**Pollution Prevention in
Corporate Strategy**
NATIONAL POLLUTION PREVENTION CENTER FOR HIGHER EDUCATION

Note on Life Cycle Analysis

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As corporations seek to improve their environmental performance, they require new methods and tools. Life cycle analysis (LCA) is one such tool that can help companies to understand the environmental impacts associated with their products, processes, and activities. LCA is controversial and still evolving as a methodology. However, the principles behind LCA thinking are being adopted rapidly by manufacturers and service organizations alike as a way of opening new perspectives and expanding the debate over environmentally sound products and processes. The goal of LCA is not to arrive at *the* answer but, rather, to provide important inputs to a broader strategic planning process.

The Origin of LCA

LCA has its roots in the 1960s, when scientists concerned about the rapid depletion of fossil fuels developed it as an approach to understanding the impacts of energy consumption. A few years later, global-modeling studies predicted the effects of the world's changing population on the demand for finite raw materials and energy resource supplies.[1] The predictions of rapid depletion of fossil fuels and resulting climatological changes sparked interest in performing more detailed energy calculations on industrial processes. In 1969, the Midwest Research Institute (and later, Franklin Associates) initiated a study of the Coca-Cola Company to determine which type of beverage container had the lowest releases to the environment and made the fewest demands for raw materials and energy.[2]

In the 1970s, the U.S. Environmental Protection Agency (EPA) refined this methodology, creating an approach known as Resource and Environmental Profile Analysis (REPA). Approximately 15 REPAs were performed between 1970 and 1975, driven by the oil crisis of 1973. Through this period a protocol, or standard methodology, for conducting these studies was developed.[3]

In the late 1970s and early 1980s, environmental concern shifted to issues of hazardous waste management. As a result, life cycle logic was incorporated into the emerging method of risk assessment, which was used with increasing frequency in the public policy community to develop environmental protection standards.[4] Risk assessments remain controversial procedures: the public is often disinclined to trust them, especially when conducted after-the-fact to justify an activity or when performed by an organization with a vested interest in their conclusions.[5]

When solid waste became a worldwide issue in the late 1980s, the life cycle analysis method developed in the REPA studies again became a tool for analyzing the problem. In 1990, for example, a life cycle assessment was completed for the Council for Solid Waste Solutions, which compared the energy and environmental impacts of paper to that of plastic grocery bags.[6] A similar study comparing disposable diapers to washable cloth diapers was also conducted.

Environmental groups around the world have also adopted life cycle analysis; organizations such as Blue Angel, Green Cross, and Green Seal use and continue to improve LCA for the purpose of product labeling and evaluation. Thus, while initially limited to the public sector, LCA has been adopted by increasing numbers of corporations and nonprofit organizations as an aid to understanding the environmental impacts of their actions. And as demand for "green" products and pressures for environmental quality continue to mount, it is quite likely that industrial life cycle analysis will become in the 1990s what risk assessment was in the 1980s.

Components of Life Cycle Analysis

Life cycle analysis takes a systems approach to evaluating the environmental consequences of a particular product, process, or activity from “cradle to grave.” By taking a “snapshot” of the entire life cycle of a product from extraction and processing of raw materials through final disposal, LCA is used to assess systematically the impact of each component process.

Ideally, a complete LCA would include three separate but interrelated components: an inventory analysis, an impact analysis, and an improvement analysis. The components are defined as follows:

- **Life Cycle Inventory**. An objective, data-based process of quantifying energy and raw materials requirements, air emissions, waterborne effluents, solid waste, and other environmental releases incurred throughout the life cycle of a product, process, or activity.
- **Life Cycle Impact Assessment**. An evaluative process of assessing the effects of the environmental findings identified in the inventory component. The impact assessment should address both ecological and human health impacts, as well as social, cultural, and economic impacts.
- **Life Cycle Improvement Analysis**. An analysis of opportunities to reduce or mitigate the environmental impact throughout the whole life cycle of a product, process, or activity. This analysis may include both quantitative and qualitative measures of improvement, such as changes in product design, raw material usage, industrial processes, consumer use, and waste management.

To date, most LCAs have focused on the inventory component, as it is the most “objective” (and therefore, least controversial) analysis to perform. Franklin Associates, an industry leader in LCA, has been improving inventory-analysis methodology over the past 20 years.[7] However, it encourages clients to extend the inventory and add the impact and improvement assessments.

Inventory Analysis

An inventory may be conducted to aid in decision-making by enabling companies or organizations to:

- Develop a baseline for a system’s overall resource requirements for benchmarking efforts;
- Identify components of the process that are good targets for resource-reduction efforts;
- Aid in the development of new products or processes that will reduce resource requirements or emissions;
- Compare alternative materials, products, processes, or activities within the organization; or
- Compare internal inventory information to that of other manufacturers.

Managers using LCA to aid decision-making can improve the validity of the results and keep the analysis focused by precisely defining the scope of the “system” to be analyzed, considering practical constraints such as time and money. This step builds the foundation for the analysis that follows and should be understood and agreed upon by those responsible for commissioning the study. A system refers to a collection of operations that together perform some defined function. The system begins with all the raw materials taken from the environment and ends with the outputs released back to the environment (see **Exhibit 1**).

Within most systems, three main groups of operations may be defined: 1) operations for the production, use, transportation, and disposal of the product, 2) operations for the production of ancillary materials such as packaging, and 3) the energy production needed to power the system. A clearly defined scope will improve the results of subsequent steps when the total process is divided into subsystems. An example of typical subsystem categories is shown in **Exhibit 2**.

The linkages between subsystems make the process of collecting consistent measurements complex. For example, subsystems must be defined so that they are large enough to provide sufficient data for analysis but not so large that data is aggregated at a level that precludes detailed analysis. In addition, subsystems should be linked by a standard basis of comparison such as equivalent usage ratios. For example, two products or subsystems may use resources at different rates, have different densities, or have different performance levels. To resolve these issues, typical usage patterns for products need to be determined so that logical comparisons can be made. For many of the system inputs, equivalent weights or volumes may need to be calculated.

Managers using LCA to aid decision making must understand that the collection of data is a complex process and that many assumptions are made in the process. Absent or incomplete data, differences in the way data were collected, variations in technologies, and the number, diversity, and potential interactions of processing steps all contribute to the complexity. Either industry- or plant-level data may be used, depending on the scope and purpose of the study; government documents, federal regulations, technical literature, industry reports, published studies, and plant visits are all important sources of data. However, the selection of the source of data can substantially affect the inventory results, and any analysis should include complete documentation of sources, assumptions, limitations and omissions. For example, comparisons should be made using data from similar time periods, as manufacturing processes often change over time as companies adopt more efficient practices.

An important step in the inventory is the creation of a process-flow diagram that will serve as the “blueprint” for the data to be collected. Each step in the system should be represented in the diagram, including the steps for the production of ancillary products such as chemicals and packaging. This step is important because it clearly depicts the relative contribution of each subsystem to the entire production system and the final product.

Overview of the Inventory Subsystems [8]

A thorough understanding of how an inventory analysis is conducted, and the limitations and assumptions inherent in the various stages is critical to effective use of LCA in decision making. The following is a synopsis of the various subsystems analyzed in an inventory analysis.

RAW MATERIALS ACQUISITION

Data are collected for this subsystem on all activities required to obtain raw materials, including transportation of the materials to the point of manufacture (see **Exhibit 3**). Typically, raw materials are traced for the primary product and all primary, secondary and tertiary packaging. Managers should review the data to make sure equivalent comparisons are used. For example, a package containing recycled materials may need increased thickness to compensate for the decreased strength of recycled materials. In this case, managers must make a tradeoff between weight of materials that will someday become part of the waste stream and virgin material content. The inventory should also include all inputs of energy, materials, and equipment necessary for acquiring each raw material. Because this dramatically increases the complexity of the analysis, criteria must be determined to eliminate insignificant contributions. This may be done by establishing a threshold for inclusion. For example, any component contributing less than five percent of inputs might be ignored.

Ecosystems are impacted in many ways by the extraction or harvesting of raw materials, but only those effects that can be quantified, such as pesticide run-off from agriculture or soil loss from logging, should be included in the inventory. Effects that cannot be easily measured, such as loss of scenic or aesthetic value, may be covered in the more subjective impact assessment. At this point, attempts to quantify renewable or nonrenewable resources for inventory calculations are subjective, as quantifiable data is not publicly available. However, maintaining separate lists of renewable and nonrenewable materials may be helpful if an impact assessment is later performed.

Energy acquisition is actually part of the materials-acquisition subsystem, but because of the complexity of the subject, it warrants its own analysis. Data collected should include all energy requirements and emissions attributed to the acquisition, transportation, and processing of fuels. This means that if gasoline is used as a transportation fuel, not only should emissions related to combustion be included, but also energy consumption and emissions due to extraction and refining. In the U.S., energy is derived from a number of sources including coal, natural gas, petroleum, hydropower, nuclear power, and wood. Utilities use many different types of energy sources to produce electricity, so the energy analysis must include a determination of the fuel mix used to generate the electricity. Generally, the national average fuel mix may be used, but industry-specific information is preferred.

Some materials are made from energy resources and are therefore assigned an energy value. For example, plastics, made from petroleum and natural gas, release energy when burned. This energy value is credited against the system requirements for the primary product, resulting in a new energy requirement that is less than the total energy requirements for the system.

MANUFACTURE AND FABRICATION

Data collected for this subsystem includes all energy, material, or water inputs and environmental releases that occur during the manufacturing processes required to convert each raw material input into intermediate materials ready for fabrication. This process may be repeated for several streams of resources as well as several intermediate cycles before final fabrication of the product (see **Exhibit 4**).

Often co-products — outputs that are neither products nor inputs elsewhere in the system— are generated in the manufacturing process. Co-products are included in LCA until they are separated from the primary product being analyzed. Raw materials, energy, and emissions should be allocated between the primary product and the co-products by their proportionate weight or volume. If scrap within one subsystem is used as an input within the same subsystem, the raw material or intermediate material required from the outside is reduced and should be factored into the analysis. If industrial scrap is used in another subsystem, it is considered to be a co-product and should be allocated to the same consumption and emission rates required to produce the primary material. Some scrap is simply discarded and should be counted as solid waste.

Differences in technology throughout the industry require certain assumptions to be made at this stage. Comparisons between different-size facilities, differing ages of equipment, different capacity-utilization rates, and differing energy consumption per unit of production must be made explicit.

The data collected for final product fabrication assesses the consumption of inputs and the emissions required to convert all materials into the final product ready for consumer purchase. Calculations follow the same procedure as in converting raw material to intermediate materials and include the same limitations.

Data collected for fabrication of the final product includes the inputs and releases associated with filling and packaging operations. As this is a necessary step for virtually any product, this step focuses on differences between processes or materials being compared. If the filling procedure is identical for the two products being compared, this step can be ignored. Both primary and secondary packaging must be included in the calculations, taking care to keep packaging per unit consistent between alternatives.

TRANSPORTATION/DISTRIBUTION

An inventory of the related transportation activities of the product to warehouses and end-users may be simplified by using standards for the average distance transported and the typical mode of transportation used (see **Exhibit 5**). Inventory of the distribution process includes warehousing, inventory control, and repackaging. Environmental controls such as refrigeration are components of both transportation and distribution. As in previous stages, clear boundaries must be established to define the extent to which issues such as building and maintaining transportation and distribution equipment will be factored into the inventory results.

CONSUMER USE/DISPOSAL

Data collected for this subsystem cover consumer activities including use (product consumption, storage, preparation, or operation), maintenance (repair), and reuse (see **Exhibit 6**). Issues to consider when defining the scope of the subsystem include:

- Time of product use before it is discarded
- Inputs used in the maintenance process
- The typical frequency of repair
- Potential product reuse options

Managers should incorporate into the analysis any industry information on typical consumer usage patterns that may make the study's results more valid. For example, consumers may occasionally use two thinner paper cups to attain the strength of a single comparable polystyrene cup. Sources of data that may help this process include consumer surveys, published materials, and assumptions. Inventory reports must include documentation of assumptions including the timeliness of the data, potential biases, and other limitations.

Various disposal alternatives exist such as reuse, recycling, composting, incineration, and landfilling. Transportation and collection of post-consumer waste should also be included in the analysis. Inventories often use a national estimate of waste management methods, citing current averages for the percentage of waste disposed of by landfilling, recycling, and incineration methods.

Recycling technology is expected to improve greatly in the future. Therefore, content levels and recycling rates should always be reported at current rates with documentation of study dates. Advances in technology will both increase rates and the number of products that are recyclable, altering both open- and closed-loop recycling options (see **Exhibit 7**).

Open-loop recycling means that a product is recycled into a different product that is disposed of after use. In these cases, the resource requirements and environmental emissions related to the recycling and final disposal of the recycled material is divided equally between the two products produced.

Closed-loop recycling refers to materials that can be recycled into the same product repeatedly. This means that the more times the product is recycled, the less virgin material is required and the greater the number of cycles over which the resources and emissions can be allocated. The environmental effects of a closed-loop product will approach zero over the life of the product. For some products, a recycling infrastructure already exists, providing data on the collection, transportation, and processing of its materials. But for many products such information does not exist, leading to the use of data extrapolated from pilot programs or forecasts.

Wastes may be defined as materials that have no intrinsic or market value. Waste occurs in some form at every stage of the life cycle. Careful analysis of waste management issues is required as disposal options vary with the seasons, geography, and the technology used by a particular facility. Further complicating the inventory is the fact that many waste streams are combinations of materials derived from several subsystems, and that waste treatment facilities may produce a variety of releases including air, water, and solid wastes. For example, reported waterborne waste data should include an analysis of the water treatment system, the land associated with the treatment system, and atmospheric and solid wastes associated with the system. Information about emissions from solid waste is more difficult to find as there is no existing method to determine the emissions of a particular product once it has been mixed with municipal waste in a landfill or incinerator. If, however, a disposal process is being used for only one type of product (e.g., composting for yard waste or recycling for aluminum cans), accurate measures are available.

Impact Assessment and Improvement Analysis

All life cycle analyses collect inventory data on raw material consumption, energy and water use, and waste production. However, a meaningful LCA should contain more than a mere inventory of inputs and outputs — it should also consider the overall contributions and risks to the environment and public health, as well as the social, cultural, and economic impacts of each option. In short, the products and processes being assessed should be seen in the context of the society they are intended to serve.

An impact assessment and improvement analysis thus *evaluates* the impacts caused by the proposed products, processes, or activities. The final result of an impact assessment is an environmental profile of the system. Impact assessment is one of the most challenging aspects of LCA since current methods for evaluating environmental impacts are incomplete at best.[9] Even when models exist, they can be based on many assumptions or require considerable data beyond that associated with the inventory.[10] Evaluating the importance and meaning of the data collected during the inventory requires judgement and interpretation. Thus, impact assessment inherits all the problems of inventory analysis while also introducing new methodological and measurement challenges.

ENDNOTES:

[1] For example, D. Meadows, D. Meadows, and J. Randers. *Limits to Growth*. New York: Universe Books, 1972.

[2] Franklin Associates. *Product Life-Cycle Assessment: Guidelines and Principles* (EPA Report #68-CO-0003). 1991.

[3] Hunt, R., J. Sellers, and W. Franklin. "Resource and Environmental Profile Analysis: A Life Cycle Environmental Assessment for Products and Procedures." *Environmental Impact Assessment Review*, Spring 1992.

[4] Stilwell, J., R. Canty, P. Kopf, and A. Montrone. *Packaging for the Environment*. New York: American Management Association, 1991.

[5] See, for example, Lowrance, W. 1976. *Of Acceptable Risk*. Los Altos, CA: William Kaufmann, 1976.

[6] Council for Solid Waste Solutions. "Resource and Environmental Profile Analysis of Polyethylene and Unbleached Paper Grocery Sacks." CSWS (800-243-5790), Washington, DC, June 1990.

[7] Franklin Associates, Ibid.

[8] For details, see Franklin Associates, Ibid.

[9] U.S. EPA, Risk Reduction Engineering Lab. *Life Cycle Design Guidance Manual*: *Environmental Requirements and the Product System* (EPA #600/R-92/226). Prepared by Keoleian, Gregory A., and Dan Menerey. Cincinnati: EPA, 1993.

[10] For examples of the range of methods available, see Hart, S., G. Enk, and W. Hornick. *Improving Impact Assessment.* Boulder, CO: Westview Press, 1984.

EXHIBIT 1: INPUTS AND OUTPUTS OF A SYSTEM

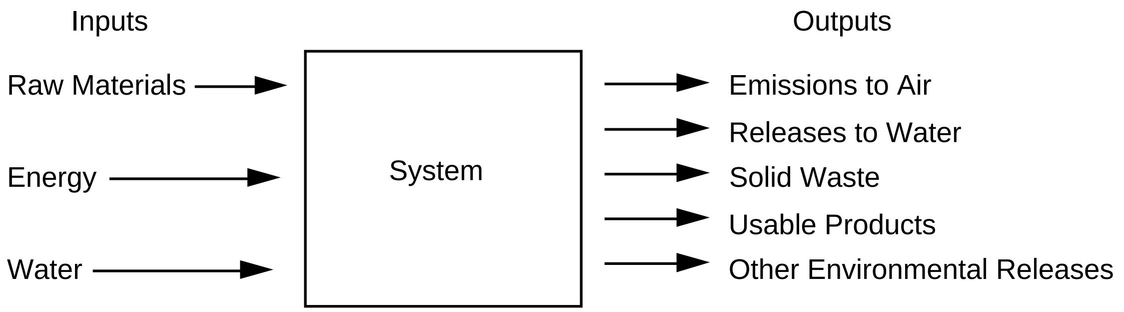
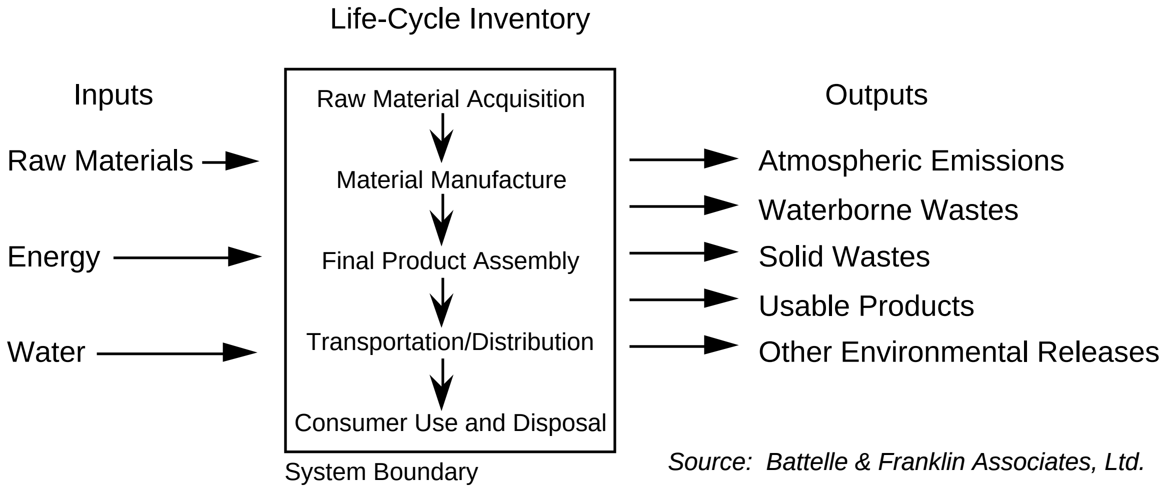


EXHIBIT 2: DEFINING SYSTEM BOUNDARIES



Source: Battelle & Franklin Associates, Ltd.

EXHIBIT 3: RAW MATERIAL ACQUISITION SUBSYSTEM

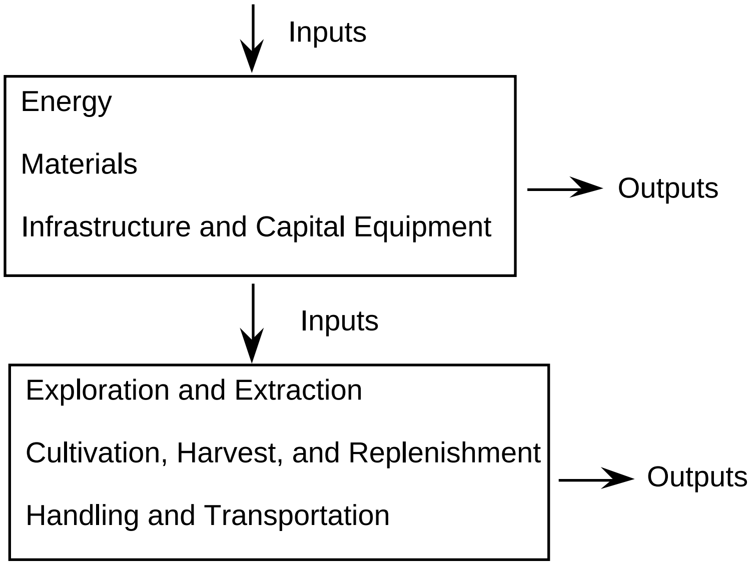


EXHIBIT 4: MANUFACTURING AND FABRICATION SYSTEM

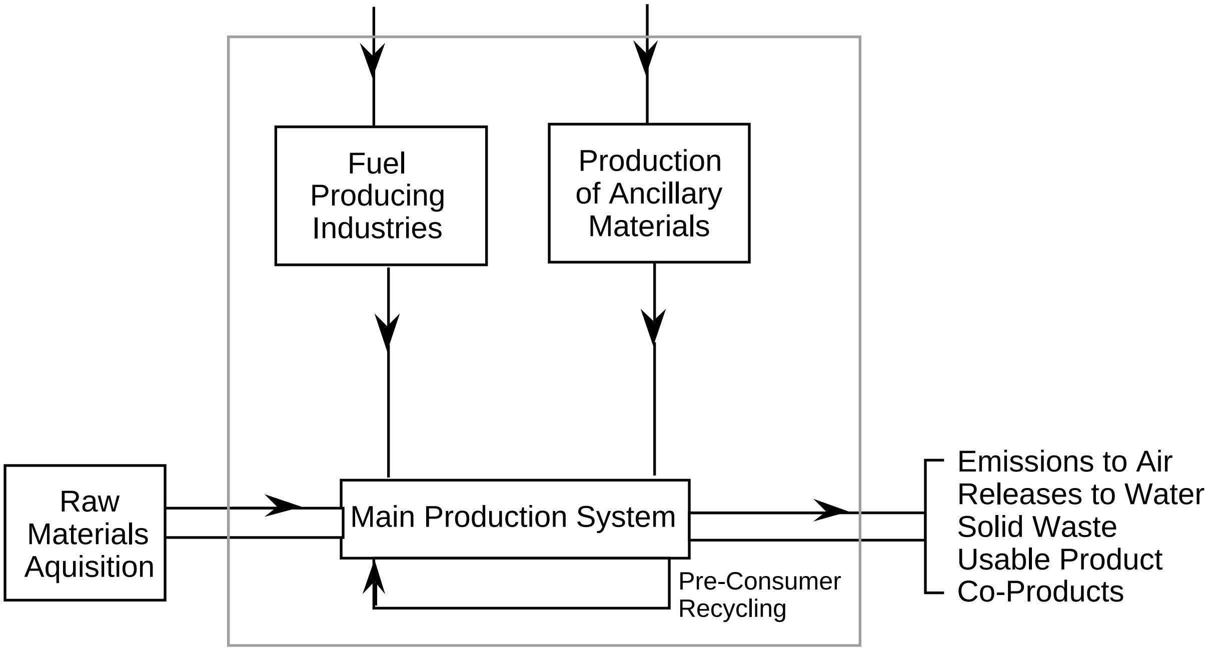


EXHIBIT 5: TRANSPORTATION/DISTRIBUTION SYSTEM

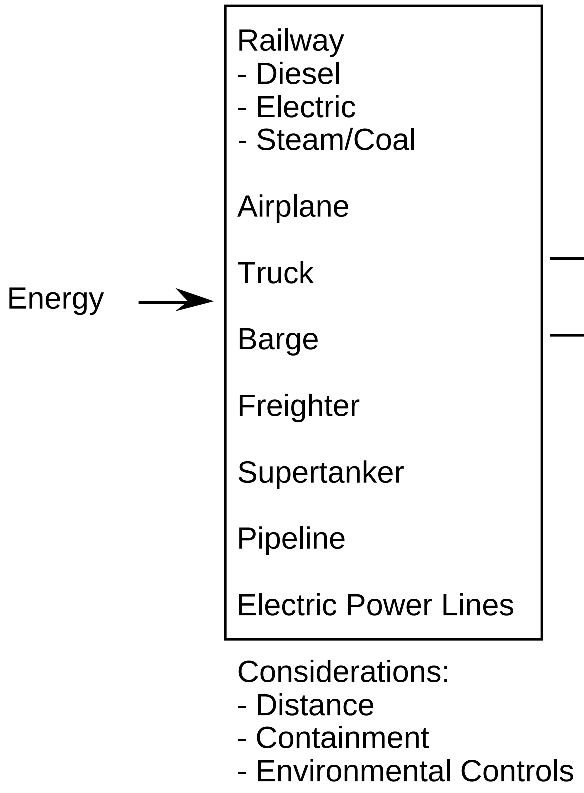


EXHIBIT 6: CONSUMER USE/DISPOSAL SYSTEM

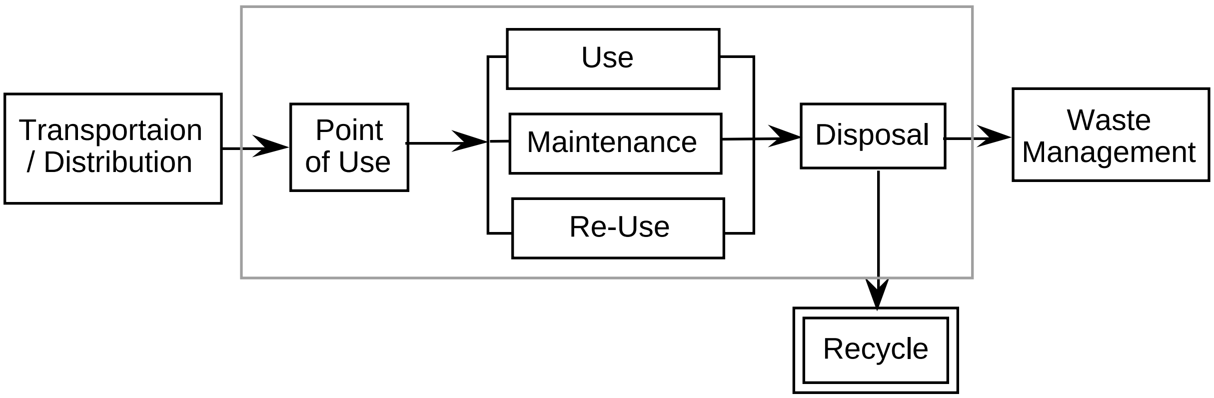
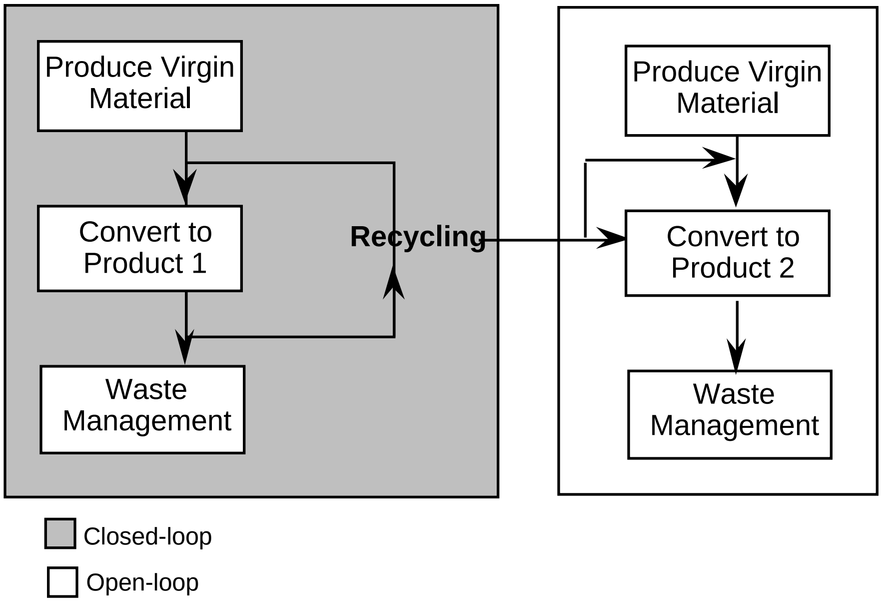


EXHIBIT 7: RECYCLING SUBSYSTEM



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