,
   - the temporal aspects, such as duration, residence time, persistence, timing, etc.,
   - the reversibility of the environmental mechanism, and
   - the uncertainty of the linkages between the characterization model and the changes in the category endpoints.

These criteria for environmental relevance were used to help select the impact indicators for the LCA component of FRED. LCIA is a developing area and the FRED LCA system relies only on existing methods and models. Therefore, not all of the criteria for environmental relevance were able to be met. Each impact indicator has a checklist and description of how the indicator meets or does not meet the ISO criteria for environmental relevance.

The following sections describe in detail the meaning of each impact category, the indicator which represents the potential for the impact to occur, the model selected to quantify the associated affects to human health or the environment, as well as the environmental relevance mentioned above.

Global Warming

Background

Global warming , or the "greenhouse effect," is defined as the changes in the Earth's climate caused by a changed heat balance in the Earth's atmosphere. After water vapor, CO_2 is the most important greenhouse gas. Normally, billions of tons of carbon in the form of CO_2 are absorbed by the oceans and vegetation and are emitted to the atmosphere annually through natural processes. When at equilibrium, the changes between absorption and emission are roughly balanced. The additional anthropogenic sources of greenhouse gases (GHG's) present in the atmosphere may have shifted that equilibrium, acting as a "thermal blanket"and trapping heat from reflected sunlight that would otherwise pass through the atmosphere.

Altering the atmosphere by trapping more heat has been modeled to have a wide variety of effects on the earth's climate, including longer growing seasons, droughts, floods, increased glaciation, loss of the polar ice caps, sea level rise and other displacements, including direct effects on human health through biological agents. The speed of these projected effects, coupled with their widespread nature, imply a devastating effect on the entire biosphere.

Calculating the FRED Global Warming Indicator

The Intergovernmental Panel on Climate Change (IPCC) global climate change model is used to estimate the potential impacts to the environment from global warming. This model converts quantities of GHG's into carbon dioxide (CO_2) equivalents using IPCC-defined global warming potential equivalency factors. Global Warming Potential Equivalency Factors (GWP's) compare the ability of each greenhouse gas to trap heat in the atmosphere relative to the heat-trapping ability of CO_2.

GHG data obtained for each LCA stage are multiplied by the relevant GWP_{100} (over a 100 year lifespan) to produce CO_2 equivalent values. As the equivalency factors are unitless values, any unit of weight can be used, as long as the unit of measurement is stated explicitly and are consistent throughout the calculation. This process is done for each GHG, with the final step being the summation of all CO_2 equivalents. The final sum, known as the Global Warming Index (GWI), indicates the product's potential contribution to global warming for each life cycle stage.

The following equation is used to calculate the GWI:

$$\text{Global Warming Index} = \Sigma_i\ w_i \times GWP_i, \text{ where}$$

w_i = weight of inventory flow i per functional unit of product
GWP_i = Global Warming Potential Equivalency Factor evaluated at 100 years
= weight of CO_2 with the same heat-trapping potential as a gram of inventory flow i

Exhibit 3-1 shows the GWP's for some substances that are considered to contribute to global warming. A 100-year lifespan was selected as the most suitable for the goal of this effort, although other bases for calculating potential equivalency (such as 20-year or 50-year factors) are available.

Exhibit 3-1. Global Warming Potential Equivalency Factors

Substance	Formula	GWP wt CO2/wt substance over a 100-year lifespan
Carbon dioxide	CO_2	1
HFC-23	CHF_3	11700
HFC-32	CH_2F_2	650
HFC-41	CH_3F	150
HFC-43-10mee	$C_5H_2F_{10}$	1300
HFC-125	C_2HF5	2800
HFC-134	$C_2H_2F_4$	1000
HFC134a	CH_2FCF_3	1300
HFC-152a	$C_2H_4F_2$	140
HFC-143	$C_2H_3F_3$	300
HFC-143a	$C_2H_3F_3$	3800
HFC-227ea	C_3HF_7	2900
HFC-236fa	$C_3H_2F_6$	6300
HFC-245ca	$C_3H_3F_5$	560
Chloroform	CH_3Cl	9
Methylene chloride	CH_2Cl_2	1300
Sulfur hexafluoride	SF_6	23900
Perfluoromethane	CF_4	6500
Perfluoroethane	C_2F_6	9200
Perfluoropropane	C_3F_8	7000
Perfluorobutane	C_4F_{10}	7000
Perfluorocyclobutane	$c\text{-}C_4F_8$	8700
Methane	CH_4	21
Nitrous oxide	N_2O	310

(IPCC, 1995)

Example

The following example uses LCI data from the BEES motor oil study (listed in Appendix A) to calculate the global warming potential for the various life cycle stages in the oil rerefining process:

Substance	Transport of Re-refined Oil for Manufacture	GWP	GWI	Re-refined Oil production	GWP	GWI	Transport of Re-refined Oil for Use	GWP	GWI	Use	GWP	GWI	End of Life	GWP	GWI
CO2 (biomass)	0	1	0	0	1	0	0	1	0	0	1	0	0	1	0
CO2 (fossil)	13.000	1	13.000	2.48E+02	1	248.000	61.800	1	61.800	0	1	0	0	1	0
Methane	0.005	21	0.105	1.23E-01	21	2.583	0.021	21	0.441	0	25	0	0	25	0
N2O	0.024	310	7.440	5.39E-03	310	1.671	0.011	310	3.410	0	320	0	0	320	0
Subtotal			**20.600**			**252.300**			**65.700**			**0**			**0**
									Total for all LC stages: **338.6g equivalent CO_2**						

Environmental Relevance

ISO Criteria	Met by Indicator	Description
Consequence Link	✔	All greenhouse gases in the LCI are evaluated for their radiative forcing potential. Changes in the heat balance of the atmosphere are the forcing function for global climate change. No attempt is made to calculate the effects on endpoints.
Environmental Condition and Intensity	NA	Does account for ambient concentrations of GHG's in the atmosphere and the intensity of the global warming effect. Does consider the variation in potency of different GHG's (e.g., methane is a more potent GHG than CO2) and the absolute contribution of GHG's to global warming in terms of CO2 equivalents. Not applicable to location-specific projected effects.
Spatial Aspects	✔	Considers the potential impact on the global climate. However, more refined spatial characterization, such as regional climate change, is not captured.
Temporal Aspects	✔	Based on the 100 year time horizon.
Reversibility		Does not consider the reversibility of global warming.

ISO Criteria	Met by Indicator	Description
Uncertainty		Does not consider the uncertainty of global warming.

Stratospheric Ozone Depletion

Background

Stratospheric ozone depletion is the unnatural reduction of the protective ozone (O_3) layer, due in part to chemical reactions with man-made substances. Stratospheric ozone is constantly being created and destroyed through natural cycles. Various ozone-depleting substances (ODS's), however, accelerate the destruction processes, resulting in lower than normal ozone levels. For example, when a particular type of ODS known as chlorofluorocarbons (CFC's) reach the stratosphere, the ultraviolet radiation from the sun causes them to break apart and release chlorine atoms which react with ozone, starting chemical cycles of ozone destruction that deplete the ozone layer.

Reductions in ozone levels will lead to higher levels of UVB (a kind of ultraviolet light from the sun) reaching the Earth's surface. Laboratory and epidemiological studies demonstrate that UVB causes nonmelanoma skin cancer and plays a major role in malignant melanoma development. In addition, UVB has been linked to cataracts. UVB also harms some crops, plastics and other materials, and certain types of marine life.

Calculating the FRED Stratospheric Ozone Depletion Indicator

The Montreal Protocol Handbook, a primary guidance document on stratospheric ozone depletion, uses ozone depletion potential, expressed as CFC-11 equivalents, as the indicator of the potential for depletion to occur. The technique used for converting ODC's obtained from LCI data to CFC-11 equivalents is the same as the method demonstrated for global climate change: multiply the emissions values by the equivalency factor, and add the resultant equivalencies to arrive at the product's overall potential contribution to stratospheric ozone depletion.

The model established by the Montreal Protocol uses the following technique for calculating the equivalency potential (EP):

$$EP = \sum w_i \text{ x } EF_i$$

where w_i = weight of inventory flow i per functional unit of product
EF_i = ozone depletion potential equivalency factor
= weight of CFC11 with the same potential ozone depleting effect as a gram of inventory flow i

Exhibit 3-2 shows the equivalency factors (EF's) for ODC's developed by the Protocol.

Exhibit 3-2. Stratospheric Ozone Depletion Potential Equivalency Factors

Substance	Formula	EF wt CFC11/wt substance ∞(at infinity*)
CFC11	$CFCl_3$	1
CFC12	CF_2Cl_2	0.82
CFC113	$CF_2ClCFCl_2$	0.90
CFC114	CF_2ClCF_2Cl	0.85
CFC115	CF_2ClCF_3	0.40
Tetrachloromethane	CCl_4	1.20
HCFC22	CHF_2Cl	0.04
HCFC123	CF_3CHCl_2	0.014
HCFC124	CF_3CHFCl	0.03
HCFC141b	$CFCl_2CH_3$	0.10
HCFC142b	CF_2ClCH_3	0.05
HCFC225ca	$CF_3CF_2CHCl_2$	0.02
HCFC225cb	CF_2ClCF_2CHFCl	0.02
1,1,1-trichlorethane	CH_3CCl_3	0.02
Methyl chloride	CH_3Cl	0.12
		0.02
Halon1301	CF_3Br	12
Halon 1211	CF_2ClBr	5.1
Methyl bromide	CH_3Br	0.64

(EPA, 1999)
* different time scale factors are available; it is recommended by the Society of Environmental Toxicology and Chemistry (SETAC, 1997) to use infinity.

Example

The following example calculates the stratospheric ozone depletion potential for a hypothetical process:

Substance	Raw Material Acquisition	EF	EP	Manufacturing Process	EF	EP	Transport of Product	EF	EP	Use	EF	EP	End of Life	EF	EP
CFC 11	0.50	1.00	0.50	10.00	1.00	10.00	0	1.00	0.00	0.25	1.00	0.25	5.00	1.00	5.00
Halon 1211	2.00	3.00	6.00	1.00	3.00	3.00	0	3.00	0.00	0.10	3.00	0.30	0.50	3.00	1.50
Methyl Bromide	1.00	0.70	0.70	4.00	0.70	2.80	0	0.70	0.00	0.20	0.70	0.14	2.00	0.70	1.40
Subtotal			**7.2**			**15.8**			**0**			**0.69**			**7.9**
											Total for all LC stages: 31.6 g equiv. CFC11				

Environmental Relevance

ISO Criteria	Met by Indicator	Description
Consequence Link	✔	All ozone depleting substances in the LCI are evaluated for their ozone destruction potential, but no attempt is made to calculate effects on endpoints.
Environmental Condition and Intensity		Does not account for ambient concentrations of ozone depleting substances in the atmosphere or the intensity of the ozone depletion effect.
Spatial Aspects	✔	Considers the potential impact on the global level of ozone, which is appropriate for this category. More refined spatial characterizations, such as regional ozone depletion, are not captured.
Temporal Aspects	✔	Evaluates the ozone depletion potential of substances integrated over their atmospheric lifetimes.
Reversibility		Does not consider the reversibility of ozone depletion effects.
Uncertainty		Does not consider the uncertainty of ozone depletion.

Acidification

Background

Acidification, or acid rain as it is commonly known, occurs when emissions of sulfur dioxide (SO2) and oxides of nitrogen (NO_x) react in the atmosphere with water, oxygen, and oxidants to form various acidic compounds. This mixture forms a mild solution of sulfuric acid and nitric acid. Sunlight increases the rate of most of these reactions.

These compounds then fall to the earth in either wet form (such as rain, snow, and fog) or dry form (such as gas and particles). About half of the acidity in the atmosphere falls back to earth through dry deposition as gases and dry particles. The wind blows these acidic particles and gases onto buildings, cars, homes, and trees. In some instances, these gases and particles can eat away the things on which they settle. Dry deposited gases and particles are sometimes washed from trees and other surfaces by rainstorms. When that happens, the runoff water adds those acids to the acid rain, making the combination more acidic than the falling rain alone. The combination of acid rain plus dry deposited acid is called acid deposition. Prevailing winds transport the compounds, sometimes hundreds of miles, across state and national borders.

Electric utility plants account for about 70 percent of annual SO_2 emissions and 30 percent of NOx emissions in the United States. Mobile sources (transportation) also contribute significantly to NOx emissions. Overall, over 20 million tons of SO_2 and NO_x are emitted into the atmosphere each year.

Acid rain causes acidification of lakes and streams and contributes to damage of trees at high elevations (for example, red spruce trees above 2,000 feet in elevation). In addition, acid rain accelerates the decay of building materials and paints, including irreplaceable buildings, statues, and sculptures that are part of our nation's cultural heritage. Prior to falling to the earth, SO_2 and NO_x gases and their particulate matter derivatives, sulfates and nitrates, contribute to visibility degradation and impact public health.

Calculating the FRED Acidification Indicator

Several indicators exist for acidification; the most common reference substances being hydrogen ions and sulfur dioxide. Either can be expressed in terms of the other. The FRED methodology uses SO_2 as the reference chemical. The method for calculating the Acidification Index (AI) is similar in approach to other impact indicators: the LCI substances that are present in the table below are multiplied by the equivalency factor (AP) to arrive at SO_2 equivalent quantities. The SO_2 equivalents for each life cycle stage are summed to calculated the Acidification Index (AI).

The following equation outlines the calculation:

$$\text{Acidification Index} = \Sigma_i\, w_i \times AP_i, \text{ where}$$

w_i = weight of inventory flow i per functional unit of product
AP_i = Acidification Potential Equivalency Factor
= weight of SO_2 with the same potential acidifying effect as a unit weight of inventory flow i

Exhibit 3-3. SO_2 Equivalency Factors for Acidification

Substance	AP wt SO_2/ wt substance
Ammonia	1.90
HCl	0.087
HF	1.61
NO	0.71
NO2	0.7
NOx	0.71

SO2	1
SOx	1

Example

The following example uses LCI data from the BEES motor oil study (list in Appendix A) to calculate the acidification potential for the various life cycle stages in the oil rerefining process.:

Substance	Transport of Re-refined Oil for Manufacture	AP	AI	Re-refined Oil production	AP	AI	Transport of Re-refined Oil for Use	AP	AI	Use	AP	AI	End of Life	AP	AI
Ammonia	1.67E-08	1.88	3.14e-08	2.95E-08	1.88	6e-08	7.92E-08	1.88	1e-07	0	1.88	0	0	1.88	0
Hydrogen Chloride	6.56E-05	0.88	5.77e-05	3.68E-03	0.88	0	3.11E-04	0.88	0	0	0.88	0	0	0.88	0
Hydrogen Fluoride	8.20E-06	1.6	1.31e-05	4.60E-04	1.6	0	3.89E-05	1.6	0	0	1.6	0	0	1.6	0
Nitrogen Oxides	3.05E-02	0.7	2.14e-02	5.20E-01	0.7	0.36	1.45E-01	0.7	0.102	0	0.7	0	0	0.7	0
Sulfur Oxides	1.92E-02	1.0	1.92e-02	1.54E+00	1.0	1.54	9.11E-02	1.0	0.09	0	1.0	0	0	1.0	0
Subtotal			**0.04**			**1.91**			**0.19**			**0**			**0**
											Total for all LC stages: 2.14 g equivalent SO2				

Environmental Relevance

ISO Criteria	Met by Indicator	Description
Consequence Link	✔	All acid precursors in the LCI are convertedto acidification potential based on their chemical equivalancies. Deposition of protons where neutralization capacity is exceeded is the forcing function of acidification..
Environmental Condition and Intensity		Does not account for ambient concentrations of acid ions in the atmosphere or the potential intensity of acidification effects to the environment. Does consider the variation in potency of different pollutants and the overall potential contribution of acid precursors to acidification in terms of SO_x equivalents. This indicator represents an upper bound to acidification.

ISO Criteria	Met by Indicator	Description
Spatial Aspects		Considers the potential for forming acid ions in a generic sense. More refined spatial characterizations, such as regional acidification, may be preferred and are not captured by this indicator.
Temporal Aspects		Does not consider the temporal aspects of acidification.
Reversibility		Does not consider the reversibility of acidification.
Uncertainty		Does not consider the uncertainty of acidification.

Photochemical Smog

Background

Ground-level ozone causes a variety of short-term and long term health effects, such as eye and respiratory irritation, and pre-cancerous lesions. The oxidative ability of ozone causes damage to forests, agricultural products and personal property (i.e., items using paint, rubber or plastics).

When fossil fuels (e.g., gasoline) are burned, a variety of pollutants are emitted into the earth's troposphere, i.e. the region of the atmosphere in which we live - from ground level up to about 15 km. The advent of increased automobile use in the last sixty years has led to increased levels of reactive organic gases (ROG's) and oxides of nitrogen (NO_x) in the air. Under certain conditions these gases, in the presence of sunlight, can undergo complex chemical reactions that create ground-level ozone. Two of the pollutants that are emitted are hydrocarbons (e.g., unburned fuel) and nitric oxide (NO). When these pollutants build up to sufficiently high levels, a chain reaction occurs from their interaction with sunlight in which the NO is converted to nitrogen dioxide (NO_2). NO_2 is a brown gas and at sufficiently high levels can contribute to urban haze. However, a more serious problem is that NO_2 can absorb sunlight and break apart to produce oxygen atoms that combine with the O_2 in the air to produce ozone (O_3). Ozone is a powerful oxidizing agent, and a toxic gas. In North America elevated levels of tropospheric ozone cause several billion dollars per year damage to crops (45 million/per year in Ontario), structures, forests, and human health. It is believed that the natural level of ozone in the clean troposphere is 10 to 15 parts-per-billion (ppb). Because of increasing concentrations of hydrocarbons and NO in the atmosphere, scientists have found that ozone levels in "clean air" are now approximately 30 ppb. A principal activity of atmospheric chemists is to study and determine how we might reverse this trend.

Calculating the FRED Photochemical Smog Indicator

The FRED LCA system uses the Maximum Incremental Reactivity (MIR) approach to calculate this indicator. The MIR approach is based on the chemical composition of air in 39 urban areas in the US, which were modeled by keeping the light and VOC concentrations constant and varying the NO_2 concentration to achieve the maximal ozone production. (NO_2 is a catalyst at low concentrations and an inhibitor at high concentrations). MIR values are very useful, as they are valid anywhere on the globe. However, they represent an upper bound of ozone production, and must be viewed in that light. In many Northern cities, there is not enough light most of the year to produce the full amounts of ozone indicated by the MIR results. (Carter, 1998) For additional information on the MIR study, see http://www.cert.ucr.edu/~carter/bycarter.htm.

Photochemical smog potential is calculated in the same way as global warming, but substituting in MIR values.

Photochemical Smog Index (PSI) = $\Sigma_i\ w_i \times MIR_i$, where

w_i = weight of inventory flow i per functional unit of product
MIR_i = Maximum Incremental Reactivity value for inventory flow i

The MIR study contains equivalency factors for a variety of chemicals; a selection of chemicals from the study is presented in Exhibit 3-4.

Exhibit 3-4. Photochemical Smog Potential Equivalency Factors (Carter, 1998)

Substance	MIR wt ozone/ wt substance
Acetone	0.48
Benzene	1.0
Carbon Monoxide	0.07
Ethanol	1.92
Ethylene Glycol	2.65
Formaldehyde	9.12
Methanol	0.99
NMHC’s	3.93
Phenol	1.86
Toluene	4.19

Example

The following example uses LCI data from the BEES motor oil study (list in Appendix A) to calculate the photochemical smog potential for the various life cycle stages in the oil rerefining process.:

Substance	Transport of Re-refined Oil for Manufacture	MIR	PSI	Re-refined Oil production	MIR	PSI	Transport of Re-refined Oil for Use	MIR	PSI	Use	MIR	PSI	End of Life	MIR	PSI
Benzene	8.79e-07	1	8.79e-07	4.03e-07	1	4.03e-07	4.16e-06	1	4.16e-06	0	1	0	0	1	0
Carbon Monoxide	1.15e-02	0.07	8.04e-04	1.90e-01	0.07	1.33e-02	5.44e-02	0.07	3.81e-03	0	0.07	0	0	0.07	0
Form	1.17e-05	9.12	1.07e-04	5.39e-06	9.12	4.92e-05	5.57e-05	9.12	5.08e-04	0	9.12	0	0	9.12	0
NMHCs	6.62e-03	3.93	2.60e-02	1.28e-03	3.93	5.02e-03	3.13e-02	3.93	1.23e-01	0	3.93	0	0	3.93	0
Subtotal			**0.0269**			**0.0183**			**0.1277**			0			0
										Total for all LC stages: 0.1729 g equivalent ozone					

Environmental Relevance

ISO Criteria	Met by Indicator	Description
Consequence Link	✔	All smog precursors in the LCI are converted to a modeled MIR scale by using the Empirical Kinetic Modeling Approach (EKMA) and varying the levels of NO_x and Reactive Organic Gases (ROG's) to obtain the highest incremental reactivity. There is an established link between NO_x and ROG's in the atmosphere and subsequent smog formation.
Environmental Condition and Intensity	✔	Does not account for actual ambient concentrations of NOx and ROG's in the atmosphere but rather uses averages from 39 cities in the U.S. to develop a base MIR model. The intensity of the impact can be considered to be a maximum estimate because NO_x and ROG's are held at levels to obtain the maximum incremental reactivity. The MIR scale does consider the variation in potency of different pollutants and the overall potential contribution of the substances to smog by relating smog precursors along the MIR scale.

Spatial Aspects		Considers the potential for forming photochemical smog in a generic sense through use of the EKMA model and average concentrations of NOx and ROG's in the atmosphere but rather uses averages from 39 cities in the U.S. More site-specific characterizations may be preferred and are not captured by this indicator.
Temporal Aspects		Does not consider the temporal variations of smog production.
Reversibility		Does not consider the reversibility of smog.
Uncertainty		Uncertainty adjusted MIR values are available but were not used. The authors of the MIR model recommend using the "best estimate" values for product categories.

Eutrophication

Background

Accelerated eutrophication is the reduction in water quality caused by excess nutrient loading. Eutrophic waters are rich in organisms and organic materials, in contrast to oligotrophic waters, which are characterized by clear water and low biological productivity. The rate of eutrophication depends on complex relationships between several factors including water chemistry and depth, volume and inflow, mineral content of the surrounding watershed, and the biota of the lake itself. Human activities can increase the rate of eutrophication through increased nutrient flows, higher temperatures, or other changes. While increased productivity is sometimes beneficial, eutrophication often has undesirable results.

Accelerated eutrophication damages the aesthetic and recreational water qualities, as well as altering species composition.. Water can become opaque with unpleasant taste and odors. This increased rate of eutrophication can cause lakes and reservoirs that normally might exist for centuries to be filled in a matter of decades. Under eutrophic conditions, the algae in the water significantly block the light passage. Under hypereutrophic conditions, the amount of biomass produced is so high that the dissolved oxygen in the water is used up, leading to fish kills.

Eutrophication in marine waters is typically caused by the addition of fixed nitrogen, while fresh waters usually respond only to phosphorus inputs. The worldwide eutrophication of estuaries is believed to be the cause of toxic algae blooms such as *Pfisteria*, and has also been implicated in cholera epidemics on the Indian sub-continent.

Calculating the FRED Eutrophication Indicator

Exhibit 3-6 shows the substances which cause eutrophication and their related equivalency values. The eutrophication index is essentially the sum of all eutrophication precursors expressed in the form of phosphate ion (PO_4) equivalents by multiplying the loading of each with its related equivalency factor. These equivalencies are derived form the work of Redfield (1942), who discovered that aquatic biomass forms with a Carbon to Nitrogen to Phosphorus (C:N:P) atomic ratio of 106:16:1.

The total eutrophication index (EI) for each alternative being assessed is calculated as follows:

$$\text{Eutrophication Index} = \Sigma_i \, w_i \times EP_i$$

w_i = weight of inventory flow i per functional unit of product
EP_i = eutrophication potential equivalency factor
= weight of PO_4 with the same potential eutrophying effect as a unit weight of inventory flow i

Exhibit 3-5. Eutrophication Potential Equivalency Factors

Substance to Air	**EP wt PO_4/ wt substance**
Ammonia	0.33
Nitrates	0.42
NO	0.2
NO2	0.13
NOx	0.13
Phosphate	1
Substance to Water	**Eutrophication Potential g PO_4/ g substance**
COD	0.022
NH3	0.33
NH4+	0.33

(Redfield, 1942)

Example

The following example uses LCI data from the BEES motor oil study (list in Appendix A) to calculate eutrophication potential for the various life cycle stages in the oil rerefining process.:

Substance	Transport of Re-refined Oil for Manufacture	EUT	EUTI	Re-refined Oil production	EUT	EUTI	Transport of Re-refined Oil for Use	EUT	EUTI	Use	EUT	EUTI	End of Life	EUT	EUTI
Ammonia	3.85e-04	.33	1.27e-04	8.67e-02	0.33	2.86e-02	1.82e-03	0.33	6.01e-04	0	0.33	0	0	0.33	0
COD	2.22e-02	0.22	4.89e-03	5.00e+00	0.22	1.10e+00	1.05e-01	0.22	2.32e-02	0	0.22	0	0	0.22	0
Nitrates	2.35e-08	0.42	9.87e-09	1.32e-06	0.42	5.54e-07	1.11e-07	0.42	4.68e-08	0	0.095	0	0	0.095	0
Phosphates	0	1	0	0	1	0	0	1	0	0	1	0	0	1	0
Subtotal			**0.0050**			**1.1333**			**0.0238**			**0**			**0**
											Total for all LC stages: 1.1621 g equivalent PO4				

Environmental Relevance

ISO Criteria	Met by Indicator	Description
Consequence Link	✔	All eutrophication precursors in the LCI are converted to biomass equivalents using the Redfield Ratio. There is an established link between nutrients in water bodies and subsequent eutrophication.
Environmental Condition and Intensity		Does not account for ambient concentrations of phosphate or nitrogen in water bodies or the intensity of the eutrophication effects to specific water bodies. Does consider the variation in potency of different pollutants that contribute to eutrophication and the overall eutrophication potential by relating the pollutants in terms of Phosphate equivalents. This measure of eutrophication is a worst-case estimate.
Spatial Aspects		Does not consider the spatial variations, local or regional, of eutrophication.
Temporal Aspects		Does not consider the temporal variations of eutrophication.

ISO Criteria	Met by Indicator	Description
Reversibility		Does not consider the reversibility of eutrophication.
Uncertainty		Does not consider the uncertainty of eutrophication.

Human Toxicity

Background

Industrial systems often release substances into the environment which can have toxic effects on human beings. In order for actual effects to occur, exposure to the substance must occur, the substance must be assimilated, and the received dose to the individual must exceed the body's ability to detoxify it.

There are a multiplicity of potential toxic effects of industrial and natural substances, ranging from transient irritation to permanent disability and even death. Some substances have a wide range of different effects, and different individuals have a widely varying tolerance to different substances. Finally, of the millions of industrial chemicals, very few have been subjected to toxicological evaluation. All these factors make an assessment of the human toxicity potential of given substances difficult at best. When evaluated on a life cycle basis, evaluating their impact is even more problematic.

Nevertheless, because human toxicity is a real and important environmental issue, the FRED LCA system incorporated an indicator based on the recommendations of the International Life Sciences Institute, which suggested that all life cycle human toxicity indicators be based on no observable adverse effects levels (NOEL's, NOAEL's) or lowest observable effects levels (LOEL's, LOAEL's). In other words, concentrations or doses of chemicals tested on humans or laboratoryanimals that caused no effect or minimal effect. Generally, the lower the NOAEL or LOAEL, the more toxic the chemical.

Calculating the FRED Human Toxicity Indicator

The FRED methodology uses Environmental Defense Fund (EDF) Scorecard, (http://www.scorecard.org) developed in conjunction with University of California at Berkeley, as an indicator of human toxicity. This indicator is actually a pair of indicators, one for carcinogenic and one for non-carcinogenic effects:

$$\text{Human Toxicity Index} = \Sigma_i\, w_i \times TEP_i$$

w_i = weight of inventory flow i per functional unit of product
TEP_i = toxic equivalency potential
= (for carcinogens) weight of benzene with the same potential

cancer-causing effect as a unit weight of inventory flow i
= (for non-carcinogens) weight of toluene with the same potential
toxic effect as a unit weight of inventory flow i

Exhibit 3-6. Examples of Human Toxicity Potential Equivalency Factors

Substance to Air	**TEP (carcinogens) wt Benzene/ wt substance**	**TEP (non-carcinogens) wt Toluene/ wt substance**
Ammonia		3.2
Benzene	1	17
Formaldehyde	0.003	7
Lead	15	1,300,000
Phenolics	0	0.045
Substance to Water		
Ammonia (NH_4+, NH_3 as N)	0	0.041
Benzene	0.99	11
Phenols		0.0038

(EDF, 2000)

Example

The following example uses LCI airborne emissions data from the BEES motor oil study (list in Appendix A) to calculate the carcinogenic human toxicity potential for the various life cycle stages in the oil rerefining process.:

Substance	Transport of Re-refined Oil for Manufacture	TEP	HTI	Re-refined Oil production	TEP	HTI	Transport of Re-refined Oil for Use	TEP	HTI	Use	TEP	HTI	End of Life	TEP	HTI
Ammonia	1.67e-08	0	0	2.95e-08	0	0	7.92e-08	0	0	0	0	0	0	0	0
Benzene	8.79e-07	1	8.79e-07	4.03e-07	1	4.03e-07	4.16e-06	1	4.16e-06	0	1	0	0	1	0
Formalde.	1.18e-05	0.003	3.53e-08	5.40e-06	0.003	1.62e-08	5.57e-05	0.003	1.67e-07	0	0.003	0	0	0.003	0
Lead (Pb)	0	15	0	0	15	0	0	15	0	0	15	0	0	15	0
Phenolics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Subtotal			**9.14e-07**			**4.19e-07**			**4.33e-06**			**0**			**0**
									Total for all LC stages: 5.66e-0 g equivalent benzene						

Environmental Relevance

ISO Criteria	Met by Indicator	Description
Consequence Link	✔	Uses CALTOX model to estimate media concentrations of pollutants and to develop relative scores. Benzene is used as the reference chemical for cancer affects and tolulene for non-cancer effects. Does not consider specific human health effects beyond the broad categories and cancer and non-cancer effects.
Environmental Condition and Intensity		Does not consider ambient environmental (beyond that imbedded in CALTOX), exposure conditions, or the intensity of human health effects for chemical pollutants. Considers the relative toxicity of cancer and non-cancer effects of chemical pollutants to humans.
Spatial Aspects		Does not consider the spatial variations, usually site-specific, in release and exposure to populations.
Temporal Aspects	✔	Considers the persistence and bioaccumulation of chemical pollutants in the environment.
Reversibility		Does not consider the reversibility of human health effects.
Uncertainty		Does not consider the uncertainty of human health effects.

Ecological Toxicity

Background

Ecological impact indicators consider potential adverse effects on populations of aquatic or terrestrial organisms. Therefore, the benchmarks used tend to address survival of populations rather than single organisms. Acute and chronic NOAEL's for aquatic (invertebrates and fish), mammalian, and avian species are considered.

The FRED Ecological Toxicity method includes measurements of relative hazard (toxicity factors or benchmarks) and environmental fate and transport (persistence and biomagnification factors). The approach involves the following steps (other than screening and significance assessment steps (also see flow chart):

1. Identify aquatic and terrestrial benchmarks for both acute and chronic toxicity.
2. Assign chemicals a default benchmark if data are missing. The geometric mean of the available benchmarks is used as the default.
3. Normalize benchmarks within each category based on the geometric mean.
4. Select the maximum normalized benchmark as the toxicity factor.
5. Identify persistence factors for pertinent environmental media.
6. Identify biomagnification factors.
7. Multiply toxicity, persistence, and biomagnification factors (TPB score) for each inventory flow within each environmental medium.
8. Multiply TPB scores by the inventory mass per functional unit.
9. Sum factors to derive total terrestrial and aquatic ecological toxicity impact indicator (ETI).

Determine the percentage of each ETI relative to the total ETI and select inventory flows contributing 0.1% (or a user-selected value) or more. Each of these steps are illustrated below.

<u>Step 1</u>: Ecological benchmarks have been derived primarily for fish and aquatic life, mammals, birds, and plants. Two broad categories of ecological benchmarks were selected. Aquatic benchmarks may be used to address releases to water and terrestrial benchmarks may be used to address releases to air or land. The LC_{50} was selected as one of the most commonly available acute benchmarks for aquatic life. In addition to the LC_{50}, acute and chronic lowest observed effect concentrations (LOEC's) or no observed effect concentrations (NOEC's), and water quality criteria are available for many chemicals. Similarly, LD_{50}'s and the lowest chronic no observed effect levels (NOEL's) reported for mammalian and avian species were selected to evaluate potential impacts to terrestrial species.

<u>Steps 2, 3 and 4</u>: The geometric mean of each benchmark type is calculated from the available data and is used as the default for missing values. Benchmarks are then normalized based on the geometric mean and the highest normalized benchmark is selected as the toxicity factor for terrestrial and aquatic impacts.

Steps 5 and 6: ILSI (1996), USEPA (1994a,b), and RTI (1993) include persistence factors. Generally, persistence factors are derived from expected environmental half lives or from residence times as estimated in multi-media fugacity models (Mackay, 1991). Recommended persistence factors are those developed in RTI (1993) and range from 0.25 to 0.75. A default value of 0.5 for organic pollutants in all media is used and a default value of 0.5 and 1 are used for metals in air and all other media, respectively.

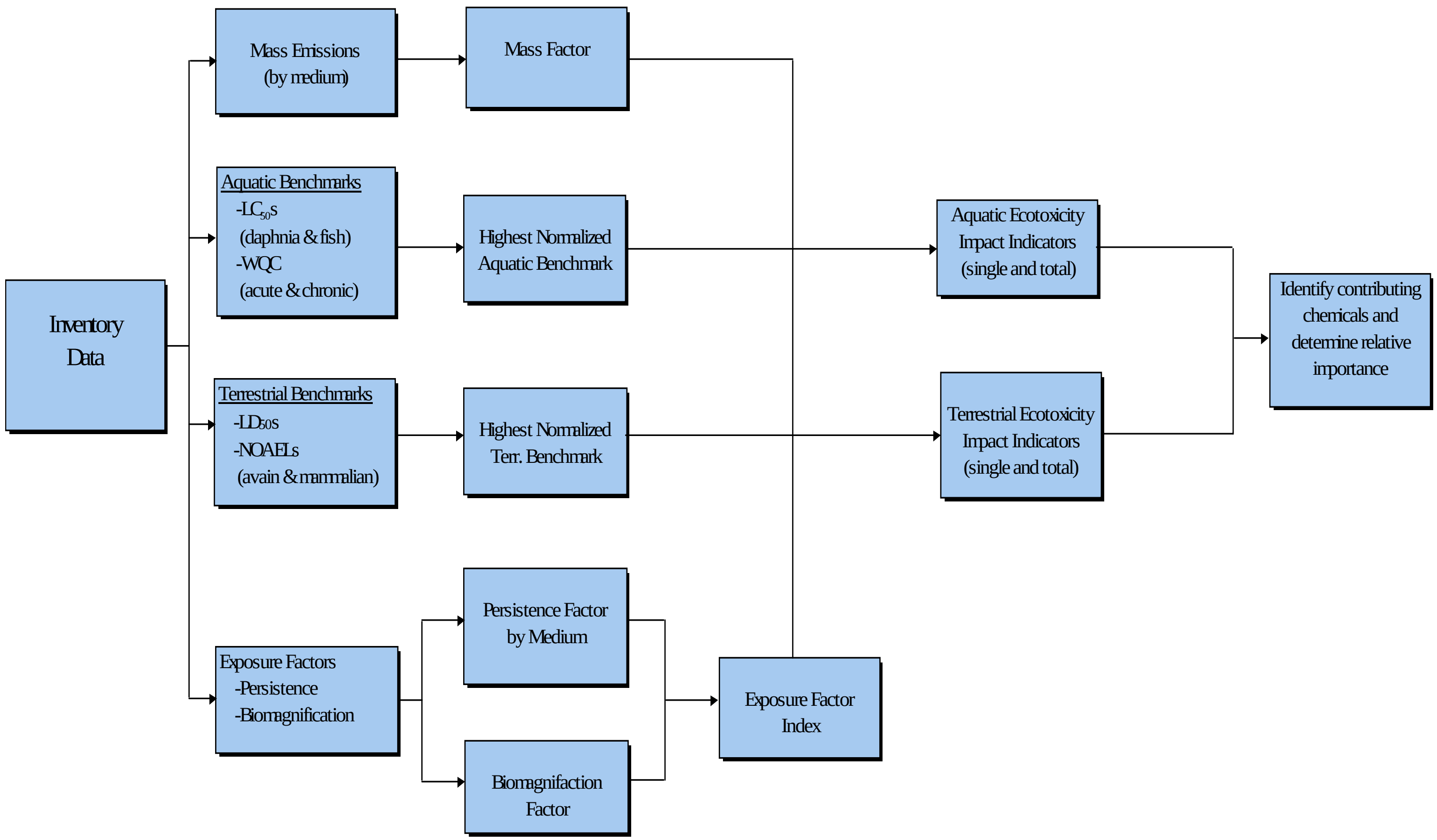
ILSI (1996) does not include biomagnification factors in their methodology but USEPA (1997, 1994a) and RTI (1993) do. It is recommended that pollutants be assigned to high, medium, or low categories to represent biomagnification potential. Biomagnification factors can be derived from K_{ow}'s or reported bioconcentration factors (BCF's) and bioaccumulation factors (BAF's). Standard biomagnification factors (low = 1, medium = 2, and high =3) are assigned to each category. A default value of 1 is used.

Step 7: Toxicity, persistence, and biomagnification factors are multiplied to derive the TPB score for each pollutant.

Steps 8, 9, and 10: Mass emission data per functional unit is multiplied by the TPB score to derive the ecological toxicity impact indicator.

Standard risk assessment practice is to assume additivity when multiple chemicals are being evaluated. Similarly, in the LCIA, ecological toxicity impact indicators for each pollutant are added to derive total scores for potential impacts to receiving media. Pollutants contributing 0.1% (or a user-selected value) or more to the total ETI would be flagged for further evaluation.

Exhibit 3-7. FRED Ecological Toxicity Method.



Calculating the FRED Ecological Toxicity Indicator

The ecological toxicity equivalency values are based on the model created by RTI for the Streamlined LCA Model Development and Demonstration Project (EPA, 1995) creates an equivalency value for chemicals based on the persistence, bioaccumulation and toxicity characteristics it exhibits in the environment. The Ecological Toxicity Index (ECOI)for the product is derived using the following equation:

$$\text{Ecological Toxicity Index (ECOI)} = \Sigma_i\, w_i \times ECO_i$$

w_i = weight of inventory flow i per functional unit of product
ECO_i = ecological toxicity equivalency potential

Exhibit 3-8. Sample Ecological Toxicity Potential Equivalency Factors

Substance to Air	ECO
Benzene	14.6
Fluorides	7.3
Formaldehyde	7.4
Hydrogen Chloride	11.0
Hydrogen Fluoride	11.0
Toluene	3.7
Vinyl Chloride	126.0
Xylenes (total)	3.7
Substance to Water	
Benzene	0.8
Hydrocarbons	17.0
Nitrates	5.7
Phenol	3.1
TCDD-2-3-7-8	6.1 E+7
Vinyl Chloride	17.0

(EPA, 1995)

Example

The following example uses LCI data from the BEES motor oil study (list in Appendix A) to calculate ecological toxicity potential for the various life cycle stages in the oil re-refining process.:

Substance	Transport of Re-refined Oil for Manufacture	ECO	ECOI	Re-refined Oil production	ECO	ECOI	Transport of Re-refined Oil for Use	ECO	ECOI	Use	ECO	ECOI	End of Life	ECO	ECOI
Benzene	8.79e-07	14.60	1.28e-05	4.03e-07	14.60	5.88e-06	4.16e-06	14.60	6.07e-05	0	14.60	0	0	14.60	0
Nitrates	1.04e-07	5.67	5.90e-07	5.83e-06	5.67	3.31e-05	4.92e-07	5.67	2.79e-06	0	5.67	0	0	5.67	0
Phenols	5.05e-05	3.06	1.55e-04	1.14e-02	3.06	3.49e-02	2.39e-04	3.06	7.33e-04	0	3.06	0	0	3.06	0
Formaldehyde	1.18e-05	7.38	8.71e-05	5.40e-06	7.38	3.99e-05	5.58e-05	7.38	4.12e-04	0	7.38	0	0	7.38	0
Fluorides (F-)	8.50e-15	7.30	6.21e-14	4.03e-13	7.30	2.94e-12	4.03e-14	7.30	2.94e-13	0	7.30	0	0	7.30	0
Subtotal			2.55e-04			3.50e-02			1.21e-03			**0**			**0**
											Total for all LC stages: 0.0365				

Environmental Relevance

ISO Criteria	Met by Indicator	Description
Consequence Link	✔	Uses established eco-toxicity benchmarks (PBT) known to result in ecological health effects. Does not consider specific ecological health effects beyond the broad category of ecological toxicity.
Environmental Condition and Intensity		Does not consider ambient environmental conditions. Uses LC_{50}, LOEC's, NOEC's, LD_{50}'s and the lowest chronic NOELs and acute and chronic water quality criteria. Highest normalized benchmark is selected as the toxicity factor for terrestrial and aquatic impacts.
Spatial Aspects		Does not consider the spatial variations, usually site-specific, in release and exposure to populations.
Temporal Aspects	✔	Considers the persistence and bioaccumulation of chemical pollutants in the environment.
Reversibility		Does not consider the reversibility of ecological effects.
Uncertainty		Does not consider the uncertainty of ecological effects.

Resource Depletion

Background

Resource depletion is related to the inputs of materials into the industrial system under study. Although resource depletion is identified as a single environmental issue for the purposes of environmentally preferable purchasing, in fact, resource depletion is an umbrella term for several sub-issues, which collectively can be considered to be of equal importance as all the remaining environmental issues related to emissions.

Resource depletion directly measures the sustainability of industrial systems. If resources are being used at or below their replacement rate, then their use does not affect the ability of future generations to maintain their quality of life. An example of a material for which sustainable use of the resource has been attained includes the use.

Biological resources have the potential to be used sustainably as well, and in some cases sustainable forestry practices appear to have achieved this ideal. However, many biological resources have gone the way of the passenger pigeon, as use rates exceeded the replacement rates.

In the US, land use patterns (also a resource depletion issue) are not typically considered to be sustainable. Agricultural practices typically lead to the loss of topsoil, and large and increasing proportions of the land have become urbanized. Land use is of particular concern for bio-based products, which typically use a large land area to produce products equivalent to mineral-based competitors.

Calculating the FRED Resource Depletion Indicator

Resource depletion impact values can be presented as a single value or as subvalues that represent each of the major types of resources being consumed. For the purposes of this analysis, we are presenting resource depletion impact values within the following subcategories:

- minerals
- fossil fuels
- wood
- land use (landfill, resource extraction area,)
- water use

These sub-categories represent the inherently different types of resources, and cannot be added together to achieve a single score.

The FRED LCA system uses the LCSEA model developed by Scientific Certification Systems (SCS) and its partners, Soil and Water to calculate the net resource depletion as a function of (1) the material's relative rate of depletion and (2) the relative degree of the resource's recycling. The equation for resource depletion is:

$$\text{Resource Depletion Indicator (RD)} = \Sigma_i\, w_i \times RDF_i$$

w_i = weight or volume of inventory flow i per functional unit of product

RDF_i = resource depletion factor

$$= \frac{\text{(Waste-Accretion)*T (Total Reserve-Current Reserve)}}{\text{Total Reserve + Recycling *T}}$$

where T is time in years, and Total Reserve is the known maximum extent (i.e., amount exploited over historical time plus current known, unexploited reserves). (See USGS, 1998)

For fossil fuel, this model uses the 50 year time horizon to project use. (T = 50)

The table below contains a sample of depletion factors from the LCSEA model.

Exhibit 3-9. Resource Depletion Factors

Resource	RDF
Coal	0.08086
Natural Gas	4.812
Oil/Petroleum	1.35
Uranium	39

For net resources depleted (or accreted), the units of measure express the equivalent depletion (or accretion) of the identified resource. All of the net resource calculations are based on the resource depletion factors:

Indicator - Net Resource	Units of Measure
Water	equivalent cubic meters
Wood	equivalent cubic meters
Fossil Fuels	tons of oil equivalents
Non-Fuel Oil and Gas	tons of oil equivalents
Metals	tons of (metal) equivalents
Minerals	tons of (mineral) equivalents
Land Area	equivalent hectares

Example

The following example uses LCI data from the BEES motor oil study (list in Appendix A) to calculate resource depletion potential for the various life cycle stages in the oil rerefining process.:

Substance	Transport of Re-refined Oil for Manufacture	EUT	EUTI	Re-refined Oil production	EUT	EUTI	Transport of Re-refined Oil for Use	EUT	EUTI	Use	EUT	EUTI	End of Life	EUT	EUTI
Coal	1.22e-04	0.081	9.88e-06	6.89e-03	0.081	5.58e-04	5.78e-04	0.081	4.68e-05	0	0.081	0	0.081	0	0
Natural Gas	3.37e-04	4.812	1.62e-03	1.28e-02	4.812	6.17e-02	1.59e-03	4.812	7.67e-03	0	4.812	0	4.812	0	0
Oil/Petroleum	3.92e-03	1.35	5.29e-03	2.03e-03	1.35	2.74e-03	1.86e-02	1.35	2.51e-02	0	1.35	0	1.35	0	0
Uranium	0	39	0	0	39	0	0	39	0	0	39	0	39	0	0
Subtotal			**0.007**			**0.065**			**0.033**			**0**			**0**
															Total for all LC stages: 0.164

Environmental Relevance

ISO Criteria	Met by Indicator	Description
Consequence Link	✔	Models the physical rate of resource consumption with respect to available in-ground stock, available standing stock, and accretion of stock. Does not differentiate whether recycled or virgin resources are consumed.
Environmental Condition and Intensity	✔	Considers the reserves of resources in the ground, in standing stock (e.g., buildings, bridges) as well as the accretion of resources through natural processes. The intensity of resource depletion is captured by relating resource consumption to available reserves and accretion.
Spatial Aspects	✔	Resource depletion is typically thought of as a global issue, and this indicator is appropriate for that level of assessment. While the model can consider the spatial variations (national or regional or local) of resource depletion, FRED does not require this level of modeling..
Temporal Aspects	✔	Considers the rate of resource depletion from known reserves.
Reversibility	✔	Does consider the reversibility of resource depletion through explicit consideration of recycling.
Uncertainty		Does not consider the uncertainty of resource depletion.

Other Issues Regarding the FRED Environmental Component

The environmental impact categories, indicators and models chosen to represent the potential for environmental impact are by no means definitive; there are many other models and systems available for use. The models chosen for FRED use globally-based data, whereas there are many models, both in existence and under development, which incorporate regional and localized data. These models better approximate the environmental impact in a given area. The designers of FRED consider impact model selection to be an iterative process. As the science and the data supporting the science develops, newer, more environmentally relevant models will gradually replace the current models. The case study below illustrates the development that is necessary for transition to more environmentally relevant models.

Case Study for Meeting ISO 14042 Requirements for Environmental Relevance: Photochemical Smog

Photochemical smog is an environmental condition that causes aesthetic, human and ecological health damages primarily at local and regional scales. The most relevant measure of the effect of VOC's on smog formation would be the actual change in smog formation in a specific airshed that results from changing the emission of specific VOC's in that airshed (Carter, 1994). The indicator used in the FRED LCA system for smog formation is the Maximum Incremental Reactivity (MIR) scale developed by Carter (1994) for use by the California Air Resources Board (CARB) for regulatory applications.

Because smog formation is highly dependent on environmental conditions, especially the sunlight and the presence of NO_x in the airshed, the concept of the MIR scale oversimplifies the complexities of the effects of VOC's on smog formation as well as its variation between locales and seasons. The MIR scale calculates ability of VOC's to yield ozone under optimum conditions, and does not meet many of the ISO 14042 requirements for environmental relevance. How could photochemical smog be modeled to be more consistent with the ISO 14042 requirements for environmental relevance?

Some recommendations for improving the photochemical smog indicator in the context of the environmental relevance requirements are highlighted below:

Consequence Link - There is already a well-established link between VOC's and the presence of NO_x in airsheds that lead to the formation of ground level ozone, and between ozone concentrations and damage to human health and the environment. No improvement is needed to satisfy this criteria.

Environmental Condition and Intensity - Ozone affects different endpoints at different levels. Natural background levels of ozone are about 25 ppbv, while crop damage has been observed at 40 ppbv and human health effects at 80 ppbv (the standard for the U.S.). In Europe, the goal is to achieve ozone concentrations which do not exceed 60 ppbv. The MIR scale was developed using average concentrations of NO_x and ROG's in the atmosphere and thus represents a generic and hypothetical airshed. To improve upon the use of a generic airshed, data from the airsheds for different cities (many already collected to develop the MIR scale) could be used to model conditions for ozone formation in specific cities, including the expected concentrations of ozone at different times of the day and of the year. The intensity of the ozone effect would then more closely related to actual conditions within a specific local rather that using maximum MIR values. Improving the environmental and intensity criteria would require more detail in the LCI about where emissions of VOC's and NO_x are occurring as well as airshed data for the location.

A simpler approach would be to evaluate the data on ozone concentration gathered in various airsheds, and use this information to modulate the MIR results. For example, one can calculate the number of days per year that the ozone concentration exceeds 40, 60 or 80 ppbv, and proportionate the MIR results according to this site-specific information.

Spatial Aspects - The MIR scale is developed using EKMA model and average concentrations of NO_x and ROG's in airsheds from 39 cities in the U.S. To improve the spatial aspects, the EKMA could be run using site-specific (and disaggregated) concentrations of NO_x and ROG's in specific locales. Improving the spatial criteria would require more detail in the LCI about where emissions of VOC's and NO_x are occurring.

Temporal Aspects - The MIR scale does consider the temporal aspects of ozone formation that it calculates the total amount of ozone generated during the atmospheric lifetime of the VOC's. One way to incorporate additional temporal aspects into this indicator would be consider the length of the ozone season. Ozone season data is collected and available for different locations.

Reversibility - Ozone causes many kinds of damage, some reversible and some not. Some examples include decreased crop productivity, eye irritation and in severe cases, permanent damage to lungs and other tissues, possibly leading to carcinogenic effects. The effects of infrequent and low-level exposure and can be reversed when ozone concentrations drop.

Uncertainty - Uncertainty adjusted MIR values are available but were not used for this indicator because the authors of the MIR scale recommend using the "best estimate" values for evaluating product categories. Uncertainty adjusted values may be used. The uncertainty of the effects of ozone on humans, animals and plants are not well characterized.

Similar kinds of assessments can be performed to yield more environmentally relevant indicators for each of the impact categories. FRED can be considered to be a baseline methodology for achieving indicators for the purpose of environmentally preferable purchasing. More sophisticated indicators may be desirable in some cases.

Chapter 4 – Presentation and Interpretation of the Indicator Results

Overview

The first three steps of the FRED LCA system yield the results associated with eight environmental and human health indicators for each product. The purpose of this chapter is to outline approaches for presentation of the indicator results, weighting among indicators, relative weights development methods, and linking of the life cycle indicator results with technical and cost information. The elements in this step relate closely to the optional elements of life cycle impact assessment, and interpretation phase of LCA. The reader should reference ISO 14042 (optional elements sections) and ISO 14043 (interpretation) for more specific information.

Because of the primary focus of this project was to outline the overall FRED framework and develop indicators, this step is presented more as possible options for consideration. Additional research will focus on examining and testing options for presentation and interpretation.

Presentation of Indicator Results

Decision-making can be greatly enhanced by effective presentation of the results. Although the numerical results may provide the detailed information for each variable that contributes to a decision, graphical presentation allows for the visual summation of the results, and their comparison to similar data-sets of the other alternatives being evaluated. Graphical presentation allows for easier interpretation and consistency in decision making, especially by non-expert decision makers. Several different methods can be used to present the numerical results of a study, and different types of graphs can facilitate different aspects of the decision.

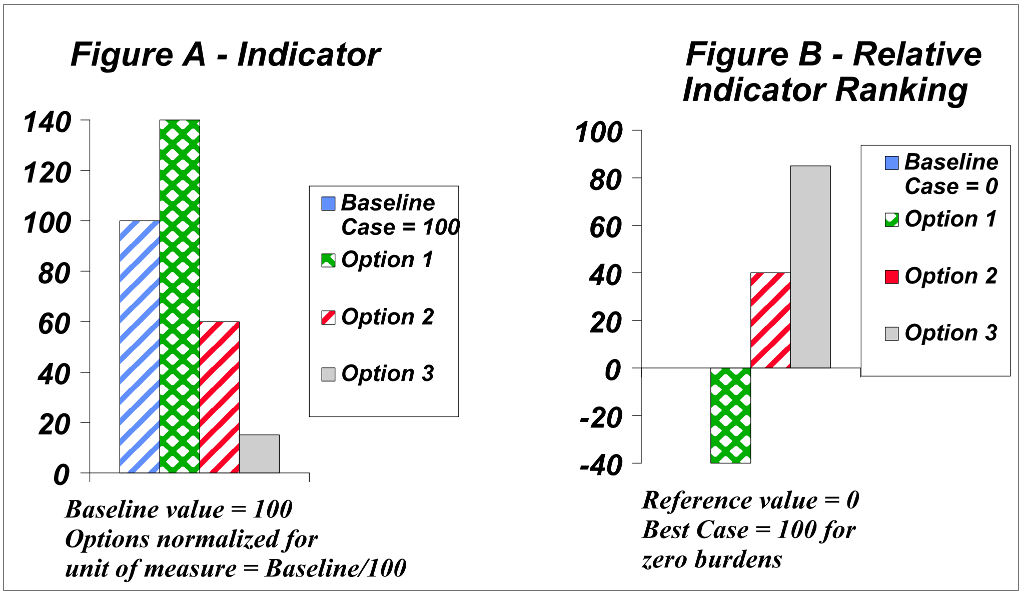


Exhibit 4-1. Graphical Presentation of Results

Exhibit 4-1 is just one example of a presentation format that can be used for environmental performance evaluation of products. The relative indicators of the system/product are presented graphically as compared to a baseline case (which can be one of the products being compared, or the product currently used in that function, if data is readily available for that product). The figure on the left in Exhibit 4-1 shows the method of translating and consolidating indicators to a common measure. The figure on the right in Exhibit 4-1 shows the next step that compares these indicators to a baseline (i.e. current product) in a sample graphical output. This type of output allows direct graphical comparison of the environmental performance several products within each of the indicators. Alternative products can be compared in each indicator 'dimension' individually. The product that may perform best can then be selected. Another method of presenting the results is to create an "environmental footprint" of the product, where the results of all the relevant indicators for the product are presented in one graphic. The "footprint" graphic may be a bar-diagram where each bar represents an indicator, a spider-web diagram (see Exhibit 4-2), where each spoke is an indicator, or other ways of graphically conveying the performance of the product along the dimensions of comparison.

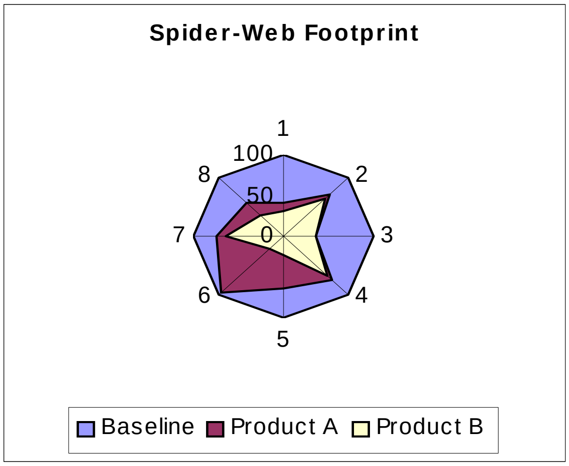
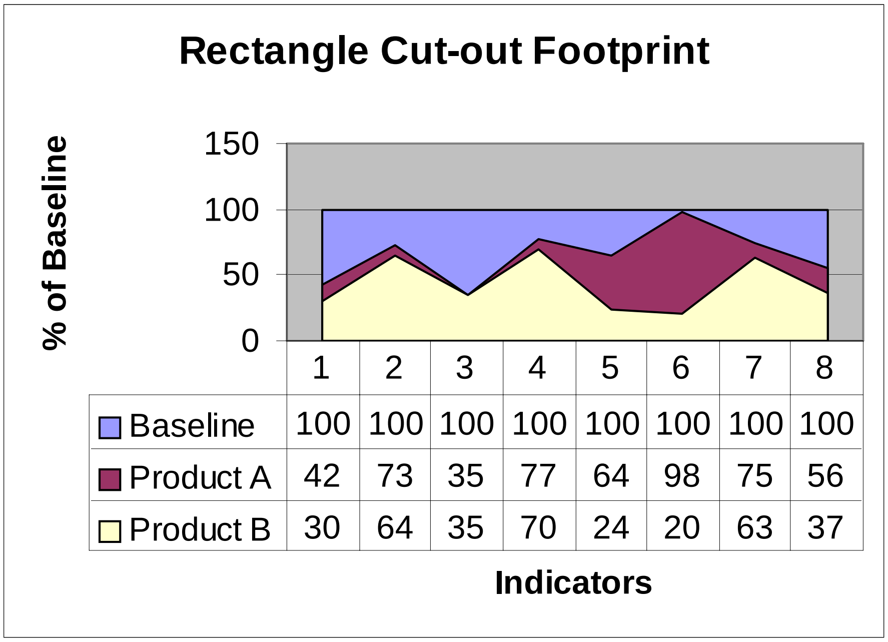


Exhibit 4-2. Spider-Web Footprint Display of Results

It should be noted, that since different units of measurement are used to measure the performance of the products for each indicator (e.g., area of land, ethylene equivalents, CO_2 equivalents, etc.) it will be difficult to create a footprint if the performance levels along the different indicators are left in their respective original units of measurement. To allow for meaningful representation of the environmental performance of the footprints of the products compared, a 'baseline' value should be assigned for each indicator, and assigned to represent the 100% graph point, so that the indicator values for other products are represented as compared to that. A meaningful way of assigning baseline values is to use the performance levels of existing product in use as a baseline, or to select the highest value for each indicator category from the collective values of all products being compared, and assigning that performance as the 100% level. In this manner, the lower the values that a product has in its "footprint", the better its environmental performance. The spider-web footprint is one graphical representation. The following rectangle, Exhibit 4-3, presents another example of "footprint" graphical representations that may be applied. Other representations may be equally instructive in the decision making process.



	1	2	3	4	5	6	7	8
Baseline	100	100	100	100	100	100	100	100
Product A	42	73	35	77	64	98	75	56
Product B	30	64	35	70	24	20	63	37

Exhibit 4-3. Rectangle Cut-Out Footprint

Weighting Among Indicators

In some cases, the presentation of the indicator results alone often provides information sufficient for decision making, particularly when the results are straight forward or obvious. For example:

- When the best-performing system/product among the alternatives studied is significantly and meaningfully better than the others in at least one indicator, and no-better-or-worse than any of the other products in all remaining indicators (as would be the case when there are overlapping error-bar ranges introduced by data variability and uncertainty). Then, *one system is clearly performing better,* hence any relative weighing of the indicators results would not change it's rank as first preference. The decision can be made without the weighting step.

- When the uncertainty and variability ranges (error bars) for the indicator results are larger than the differences in indicator values among the compared systems/products, then the results are *inconclusive* and adding a weighting step will not change that fact. Also, there is uncertainty introduced in the indicator-modeling step of the comparison. This additional uncertainty may render the analysis inconclusive if there are small differences among inventory data that are meaningful. Hence there are two types or results where the environmental comparison can not demonstrate enough differentiation to select one product, and the decision could be based solely on technical and cost considerations.

- When there are *trade-offs* in the environmental performance of two systems, then there may be value in performing the weighting step.

Weighting is the process of converting indicator results by using numerical factors based upon value judgements. The primary objective of weighting is to integrate information on indicator results with stakeholder values to establish the relative significance of the indicators of the studied system. Stakeholder values (multipliers for the relative importance that stakeholders have assigned to an indicator) are often the basis for those numerical factors. *The challenge is how to adequately capture and express the full range of stakeholders' values when the numerical factors are determined.*. These challenges have been recognized and discussed in the international LCA community as part of the ISO efforts, SETAC, and government publications (RTI, 1995, SETAC 1992, SETAC 1998).

Several issues exist that make weighting a challenge. The first issue is subjectivity. According to ISO 14042, any judgement of preferability is a subjective judgement regarding the relative importance of one indicator over another. Additionally, these value judgements may change with location or time of year. For example, a federal procurement official located in Los Angeles, CA, may place more importance on the values for photochemical smog than would a procurement official located in Cheyenne, WY. The second issue is derived from the first: how should FRED 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 in fact used successfully for decision making. Some of those approaches that are applicable to the FRED LCA application are described below. For a more detailed discussion on weighting approaches see RTI (1995) and SETAC (1992). The following approaches can provide ideas on how to incorporate the views of stakeholders who will be affected by the outcome of a decision, as well as providing a systematic process to determine those numerical factors.

Relative Weights Development Methods for the Weighting Step

Several methods exist to derive relative weights for indicators. Further description of the techniques outlined below as well as other techniques see RTI (1995).

Adopt an Existing Weighting Scheme

One way to derive relative weights for a valuation is to adopt an existing scheme. Such a scheme was developed by the U.S. EPA Science Advisory Board in 1990. However, caution should be used in applying pre-developed weighting schemes, as they can become dated as environmental science and understanding progresses, and also these tend to accommodate global priorities as more significant than local environmental priorities, which may also vary significantly from one region to another, based on multiple variables such as availability of water, availability of landfill space, local atmospheric conditions, population density, etc.

The U.S. EPA's Science Advisory Board (SAB) report *Reducing Risk: Setting Priorities and Strategies for Environmental Protection* (EPA, 1990) provides some useful suggestions that help in assigning relative importance to environmental attributes of a product. The EPA determined that its Environmentally Preferable Products (EPP) Guideline will utilize and possibly build upon the SAB results in evaluating products (EPA, 1995).

Additionally, Harvard conducted a study in 1992, which can be used to establish the relative importance of indicators.

Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) is a multi-criteria decision-making methodology that enables consideration of extensive sets of dissimilar qualitative and quantitative criteria in making a decision. AHP juxtaposes the qualities and features of the options with the relative importance of the evaluation criteria to derive an aggregate measure of performance. This analysis is based on a scientifically defensible mathematical algorithm, adding credibility to the ranking. The method can handle large numbers of criteria, arranged on a simple level, or resolved on hierarchical levels.

AHP is based on the concept that assigning relative importance can be done more accurately and reliably by using comparisons among competing issues rather than by using an arbitrary valuation scale. The simplest and most reliable basis of comparison being that of a pair, in AHP relative weights are developed using exhaustive *pairwise* comparisons among competing issues. The derivation of relative weights is based on simple matrix algebra (RWS, 1990). AHP also provides a mathematical measure of data consistency, giving users feedback on the quality of judgmental information. AHP supports consistency in judgments by making use of a common comparison vocabulary and framework.

There is software available that allows the performance of the AHP calculations required to develop the relative weights and ranking (ExpertChoice™), that greatly simplifies the task for the user, to the level of providing feedback to the software as to the perceived relative importance of the attributes compared, two at-a-time.

Modified Delphi Technique

The Delphi Technique is a procedure originally developed by the Rand Corporation for eliciting and processing the opinions of a group of experts knowledgeable in the various areas involved. The Delphi Technique addresses the need to structure a group communication process to obtain a useful result for a given objective. In essence, the Delphi Technique attempts to create a structured format to elicit collective knowledge.

In response to a number of shortcomings associated with the Delphi Technique (see Linstone and Turoff, 1975), a modified Delphi technique has been developed. This modified Delphi technique provides a systematic and controlled process of queuing and aggregating the judgments of group members and stresses iteration with feedback to arrive at a convergent consensus.

The weighting procedure can be simply employed. A deck of cards is given to each person participating in the weighting. In this example each card names a different technical specialty. Each of the participants is then asked to rank the technical specialties according to their relative importance to explaining changes in the environment that would result from a particular system. Then each individual is asked to review the list and make pairwise comparisons between technical specialties, beginning with the most important specialty. The most important technical specialty is compared with the next important specialty by each individual, and the second technical specialty with respect to the first.

To accomplish the second part of this technique (i.e., to rank attributes within a technical specialty), each participant or group independently ranks attributes in his or her own specialty. The information from these pairwise comparisons can then be used to calculate the relative importance of each of these specialty areas; a fixed number of points (e.g., 1,000) is distributed among the technical specialties according to individual relative importance.

After the weights are calculated from the first round of this procedure, the information about the relative weights is presented again to the experts, a discussion of the weights ensues, and a second round of pair-wise comparisons is made. The process is repeated until the results become relatively stable in successive rounds.

Decision Analysis Using Multi-Attribute Utility Theory (MAUT)

Simply stated, decision analysis is a method that breaks down complex decisions involving multiple issues into constituent parts or individual attributes to provide a better understanding of the main factors guiding the decision. Decision analysis using MAUT is useful when deciding between largely different types of considerations. In addition, it provides a logical structure for analyzing complex weighting issues.

The first step in decision analysis is to identify all important objectives and attributes. While this step may seem obvious, it is necessary to ensure that the valuation focuses on the right problem. The objectives and attributes of the decision at hand may be identified by using tools such as an objectives hierarchy (Keeney and Raiffa, 1976). Whether the objectives and attributes are determined through a top-down or bottom-up approach, the final set of attributes should have certain characteristics. An overall objective would be at the top and a comprehensive set of issue-specific objectives are then derived that are consistent with the overall objective. Finally, attributes that are meaningful, measurable, and predictable are derived for each specific objective. According to Keeney and Raiffa (1976), who describe the entire MAUT process in detail, the set of attributes should be:

- comprehensive,
- as small as possible in number,
- non-overlapping,
- judgmentally independent, and
- operational.

Linking FRED LCA with Technical Performance and Total Ownership Cost

As was mentioned in Chapter 1, the goal of FRED is to apply LCA in an overall formework for examining the environmental perferability of a product system. FRED also provides the foundation for linking the life cycle indicator results with consideration to technical and economic factors for decisionmakers. To this end, environmental, economic and technical feasibility aspects of the project are examined. A variety of approaches can be used to assist in the decision making process. One such approach is described here. The ranking can be performed with a variety of approaches. One such approach is Analytic Hierarchy Process method as described previously in this chapter. The ranking produced will pinpoint at the most appropriate option, considering all aspects of product development, use, and disposal (see Exhibit 4-4).

Exhibit 4-4. Examples of Ranking within FRED

	Baseline	**Option 1**	**Option 2**	**Option 3**	**Option 4**
Environmental Performance	Medium	Low	High	Medium	Low
Cost	Low	Medium	Medium	Low	Medium
Technical Feasibility	High	Low	Low	Medium	High

Summary

As we described earlier in this reference guide, Step 4 is still under development. However, certain findings from the pilot projects and development of the eight life-cycle indicators occurred. First, presentation of results in graphic formats facilitates the understanding and interpretation of the indicator results. Graphic presentation allows for easier interpretation and consistency in decision making, especially for non-experts. Second, weighting among indicators is not always necessary. Depending upon the indicator results, the differences may be straightforward and obvious. In those cases, weighting would not be necessary. The advantage is that in these instances the subjective nature of weighting is eliminating and the information is presented more objectively.

Chapter 5 - Conclusions

FRED, the Framework for Responsible Environmental Decision-Making, introduces a decision making framework for achieving a balance among price, technical performance, and environmental preferability. This guidance document focuses on developing an approach for quantifying a product's environmental performance. In conducting three pilot tests to refine and validate the application of LCA, several conclusions were reached. These conclusions and recommendations on the next steps are presented here.

Conclusions Regarding FRED

The decision making framework introduced in this reference guide has been specifically developed to facilitate the inclusion of environmental preferability in the procurement process. In terms of meeting this objective, the following observations and conclusions have been drawn.

- As noted in the EPP draft guidance, environmentally preferable procurement depends on balancing environmental preferability, price, and performance.
- Life cycle assessments are a comprehensive, practical and fair method for measuring environmental preferability.
- Obtaining quality life cycle inventory data is critical to making an accurate assessment.
- The "greening government" requirements of Executive Order 13101 can be met by applying the FRED LCA system.

The impact assessment approach outlined in FRED helps to further define impact criteria and move the practice toward a more consistent appraoch. Currently, the selection of criteria in LCIA may significantly influence the outcome of the assessment by under-emphasizing potential impacts. For example, global warming is evaluated as a single category while human health is sub-divided into cancer and non-cancer impacts. Depending on how interpretation is conducted, the number of categories will influence the results. While the complexity of attempting to identify all impact considerations was beyond the scope of this simplified LCA study, it serves to illustrate the need for further development of impact categories and criteria in order for LCIA to have a consistent foundation that is accepted globally.

Conclusions Regarding the FRED Environmental Component (i.e. the FRED LCA System)

As explained earlier in this document, a cradle-to-grave, multi-media Life Cycle Assessment (LCA) methodology is applied within FRED to measure environmental preferability of products and services. This application of LCA focuses data collection by first identifying the product type, and the impact categories and indicators being assessed, and then determining the specific, associated data needs, greatly focusing the LCA application and significantly increasing the efficiency of the analysis.

As a result of this effort, the FRED LCA system was demonstrated to be a feasible approach to supporting Environmentally Preferable Purchasing (EPP) decision-making. While the final choice between product alternatives, that is, deciding which is "better," is left to the final decision-maker, this research study has taken the first steps to providing scientific input to the decision-making process. Federal government agencies can improve the ability for FRED-LCA to function as a tool for evaluating environmental preferability by:

- Allowing vendors to provide LCA inventory data or LCA indicator results to procurement officials in order to facilitate comparisons of different products using the FRED-LCA system. In particular, development of site-specific data over the entire vendor chain will permit the development of indicators with a high degree of environmental relevance.
- Developing agency-specific data gathering tools and databases. This will lead to more uniformity in the data utilized in EPP evaluations.
- Using FRED-LCA in other pilot EPP projects. The more experience is gathered with FRED, the better the ultimate results of the analysis, and consequently the more informed the decision-making.
- Using FRED LCA to support other decision-making activities besides facilitating procurement selections. For example, FRED LCA could possibly be used to track and monitor an organization's environmental performance, identify opportunities for process improvements, and identify environmental aspects, as defined by ISO 14001. These possible additional uses of FRED LCA were not explored in developing this reference guide and thus still require validation.

Lessons Learned Regarding the Pilot Projects

To assist in refining the application of Life Cycle Assessment (LCA) within FRED (i.e., referred to as the FRED LCA system) , three LCA pilot projects were conducted to evaluate the process as well as the output. These included pilot projects on motor oil, wall insulation, and asphalt coatings. Specific information regarding the scope, data, and findings from these pilot projects is located in Appendices A, B, and C to this report. Conclusions from these pilot projects regarding the application of LCA within FRED include:

- The FRED LCA system can be performed in a much shorter time period than is typical for a more detailed LCA study. This, more practical duration for procurement decisions, is achieved through the focusing of data collection needs and simplified impact assessment.
- Process and site specific data can most readily be collected from the participating product vendor and suppliers/customers interacting directly with the vendor. Other contributing organizations further up and down the vendor chain (such as raw material suppliers and energy providers) are more likely to be derived form industry averaged data sets.
- As demonstrated by the pilot projects, data collection for the application of LCA within FRED can be accomplished by a small business/vendor. The simplified LCA application within FRED focuses the data collection needs to the point that even a smaller size business can fulfill the data needs without being overly burdened.

Next Steps

This reference guide focuses solely on providing direction for applying LCA within FRED to compare the environmental preferability of competing products. Guidance will be needed on the methodologies used within FRED to evaluate cost (e.g., total ownership cost) and performance (i.e., using system functional analysis within the LCA scope and goal definition step to measure the ability of competing products to meet technical requirements). Additional FRED reference guidance will focus on evaluating the tradeoffs among each selection criteria. Next steps to be taken in facilitating the application of FRED to the procurement process include:

- Providing detailed guidance on the level of data quality characteristics required to support public procurement decisions of various levels.
- Developing the total ownership cost and technical performance evaluation component of FRED.
- Developing models of environmental impact that accomodate more site-specific information and therefore better fulfill the ISO requirements for environmentally relevant indicators.
- Developing additional impact indicators for land use. This will be especially important for assessing bio-based products.
- Developing guidance on how to report the combined environment, cost, and performance results from FRED.
- Developing a users guide, possibly a software based tool to collect, evaluate, and interpret procurement data.
- Creating incentives (e.g., regulatory, contractual, voluntary, etc.) for vendors and other organizations to provide product-specific data for use in FRED.
- Conducting additional pilot projects to validate FRED's applicability to the procurement decision making process. Three pilot projects were conducted in developing this FRED LCA system reference guide. These pilot projects were used to refine the choice of environmental and human health impact models to be included in FRED as well as to validate the impact indicator results. In the future, additional pilot projects will be needed to validate the other components of FRED (cost and performance) as well as to develop the trade-off analysis within FRED.

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