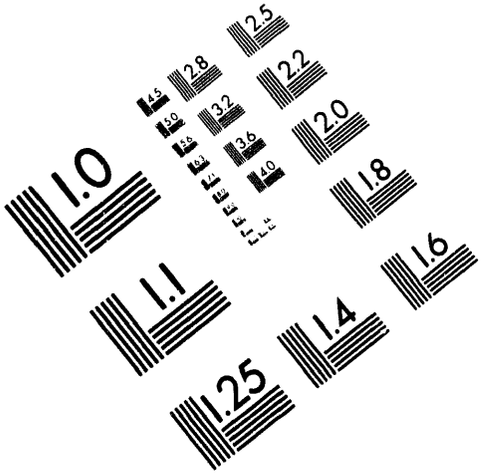

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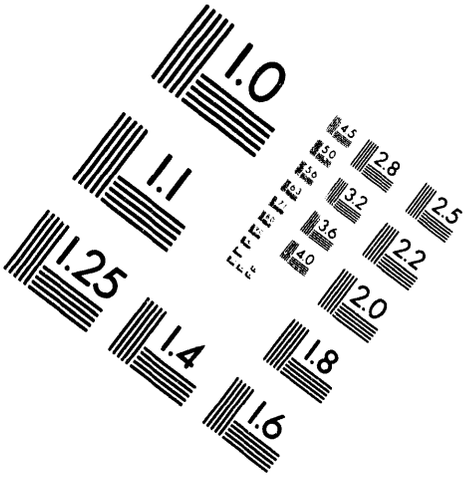

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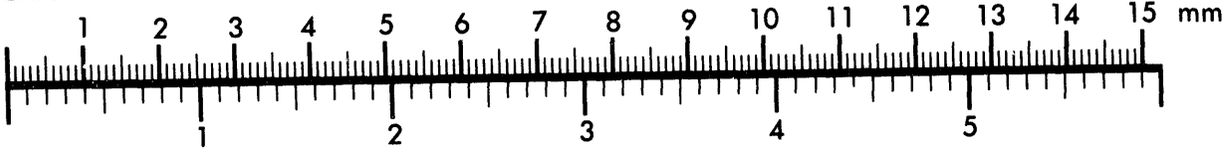

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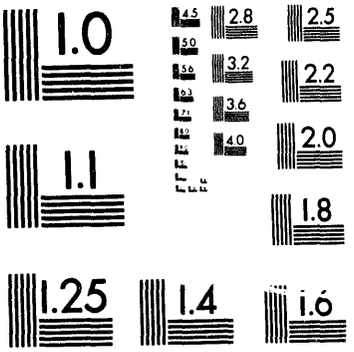

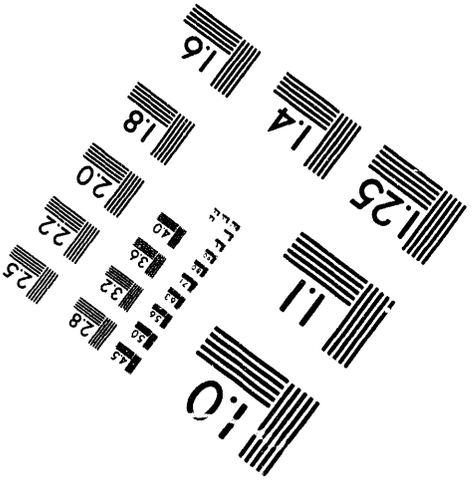

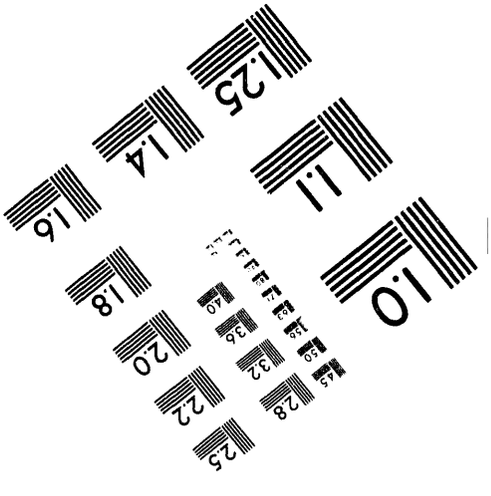

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LIFE-CYCLE ASSESSMENTS: LINKING ENERGY, ECONOMICS, AND THE ENVIRONMENT

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LIFE-CYCLE ASSESSMENTS: LINKING ENERGY, ECONOMICS, AND THE ENVIRONMENT

Paper Number 571

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H:1. SYNOPSIS

This paper describes life-cycle assessments, an analytic approach to evaluating the energy, environmental, and economic impacts of alternative technology options.

H:2. ABSTRACT

The Pacific Northwest Laboratory has been involved in a number of life-cycle assessment (LCA) projects that assess the complete lifetime energy, economic, and environmental impacts of alternative technology options. Life-cycle assessments offer one-stop shopping answers to the total energy and environmental implications of alternative technologies, as well as providing employment and income consequences. In one recently completed study, the lifetime impacts of scenarios involving the production and use of biomass ethanol transportation fuels were assessed. In an ongoing study, the lifetime impacts of electric-powered vehicles versus conventional fuels are being assessed. In a proposed study, the impacts of recycled office paper versus office paper from virgin sources would be assessed. A LCA proceeds by developing mass and energy

inventories during all phases of the life-cycle. Special attention is given to energy consumption and environmental releases. Economics are incorporated by evaluating the macroeconomic impacts of the alternative policies, such as employment, wages, and output. Economics can also be incorporated by attempting to place values on the damages imposed by the environmental releases associated with alternative scenarios.

This paper discusses life-cycle assessment techniques and their application to building energy issues. Life-cycle assessments show great promise for analysis of buildings energy policy questions.

H:3. INTRODUCTION

LCAs examine the environmental impacts of a product from a "cradle-to-grave" perspective, considering all stages in the product life cycle: resource extraction, resource transportation, resource conversion to a manufactured product, product distribution, end-use, and all associated secondary processes (waste management, recycling, manufacturing of secondary material and energy inputs, etc.). LCAs allow the environmental and energy consequences of alternative technologies to be compared, accounting for all stages of the technology.

In the federal sector, LCAs are being used to better understand the energy and environmental impacts of technologies that are being developed as part of major R&D

programs. As one example, in fiscal year 1994, the U.S. Department of Energy (DOE) will spend over $40 million dollars on R&D associated with biomass-derived fuels (e.g., ethanol). From a life-cycle perspective, biomass-derived fuels require dedication of large quantities of land to biomass agricultural plantations, plantation operation (including fertilizer application), operation of ethanol production facilities, and increased transportation requirements relative to gasoline. The energy and environmental impacts associated with biomass-derived fuel are complex. Consequently, DOE is seeking to understand the full life-cycle implications of biomass-derived fuels so that intelligent decisions can be made within existing R&D programs to minimize the environmental impacts associated with the technologies that will be commercialized as part of DOE's large R&D programs. In addition, DOE must understand the highly complex gasoline life-cycle so that there is a clear understanding of net reduction in national environmental impact when a gallon of gasoline is displaced by a gallon of biomass-derived fuel. Due to the complexities of the gasoline and biomass-derived fuel life-cycles, it is clear that the traditional perspective of only considering the difference in vehicle tailpipe emissions when alternative fuels are used is not a fair comparison.

PNL participated in the biomass-ethanol study, and is currently involved in a LCA of electric vehicles. In addition, PNL is currently working with EPA, EPRI, and the World Bank as part of a consortium to develop data for use in LCAs concerned with electricity generation and use.

This paper describes the basic components of a LCA, and discusses the methodologies required to complete each of the components. The paper concludes with a pair of examples of the application of LCA to building sector energy issues.

H:4. PRINCIPLES OF LIFE-CYCLE ASSESSMENT

LCA tools and techniques have been developed over the last several years by the Environmental Protection Agency (EPA), the Society of Environmental Toxicology and Chemistry (SETAC) and the Department of Energy. An LCA is defined to consist of three major elements: (1) inventory assessment; (2) impact assessment; and (3) economic valuation[1] - as depicted in Figure 1.

[Figure 1 goes here]

Inventory assessments compile mass and energy balances [i.e., quantification of material inputs, material outputs (including products, co-products, and environmental releases), energy inputs, and energy outputs], and define labor requirements associated with the life cycle of a technology. Most LCAs conducted to date have consisted solely of inventory assessments. An inventory assessment provides a great deal of information useful in the evaluation of technologies: an inventory assessment can quantify the releases of criteria air pollutants; can quantify greenhouse gas emissions; and can quantify the life-cycle energy consumption associated with alternative technologies.

Frequently these quantities are sufficient to allow comparison of technologies. In some cases, however, it is desirable to translate the inventory into impacts, and to attempt to value those impacts. In this case, it is necessary to continue with the impact assessment and the economic valuation elements.

Impact assessments estimate human health, ecological impact, and economic impacts based on data compiled during the inventory assessment. Impact assessments can be extremely difficult, complex, and expensive to perform. In some cases, it may be impossible to defensibly translate inventories into impacts.

Economic valuation tools are used to calculate the social costs and benefits of human health, ecological, economic, and employment impacts. The aggregate net social benefits (or costs) derived from a technology can be used to compare alternative technologies or policies. Like impact assessments, economic valuations can be difficult, complex, expensive, and sometimes impossible to defend.

The results of a LCA include not only a quantitative assessment of the social costs and benefits of a technology, but also identify key activities/processes in the life cycle warranting further environmental R&D or policy consideration. A completed LCA allows the identification of critical processes upon which waste reduction or emission control activities can be focused.

Each major element in a LCA is discussed in more detail in the following sections.

H:4.1 Inventory Analysis

There are five basic methodological steps for conducting a life-cycle inventory assessment. These steps and their associated substeps are outlined in Box 1.

[Box 1 goes here]

Each of the steps described in Box 1 is designed to help ensure that the results of the inventory assessment adhere to the criteria described below. The criteria were originally developed by SETAC (1991) and have been modified slightly.

- Scientifically Based--Only scientifically-based analysis is used to distinguish between product/technological alternatives or to ascertain life-cycle improvement.

- Quantitative--All inputs and outputs are quantified and documented using current databases or measurements with suitable quality control. Uncertainties and assumptions in data and methodology are specified.

- **Appropriate Detail--The inventory is carried out to a level of detail commensurate with the purpose of the study, with the availability of data, and with the projected effect of a given parameter on the study conclusions.**

- **Replicable--The data sources and methodology are sufficiently described or referenced so that comparable results would be obtained from a skilled replication or evidence would exist to explain any deviations.**

- **Comprehensive--All significant raw material and energy uses and environmental releases are included, or any elements missing because of data availability or cost and time constraints are clearly documented.**

- **Broadly Applicable--The analysis is sufficiently broad in model conception that the results can be applied to the range of situations expected.**

- **Consistent--The findings are consistent with those of prior studies, or the reasons for inconsistencies are specified; format is consistent with worldwide practice.**

- **Peer Reviewed--The report should be peer reviewed, using an accepted protocol.**

- Useful--The users of the document can make appropriate decisions concerning the area listed, any limitations to the utility of the report should be noted, and presentations should be clear and understandable.

Ideally, a 100% complete material and energy balance [i.e., a complete list of energy inputs, material inputs, energy outputs, and material outputs (including products, co-products, and residuals)] would be compiled for every unit process in each life-cycle scenario evaluated. However, due the complex nature of the data collection task, it is always necessary to prioritize which items will be inventoried. This always creates the potential for omitting an important inventory item from consideration; however, through careful scoping this risk can be minimized.

H:4.2 Impact Analysis[2]

As a starting point, it is important to note that while inventory assessment and impact assessment are often described as discrete steps of a linear process, in practice they need to be conducted in an iterative and interactive way. Only by considering impact issues of concern can the inventory assessment be designed and conducted in such a way as to provide adequate data to the impact assessment stage. Likewise, only by considering the various production processes in the inventory map can the impact assessment be focused on the key, relevant impact issues of concern. This iterative relationship relies on the analyst starting *a priori* with a general set of inventory items to measure as well

as a general set of impact issues to evaluate, and then successively refining these sets until they are coordinated with each other.

The impact assessment phase of an LCA is concerned with identifying and evaluating the major social and environmental impacts of the production processes being analyzed, based on the data derived from the inventory analysis. It should be noted that the impact assessment is not designed to be an actual cause and effect analysis, but rather an analysis that relies on scenario-building and modeling to identify the likely impacts and the potential severity of impacts arising from the production process. This approach allows for a comparative analysis of impacts between various scenarios, rather than an actual determination of impacts from any one scenario.

Major impact categories (also know as "end points" or "receptors") used in impact assessment include:

- human health, including worker exposure and general population exposure;
- ecological health, including both species-level impacts (loss of salmon runs) and ecosystem-wide impacts (loss of biological productivity and biodiversity);
- resource sustainability, including impacts to both renewable and non-renewable resources; and

- non-environmental social welfare, including such impacts as economic impacts, cultural heritage impacts, impacts to community infrastructure, and so forth.

These categories can, of course, be further broken down. For example, human health impacts can include impacts ranging from direct toxicity effects of inventory outputs to noise effects to cancer arising from decreased stratospheric ozone. Ecological health impacts can include impacts such as toxicity effects on specific species, impacts to many species due to habitat loss, impacts on biological productivity (e.g., forest productivity), or impacts on biodiversity.

A key concept in impact assessment is the idea of "stressors." Stressors are the physical, chemical, or biological factors resulting from a production process (i.e., both inventory inputs and outputs) that specifically lead to impacts on the various end points identified - human health, ecological health, etc. Most obviously, stressors include the chemicals emitted into the environment from a production process that are directly harmful (i.e., toxic) to humans or ecosystems. In addition, however, stressors include non-toxic chemicals that also have impacts on humans or the environment, such as greenhouse gases (which generally do not pose toxic hazards, but can lead to global warming). Stressors also include non-chemical factors such as noise, resource consumption, and land use changes. Categorizing the information that comes out of the inventory analysis into a series of stressor categories allows the transition from inventory

analysis into impact assessment. (Again, this relies on an iteration between identifying inventory outputs and impact issues of concern.)

An impact assessment includes four basic components:

- scoping/classification of stressors and endpoints of concern;
- stressor/end point model development;
- specific impact assessments; and
- impact integration.

The first component - scoping/classification - entails identifying stressor and environmental endpoints that are relevant to the specific study. As a first step, the reference environment being used in the study needs to be defined: will the study consider global impacts? will the study focus on a specific region of the country for impacts? will the study consider certain key species as receptors? and so forth. As the general reference environment is being defined, specific endpoints also need to be identified. For example, endpoints for acid deposition impacts might include fish mortality in acidified lakes; forest productivity, and so forth.

The second component - model development - involves characterizing the functional relationship between stressors and impact category endpoints. As a starting point, the

general impact pathways that link the stressors to key endpoints need to be identified. For example, sulfur dioxide causes fish mortality by first being emitted into the air, converted into acid forms through mixing with air vapor, transported large distances in space, then deposited as acid rain on lakes. This schematic pathway then needs to be further refined (as possible) into a functional model that can be used to estimate the likelihood and severity of impact.

The third component of the impact assessment entails applying the model identified for each stressor category to the specific data that result from the inventory analysis. This provides an initial estimate of the likelihood and severity of impacts arising from the production processes being examined.

The fourth component of the impact assessment involves integrating the various impacts that have been estimated into a consistent picture of impacts. For example, it is important to not "double count" impacts: e.g., fish loss due to algal bloom should not be counted in addition to fish loss due to toxic effects - if the same fish endpoints are used in each case. On the other hand, it is important to insure that the full chain of impacts - and the potential connection between impacts - are accounted for. For example, fish loss may need to be connected to impacts on other species (e.g., predators), which may in turn have implications for larger ecosystem stability.

While the above picture of impact assessment has described a relatively straightforward procedure, in practice there are many issues that must be addressed for the impact assessment to be successful. For example, in theory the impact assessment should include a comprehensive accounting of impacts to the environment arising from production processes. However, in practice such a comprehensive analysis can quickly become infeasible for a variety of reasons, including: adequate data to describe the relationship between stressors and endpoints does not exist; there is not an adequate theoretical understanding of the relationship in the first place; or simply, the modeling effort is too resource-intensive. A key issue when performing an impact assessment - and when iterating between inventory assessment and impact assessment - is to insure that the objectives of the assessment (level of detail, certainty of impact, etc.) are matched to the available analytic resources. For example, a more superficial screening effort to identify generic categories of impact can be based on less rigorous analysis than a detailed risk assessment. Likewise, it may not be possible to include all impacts into the analysis, but rely on a prioritization scheme that focuses only on those impacts of greatest concern.

H:4.3 Impact Valuation

Few life-cycle assessments have attempted to translate inventory analysis into impacts, and to then attempt to value those impacts. Valuation of impacts, while difficult and subject to criticism, can be a vitally important stage of the analysis. Valuation allows a

ranking to be developed among competing scenarios on the basis of their environmental damages, while a strict inventory analysis is unable to rank alternatives when they are characterized by a number of parameters.

Valuation of environmental impacts is an extremely difficult and complex task, and the results are frequently controversial.

Valuation of the impacts associated with technologies is usually based on determining the amount that individuals would be willing to pay to avoid the impacts, called the Willingness To Pay (WTP). This can be accomplished by directly asking individuals their WTP, or by attempting to determine how much individuals value the services they receive from the resource, and inferring their WTP from that value. Direct elicitation of an individual's WTP is obtained through the Contingent Valuation Method (CVM), where value is based upon how respondents react to hypothetical markets. This approach provides what economists call a "stated preference." The second type of approach embraces a number of indirect methods that yield what economists call a "revealed preference", and these approaches are based upon behavior observed in real markets.

The CVM requires an extremely carefully designed survey, where individuals state their WTP to avoid a well-defined impact. The advantage of the CVM is that the

results it obtains are easy to interpret: individuals directly state the value of the resource. The CVM is also less data intensive than many of the revealed preference techniques. Most importantly, the CVM can be used in cases where revealed preference techniques are impossible, such as in determining passive use values. The CVM also has its disadvantages, of course. The most important is the fact that the CVM frequently requires respondents to attempt to value something that they have no real world experience in valuing. While this problem can be minimized through careful survey design, there is no way to eliminate doubt as to the validity of responses given to CVM surveys. The use of the CVM was recently examined by a blue-ribbon panel of economists set-up by NOAA. The panel consisted of Kenneth Arrow (co-chair), Robert Solow (co- chair), Edward Leamer, Paul Portney, Roy Randner and Howard Schuman, and reported its results in the Federal Register (58 FR 4601, Friday, January 15, 1993). The panel concluded that the CVM could be used to determine lost values from natural resource damages, given that a fairly strict set of conditions on the construction and fielding of the survey instruments. The CVM is particularly useful in determining passive use values, where revealed preference techniques cannot be used.

Revealed preference methods rely on the fact that while individual's values for non-market goods cannot be directly observed, it is sometimes possible to observe the values that individual's place on closely related market goods, called complementary goods. The most commonly used revealed preference method for valuing recreational

use values is the travel cost methodology. This is actually a number of methods, all of which have in common the fact that recreationists frequently must incur some cost to obtain the recreation services they desire. The value that an individual places on a recreational experience is presumably equal to or greater than the costs that the individual must incur to obtain the experience. In the case of an individual driving into the forest on a camping trip, the value of the experience is assumed to be at least equal to the cost of gasoline, automobile depreciation, supplies, and the value of the time spent obtaining the experience. A travel cost study would proceed by estimating the amount people spend on obtaining the non-market good, and statistically linking that to the characteristics of the good. The resulting statistical demand curve can be used to estimate the losses incurred due to a change in the characteristics of the good.

H:6. APPLICATION OF LCA TO BUILDING SECTOR ENERGY ISSUES

The major benefit of applying LCA to buildings energy issues it the ability to sort out the relative environmental impacts of alternative building energy technologies. This paper will discuss applying LCA to two building energy technologies: compact fluorescent lighting and CFC-free heatpumps.

Compact fluorescent lighting systems can provide significant energy savings over incandescent lighting. Replacement of incandescent lamps with compact fluorescent lamps can easily achieve energy savings in excess of 50%. The U.S. Environmental

Protection Agency (EPA) has a "green-lights program" that promotes the use of fluorescent lights rather than incandescent lights. One concern that has been raised is that EPA is promoting the use of fluorescent lamps which are ending up in the solid waste stream, going to landfills and causing mercury releases to the groundwater and surrounding soils. That concern has caused some organizations to react by trying to prevent the disposal of fluorescent tubes in landfills. If a decision is made to restrict the disposal of fluorescent tubes, consumers, both industrial and private, will have an incentive to resume using incandescent lamps, which don't release heavy metals when landfilled. However, from a life-cycle perspective, the fluorescent lamp uses about half as much electricity as the incandescent lamp and is drawing upon about half the natural resources. As a result, there are reductions in heavy metal emissions from power plants and mining and extraction sites. Incandescent lamps consume much greater quantities of electricity, and from a life-cycle perspective, an incandescent lamp releases about four to ten times as much mercury into the environment (NEMA 1992; Fava 1993). One needs also consider the fact that a compact fluorescent lamps can be expected, on average, to last at least ten times longer than incandescent lamps, thereby reducing the total volume being sent to landfills. The bottom line is that our conclusions may be quite different from a life-cycle perspective than from a narrow, single unit process perspective.

Another example of the use of a LCA-type of analysis would be the issue of replacing CFCs in the compressors of heatpumps. CFCs are potent greenhouse gases, and are being phased out of all uses in the U.S. However, CFCs also constitute an excellent working fluid in a compressor. If a CFC alternative is a less efficient working fluid, the meeting a given heating and cooling load could require greater energy consumption. In such a case, the increased emissions of greenhouse gasses from electric utilities could outweigh the reductions from phasing out CFCs. One study has estimated that if the replacement fluid is less efficient by as little as 2% to 5%, the global warming benefits of CFC reduction would be eliminated.

H:7 LIMITATIONS OF LCA

LCAs are not suitable for all technology policy questions. At their current stage of development, the inventory assessment stage of a LCA is expensive and time consuming, with tremendous data requirements. The impact assessment and economic valuation elements are still extremely difficult, despite many years of effort on the part of economists, biologists, ecologists, and a host of other disciplines.

The inventory assessment element of a LCA should be getting more manageable in the future. As data are collected for LCAs, they should become available to researchers for use in studies with overlapping unit processes. One promising area for this type of piggybacking is in the characterization of electricity generation processes. Electricity

generation enters as a process in any LCA where electricity is used. As the electricity generation processes is described in LCAs to a greater and greater extent, persons conducting LCAs will be able to virtually use electricity unit processes "off the shelf". It is toward this end that PNL is working with EPA, EPRI, and the World Bank as part of a consortium to develop data for use in LCAs concerned with electricity generation and use.

H:8 ENDNOTES

1. SETAC 1993 includes "economic valuation" as a component of "impact assessment." For the purpose of this paper, the two are treated as distinct elements because each element has a distinct technical approach, and each requires a distinct set of analytical skills (e.g., risk analysis and toxicology for the impact element, and economics for the valuation element).
2. A useful reference that summarizes many issues related to impact assessment is A Conceptual Framework for Life-Cycle Impact Assessment:, published by the Society of Environmental Toxicology and Chemistry (SETAC 1993). This document is the result of a consensus-based workshop designed to develop a clear and consistent conceptual framework for impact assessment. As such, the document provides a useful organizing structure for impact assessments, but does not necessarily include detailed methodologies to support directly implementable approaches.

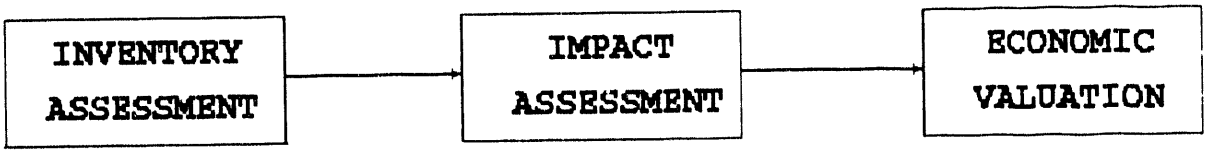

Figure 1 LCA Elements

Box 1– Steps for Conducting a Life-Cycle Inventory Assessment

1) Define the study emphasis and perspective.

   - Define an analytical emphasis that considers each of EE's three LCA objectives.
   - Identify whether a site-specific, regional, or national assessment perspective is appropriate.
   - Select a study timeframe.
   - Clearly identify the basic inventory items that must be included in the assessment.

2) Define an end-use level-of-service [in this case, ream of paper consumed] that draws upon the technology of interest.

   - Identify the major attributes of the end-use service (e.g., geographical location, magnitude of the activity, operating characteristics, etc.).
   - Identify a benchmark end-use level-of-service.

3) Identify the processes of the LCA that provide the level-of-service defined in step 2) and build a LCA map.

   - Identify the major operational-phase inputs (e.g., energy and materials) required for the end-use process to function.
   - Add the unit processes that produce the major inputs to the end-use process.
   - Identify the major inputs associated with the processes that were identified in the preceding substep, and continue to add new processes and identify additional inputs until the point of resource extraction is reached.
   - Review each process on the LCA map and determine if major non-useful byproducts are produced, and in each case where this occurs, add another unit process to the TEC map to "manage" the byproduct.

Box 1 (Contd)– Steps for Conducting a Life-Cycle Inventory Assessment

4) Quantitatively characterize the individual unit processes.

- Examine each process in the LCA and quantify its major attributes (e.g., geographical location, magnitude of the activity, and operational characteristics)

- Identify and quantify all operational inputs and outputs associated with each unit process or activity that are relevant to the goals of the assessment. Pay particular attention to useful byproducts. Document inputs and outputs in a standard data presentation format.

- Assess the quality of individual pieces of data as they are collected. Make a record of the data assessment in the form of a data quality indicator.

- Quantify the major attributes, inputs, and outputs associated with the pre- and post-operational phases of each unit process. Document inputs and outputs in a standard data presentation format.

- The characterization procedure will lead to the identification of additional unit processes that support the LCA. As appropriate, add new processes to the LCA map.

5) Organize the individual unit process characterizations into an overall representation of the LCA.

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