TUTORIALS

- **Life Cycle Assessment**
- **Economic Input-Output Analysis**
- **Basic Thermodynamics with Emergy Analysis**
- **ECO-INIDCATOR 99**

Life Cycle Assessment:

A scientific way of considering environmental implications of a product or service through all stages of its life cycle is Life Cycle Assessment, sometimes also called “Life Cycle Analysis”, “Life Cycle Approach”, “Cradle to Grave Analysis” and “Eco-balance” (Jensen A., 1998; Graedel T., 1998). It represents a rapidly emerging family of tools and techniques designed to help in environmental management and, longer term, in sustainable development (Ehrenfeld J., 1997). It has also become the mainstay of ISO 14000 series of standardization guidelines (ISO, 2001). Life Cycle Assessment methodology is described in four phases: goal and scope definition, inventory analysis, impact assessment and interpretation/ improvement (Jensen A., 1998).

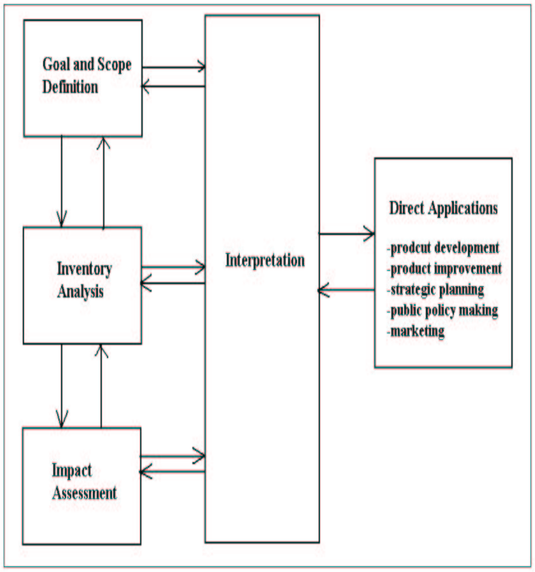


Figure 1: Life Cycle Assessment

Goal and scope definition involves determination of system boundaries such as geographical boundaries, life cycle boundaries (due to limitation in the life cycle) and boundaries between biosphere and technosphere. Due to subjectivity and arbitrariness of definition of system boundaries this step is extremely crucial. Modifications in the system boundary may lead to drastic changes in the conclusions (Lave L. 1995). If we consider each and every stage during the product's life cycle, the exercise becomes very tedious. Hence only important stages are considered excluding several direct and all indirect interactions. For example, production of an automobile requires machinery that, in turn, is made from other machinery. The machinery is made from steel, which is made from coal, iron ore and so on. Building the machinery requires use of automobiles, gasoline, shoes and electricity. Since it is impossible to trace directly through all the direct and indirect interactions, the standard recommendation of SETAC LCA is to disregard the environmental implications of machinery and other capital equipment and concentrate on the most important process materials. This approximation leads to unrealistic results as demonstrated by Lave et al (Lave L., 1995)

Inventory analysis is the second phase of life cycle assessment. It includes collection and treatment of data to be used in preparation of a material consumption, waste and emission profile for the process in question. Site-specific data may be collected from sources such as specific companies, specific countries and specific areas. Data may also be collected from public sources such as trade organizations, federal agencies and surveys.

Impact assessment, the third phase in life cycle assessment, involves classification of inventory input and output data into various impact categories such as global warming, ecotoxicological impacts, acidification, eutrophication etc. This phase also involves characterization of inventory data by assigning the relative contribution of each input and output to the selected impact categories (Jensen A., 1998) For example, different emissions are converted into equivalents of CO_2 for global warming and SO_2 for acidification potential. Determining relative importance of various impact categories i.e. human toxicity versus global warming potential etc. is left to users and designers and comprises valuation/weighing phase of Life Cycle Assessment.

Though conventional Life Cycle Assessment has been used extensively for both products and processes (Azapagic A., 1999; Kniel G., 1996), it suffers from several shortcomings. First, there is lack of comprehensive data. Especially company-specific data regarding raw materials and emissions is difficult to obtain for propriety reasons. Secondly, there are no strict guidelines for drawing system boundaries that can consider all direct and indirect interactions between all the stages in a products life cycle. Finally, the available data is in disparate units. Arbitrary evaluation techniques are used to compare, say, global warming potential expressed in tons of CO_2 equivalents and acidification potential expressed in tons of SO_2 equivalents. Lave et al have demonstrated a technique wherein all direct and indirect interactions between all stages in a product's life cycle can be successfully considered (Lave L, 1995). The technique is based on economic input-output analysis.

Economic Input-Output Analysis:

Economic input-output analysis was developed by Prof. Wassily Leontief for which he received a Nobel Prize in 1973. Economic input-output analysis is a static general equilibrium model that describes interactions between different sectors of the economy. Leontief assumed that there exists linear relationship between a sector's inputs and outputs. For example, if $20,000 worth of steel were required to produce $10,000 worth of cars, $40,000 worth of steel would be required to produce $20,000 worth of cars. Input-Output analysis has been extensively used for planning and forecasting purposes throughout the world. Most of the developed countries and many industrialized countries compile national input-output accounts for their economies on a periodic basis. In U.S. this laborious job has been taken up by the Bureau of Economic Analysis or BEA.

Economic Input-Output Analysis captures interactions between different economic sectors and presents them in a tabular form (Miller R., 1985). This is explained with the help of Figure 2. This was of representing interactions between different components is quite common in science and engineering. For example, S1, S2 and S3 may represent process equipment such as a reactor, a distillation column and a heat exchanger in chemical process design; photosynthetic tissue, herbivores and carnivores in ecological sciences or three industrial sectors in economics as long as the linearity assumption is valid. Figure 3 shows the general structure of an inter-industry transaction table (Wei J., 1979).

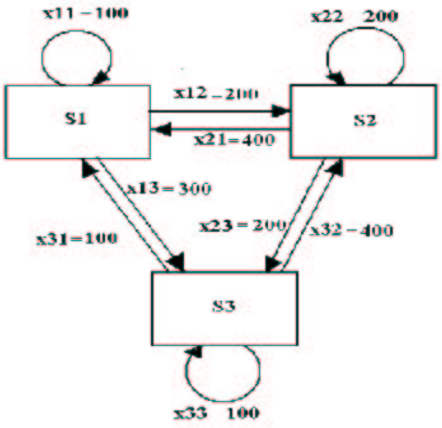
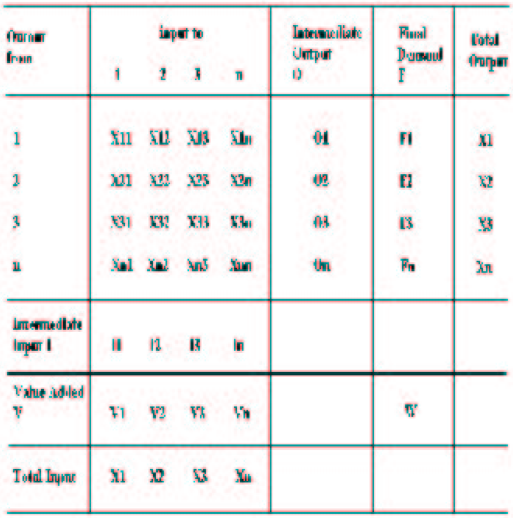


Figure 2: Economic Input-Output Analysis

Final demand represents sale of goods and services to consumers, government establishments etc. whereas "value added" represents the actual contribution of the industry sector in producing its output. Transaction table breaks value added into three components: Employee compensation, indirect business taxes and property type income. As seen in Figure 3, static input-output analysis assumes that monetary input of an industry sector equals its total monetary output.



Output from	Input to				Intermediate Output O	Final Demand F	Total Output
	1	2	3	n			
1	X11	X12	X13	X1n	O1	F1	X1
2	X21	X22	X23	X2n	O2	F2	X2
3	X31	X32	X33	X3n	O3	F3	X3
n	Xn1	Xn2	Xn3	Xnn	On	Fn	Xn
Intermediate Input I	I1	I2	I3	In			
Value Added V	V1	V2	V3	Vn		V	
Total Input	X1	X2	X3	Xn			

Figure 3: Inter-Industry Transaction Table

$$\sum_{i=1}^{n} X_{ik} + F_k = I_k + V_k = \sum_{i=1}^{n} X_{ki} + F_k = O_k + F_k = X_k$$

…(1)

Another convenient way of representing these interactions is direct requirements matrix, D. An entry in direct requirements matrix, say D_{ij}, represents dollar worth of inputs from sector i required to produce once dollar worth of output by sector j.

$$D_{i,j} = \frac{X_{i,j}}{X_j}$$

…(2)

Direct requirements matrix also enables one to calculate total input requirement of an industry given a change in final demand. In order to calculate total requirements of a sector one must consider higher order interactions as well. For example, an increase in demand for automobiles would entail corresponding increases in direct inputs such as steel and plastic. However changes in direct inputs will have further cascading effect throughout the economy. Additional production of steel will require additional consumption of iron ore and electricity. Additional generation of electricity will require additional consumption of coal. To consider these higher order interactions a total requirements matrix, T, is developed.

$$T = (I - D)^{-1} \approx I + D + D^2 + D^3 + ... + D^n \qquad \text{…(3)}$$

Thus, in short, one may think of an input-output model as a first order Taylor series approximation to the actual, more complicated relationship (Lave L, 1995). Economic Input-Output Analysis has been extensively used for forecasting, sensitivity testing, flow and structural analysis and decision-making. Economic Input-Output analysis has also been used in Life Cycle Assessment to overcome the problem of system boundaries (Lave L., 1995; Joshi S., 2000). The resultant methodology is called Economic Input-Output Analysis (EIO-LCA) and introduces consistent and comprehensive definition of system boundary. It enables one to consider environmental impacts at all stages in a products life cycle.

Despite its advantages, Economic Input-Output Analysis ignores majority of ecological goods and all the ecosystem services. These are “free” inputs from nature necessary fro any industrial activity, for example we exploit forests for timber but do not pay the biosphere in return. We also rely on wind to dissipate gaseous emissions but do not pay the atmosphere in return. Failure to consider ecological goods and ecosystem services may lead to large errors as their net worth is estimated to be twice as much as the global gross national product (Costanza R., 1997)

In this paper input-output data is used to evaluate interactions between various industry sectors. Thus if we know the consumption of natural resources by a handful of industry sectors that lie at the boundary of the econosphere and ecosphere (for example, petroleum refining, coal extraction, water and sanitary services etc.) and interactions between different industry sectors we can evaluate dependence of all industry sectors on natural resources. Ideally, this would require material flow or energy flow input-output data for the entire economy. Unfortunately such data is not available. Hence we use economic input-output data to represent interactions between different industry sectors. Since money flow is usually considered to be proportional to and in reverse direction of energy flow, use of monetary input-output data in this analysis is a fair assumption. However as more comprehensive and accurate material flow and energy flow accounts for the economy become available in due course of time we can apply the same methodology with minor modifications.

Thermodynamic Analysis:

Interactions between the economic system and the environment manifest themselves in material and energy flows that can be studied using concepts of thermodynamics (Ruth M., 1993). Material and energy balance, pinch analysis and exergy analysis are a few examples of thermodynamics based analytical tools used in engineering disciplines to study complex systems (Morris D., 1991; Boehm R., 1997). We can also use thermodynamic concepts of energy, exergy and emergy in studying ecological and economic systems. Energy is a state variable that is often misunderstood to be a measure of the ability to do work. According to the second law of thermodynamics, for all real and hence irreversible processes, the actual amount of energy available to do work is less than the total energy content. This available energy, or exergy is the amount of work that a system can do when it is brought to equilibrium with its surroundings via a reversible process initially adibatically to T_0, isothermally to P_0 and finally with equilibrium with surroundings or dead state (Dewulf J. et al, 2000). Exergy analysis has been used extensively for identifying inefficiencies and opportunities for saving energy in industrial systems (Szargut J., 1988). Although exergy is a more useful concept than energy, it provides information only about the current state of the system and its future ability to do work. It however, does not provide any information about the quality of the available energy or the thermodynamic history of the product or service at a global scale. These shortcomings are overcome by the concept of emergy.

Emergy analysis is quite common in ecological literature (Odum H., 1996; Qin P., 2000). Emergy is the embodied energy or energy memory in any product or service. It is defined as the total amount of energy needed directly or indirectly to make any product or service. This is explained with the help of Figure 4.

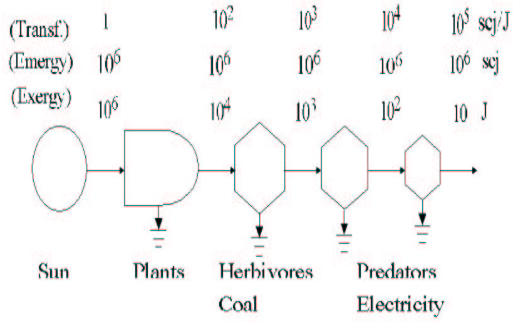


Figure 4: Emergy Analysis

As shown in Figure 4, emergy of each product in an energy transformation series remains the same. Every energy transformation series on earth is initiated by three fundamental sources of energy, namely solar radiation, geothermal heat and tidal forces. The basic idea in emergy analysis is to identify the energy transformation series vital to the product/service in question and determine the amount of energy from fundamental sources necessary to initiate that energy transformation series. For example, in figure 4, to get 10J of electricity an energy transformation series involving such steps as coal formation by decomposition of detrital matter, production of green plants by photosynthesis etc. is required. This energy transformation series is initiated by 10^6J of solar radiation. Hence emergy of electricity as well as every other product in this energy transformation series is 10^6J of solar radiation. Emergy analysis is very useful when disparate units such as economic and ecological are to be considered simultaneously (Geber U., 2001; Lagerberg C., 1999). Moreover emergy analysis is built on an ecosystem perspective, acknowledging ecosystem structure and functions, which is appropriate in this research. Fundamentally, emergy is not different from exergy. Emergy can be viewed as cumulative exergy consumption over the energy transformation series with proper choice of allocation technique.

Following figure shows some emergy based indices and ratios that can be used to measure the environmental sustainability of an industrial activity

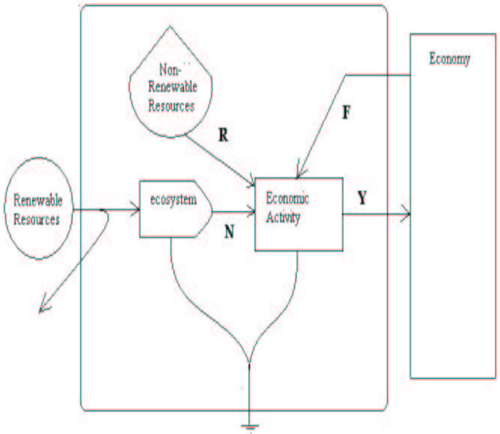


Figure 5: Emergy Based Indices and Ratios

$$Y = R + N + F$$

Emergy Yield Ratio = Y/F

Environmental Loading Ratio = (N+F)/R

Environmental Sustainability Index = EYR/ELR

In this definition of emergy based indices, financial resources are considered to be different from natural resources. In reality the interactions between economy and ecosystems are much more complicated and such distinction between financial and natural resources leads to some problems as is discussed in subsequent sections. Besides, such simplified system diagram does not consider emission of toxic substances from various industrial processes and their impact on human and ecosystem health. In this paper we use a methodology called ECO-INDICATOR 99 to evaluate impact of emissions on human health ecosystem health and resource depletion.

Impact assessment using ECO-INDICATOR 99:

In this approach damages to human health are expressed as Disability Adjusted Life Years or DALYs. Models have been developed for respiratory and carcinogenic effects, the effect of climate change, ozone layer depletion and ionizing radiation. The methodology is divided into four steps namely fate analysis, exposure analysis, effect analysis and damage analysis. Fate analysis links emissions expressed in mass flow units to a temporary change in concentration over a specific geographical area. Exposure analysis links this temporary concentration to a dose. Effect Analysis links the dose to a number of health effects and Effect analysis links the health effects to DALYs, using estimates of the number of Years Lived Disabled (YLD) and Years of Life Lost (YLL). Figure 7 shows a pictorial representation of ECO-INDICATOR 99 methodology to calculate DALYs. The report presents DALY values for several pollutants (Goedkoop M., 1999).

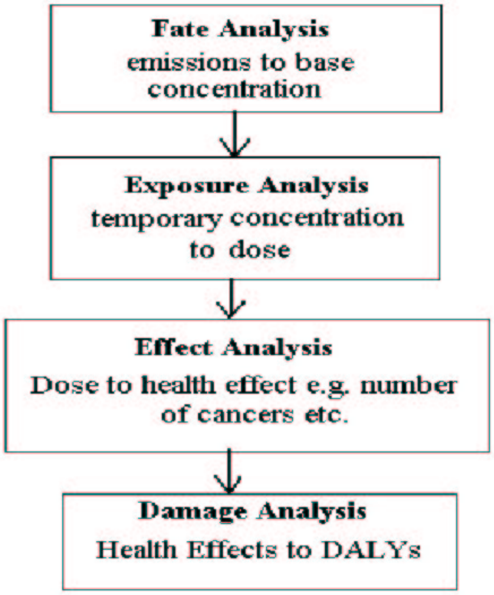


Figure 6: Eco-Indicator Methodology

Damages to ecosystem quality are expressed as the percentage of species that have disappeared in a certain area due to the environmental load. Ecotoxicity is expressed as the percentage of all species present in the environment living under toxic stress. This is the Potentially Affected Fraction or PAF. PAF is converted to a more observable quantity, namely Potentially Disappeared Fraction or PDF using a rather arbitrary conversion factor. Acidification and eutrophication are treated as a single impact category. Here the damage to target species (vascular plants) in natural areas is modeled. Land-use and land transformation is based on empirical data of the occurrence of vascular plants as a function of the land-use type and area size. Resource extraction is related to a parameter that indicates the quality of the remaining mineral and fossil resources. In both cases the extraction of these raw materials will result in a higher energy requirement for future extraction.

Though far from complete, ECO-INDICATOR methodology is very useful in estimating the impact of emissions on human health and ecosystem health. The report presents DALY and PDF values for a large number of commonly occurring chemicals.

Any questions or suggestions can be forwarded to ukidwe@che.eng.ohio-state.edu