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Eco-LCA: An Emergy Inspired Approach and Software to Account for the Contribution of Natural Capital to Economic Activity

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ABSTRACT

One of the main fortes of emergy analysis is its ability to account for the contribution of ecosystem goods and services, or natural capital. Other holistic analysis methods including life cycle assessment, energy and exergy analysis have ignored this crucial contribution from nature, which is the very basis of sustainability. We introduce a novel approach for an Ecologically-Based Life Cycle Assessment (Eco-LCA) that quantifies the dependence of economic activities on nature in biophysical units. The results of Eco-LCA are presented as a hierarchy, with raw data in mass or energy units forming the finest scale of the hierarchy and emergy or ecological cumulative exergy consumption (ECEC) forming the coarsest scale. Conventional energy and exergy (industrial cumulative exergy consumption) form the middle layers of this hierarchy. Information about several emissions is also included. Ecosystem goods and services that are considered in this tool include fossil fuels, minerals, air, wind, pollination, fish, water from various sources, land and many others. A web-based, free software tool is being developed to permit Eco-LCA of 488 sectors of the U.S. economy. This tool is based on an ecological-economic model of the 1997 U.S. economy. Illustrative examples will demonstrate the use of Eco-LCA for comparing the life cycle of common products. Transformities calculated from this tool will be compared with those obtained via other studies. Attention will also be drawn toward resources for which transformities are not yet available.

INTRODUCTION

Human beings benefit from a variety of resources and processes that are provided by ecological systems. Collectively, these benefits are called ecological goods and services. They are the very fundamental resources sustaining our society. To meet the growing human demand causing the degradation of ecosystems, it is important to better understand the mechanisms governing of ecosystems and the way our life style and activities affect the provision of ecosystem services. Over the last several years, ecologists, ecological economists and others have been very active in identifying and better understanding the role of ecosystem goods and services in supporting human well-being. Several studies have identified the crucial role of various ecosystem goods and services for sustaining human activities. In one of the earliest and best known efforts to quantify the role of nature in monetary terms, Costanza et al. (1997) claimed that natural capital was more valuable than the global gross economic product. Despite many criticisms of this study (Costanza et al. 1998), it was successful in drawing attention to the important role of ecosystems. Many such studies have been carried out since (Balmford et al. 2002, Daily 1997, Daily et al. 2000), mostly at national or regional levels. The recently completed Millennium Ecosystem Assessment (MEA) (2008) is the most comprehensive study of the state of natural capital. It found that human beings have altered the ecosystem more rapidly and extensively in the past 50 years to meet human demands than in any comparable period of time in human history. Among the 24 ecosystem services the study examined, 15 are being degraded or used unsustainably, including fisheries, erosion regulation, and pollination.
However, these studies evaluated ecosystem from ecological or economic perspectives, focusing on either a single ecosystem without using a holistic view or on the total contribution on a national level. These studies do not connect with engineering information and are hard to apply for engineering decision making. Knowledge about flows of energy and materials is proving to be useful for evaluating and understanding the behavior of industrial and ecological systems. A holistic view is essential to avoid shifting problems along the life cycle when comparing industrial products or services. Approaches that are relevant are life cycle assessment (LCA) (ISO14000), material flow analysis (Brunner and Rechberger, 2003), net energy or full fuel cycle analysis (Bullard et al. 1978, Spreng 1988), exergetic LCA (Cornelissen and Hirs 2002, Dewulf 2005), cumulative exergy consumption analysis (Hau and Bakshi 2004, Szargut et al. 1988), emergy analysis (Bargigli et al. 2004, Odum 1996), and ecological footprint analysis (Wackernagel 1996).

Most of these methods, including conventional LCA and materials and energy flow analysis (MEFA) focus mainly on industrial processes in the life cycle, their use of nonrenewable resources and impact of emissions, but ignoring the vital role of natural capital in sustaining all economic activities. The carrying capacity of biological systems is limited, the same as nonrenewable resources. Therefore, these methods would fail to identify impacts of ecosystem disruption to industrial activities and may even encourage decisions that further deplete the very services that sustain all activities!

Emergy analysis and ecological footprint analysis are two methods which consider the role of natural capital in sustaining human activities. Emergy is capable of converting all resources into solar equivalent joules based on ecosystem structure, and leads us to use ecological knowledge in engineering decision-making (Odum 2007, Tilley 2003). Ecological footprint converts resource use and emissions into equivalents of land area and is related to carrying capacity. Both methods are directed toward representing the impact of human activities in terms of highly aggregated indicators. Such quantification in terms of a common numeraire is appealing, but faces challenges due to uncertain data and inability to account for all types of resources. For example, although emergy analysis does account for many ecosystem goods and services, reliable data are not yet available for representing all planetary processes or for including crucial resources such as pollination services and atmospheric gases (Hau and Bakshi 2004). Ecological footprint analysis limited itself to land use. However, soil erosion is not accounted for, although it is closely related to land use (van Kooten and Bulte 2000). Moreover, ecosystem services and functions do not necessarily show a one-to-one correspondence (Costanza et al. 1997). One ecosystem may contribute to two or more ecosystem services. For example, a forest provides wood, but also plays a particularly important role in water resources in terms of quantity and quality. Aggregate results usually quantify only one of these services, leaving other contributions uncounted. It is also important to emphasize that many ecosystems are interdependent. The existence of one service might need the interaction of several ecosystems (Farber 2002). Although emergy analysis and ecological footprint analysis are appealing and intuitive, any approach that provides highly aggregate results may disguise important details, is controversial due to challenges in converting all resources to a common unit, and may also implicitly assume substitutability between the resources being aggregated.

Recognizing the central role of natural capital for sustainability, this work describes a fundamentally different approach adopting the merits of LCA, emergy analysis and materials and energy flow analysis methods. This “Ecologically-Based LCA” or Eco-LCA accounts for the contribution of ecosystem goods and services to industrial activities. Inputs from nature include water use from different sources, soil erosion, land use, wind, sunlight and bio-geo-chemical cycles, besides the traditional inclusion of minerals and fossil fuels. Hierarchical structures are proposed to represent the result. Individual resources form the bottom layer with their raw units, such as grams, joules or acres. They are normalized by national consumption level to identify the limiting resources. Resources can then be characterized and categorized into a few classes such as ecosystem goods, ecosystem services, renewable, nonrenewable etc. These mid-point categories are further combined to yield end-point indicators which stand on the top of the hierarchy. This approach can retain the information at different levels, and assist decision makers, who have different objectives. Even if the transformity of a
certain resource is not available temporarily, it can still be kept in the analysis and normalization is applicable. Information on resources is available in diverse units, which are difficult to combine and highly multivariate. Various physical methods such as mass, energy, cumulative exergy and emergy are explored for the proposed categorization. The final indicators are cumulative mass consumption, cumulative energy consumption, industrial cumulative exergy consumption (ICEC) and ecological cumulative exergy consumption (ECEC) that is equivalent to emergy (Hau and Bakshi 2004).

A process-based model, an Input-Output (IO) model and a hybrid model have been developed for LCA and energy analysis. Their use in Eco-LCA framework was explored. The IO model divides the U.S. economy to 488 sectors with each of them covering a group of similar products and services. An input-output model of the United States was applied in the proposed approach. This model is related to previous work by Ukidwe and Bakshi (2007), but considers a much larger range of ecological inputs in many different units. The special benefit of this model for emergy analysis is that it provides emergy to money ratios for each industry. Use of these ratios can give more accurate results than the single ratio commonly used in emergy analyses (Odum 1996). Moreover, since the information on each resource is retained in the model, double counting caused by adding renewable environmental emergy and the renewable portion of purchased emergy can be avoided. Software for using this model is being developed and will be demonstrated via applications to typical LCA problems such as comparison of ceramic versus glass cups.

METHODS

Eco-LCA extended the boundaries of traditional materials and energy flow analysis to account for the contribution of ecosystem goods and services. The general approach for Eco-LCA will complement and enhance conventional LCA. The Eco-LCA inventory is built from data about ecosystem goods and services that are necessary for the selected system. It utilizes existing procedures and best practices for steps such as goal definition and scope, boundary selection and inventory analysis. Inventory data can be quantified by the Process Model, the IO Model, and the Hybrid Model. Eco-LCA is unique in its ability to represent results in a hierarchical structure retaining all the information available. Flows of individual resources form the finest scale; categorization and aggregation based on different schemes form the middle layers, and unitary values in terms of cumulative mass, energy, exergy and emergy are given on the top of the hierarchy.

Resources and Data Sources

 Provisioning services are always accompanied by concomitant material and energy flows, and hence they can be quantified independent of human valuation. Examples are fossil fuels, minerals, and solar energy. They are included in our model. Quantifying regulating and supporting services requires a more thorough understanding of their mechanisms. This work incorporates the best quantitative knowledge currently available, such as carbon sequestration in soils and plants, bio-geo-chemical cycles, the water cycle, and pollination. The evaluation of cultural services is value-based, which is more dependent on human judgment, and hence they are not included in this work.

Inventory data were collected from multiple sources. The Department of Energy provides the fossil fuel, nuclear energy, electricity use, and some renewable energy sources. The Department of Agriculture has the data for water and land use. Mineral consumption can be found from the U.S. Geological Survey. Pollution data are maintained by the U.S. EPA. Certain non-governmental organizations also collect resource consumption data, such as the World Resources Institute. The Input-Output model, which is compiled periodically by Bureau of Economic Analysis, was also applied to our method.

Choice of Unit

Natural resources exhibit a variety of attributes, such as economic value, mass, energy or exergy, and emergy developed by system ecologists. An important challenge in life cycle evaluation is the
need to interpret multiple attributes representing different types of resources consumed. It is a question of debate which attribute can represent the quality of resources best (Cleveland 2000). However, each of them shows importance for certain applications. Previous studies used the units of mass, energy, exergy and emergy to represent resource quantities. All of them will be supported in Eco-LCA to fulfill the needs of decision makers at various levels. The unit conversion process is presented as a hierarchy. Raw data are usually obtained in the unit of mass or energy. Not all the resources can be expressed by both mass and energy units. For example, solar energy does not have weight, minerals do not have fuel content either, and it is not appropriate to evaluate land in terms of mass or energy. Exergy captures the available energy in resources, and theoretically it can measure all the resources. Transformity data of many resources for converting mass or energy to exergy and emergy are obtained from books and technical papers (De Meester et al. 2006, Odum 2000, Odum et al. 2008, Szargut et al. 1998).

Mathematical Calculation

Both LCA and MEFA can use the process model, the IO model, or the hybrid approach to quantify input streams. They are also the mathematical foundation for Eco-LCA computation.

The process-based model is the most commonly used approach in LCA studies, and it can be applied using many commercial software products and the LCI database (Gabi, SimaPro). Within the process-based analysis, the resource requirements and pollutant releases of the main production processes and some important contributions from suppliers of inputs into the main processes are assessed in detail. The system boundary is usually chosen with the assumption that the additional upstream production stages have small effect on the total inventory and ignorance of them will not change the credibility of results (Lenzen 2001). The assumptions may be based on the relative mass, energy or economic values in the upstream flows (Raynolds 2000). Although it is impossible to achieve 100% completeness in evaluating the system, this method can give insight at the process level, and improve efficiency of resource use.

Input-Output Analysis was developed by Wassily Leontief (1936) to study inter-industry relationships. The method tracks the monetary transactions between each pair of industries, which are also called sectors. Ukidwe and Bakshi (2005, 2007) developed thermodynamic input-output models of the 1992 and 1997 U.S. economies and used them to provide insights into the relative flow of natural and economic capital in industrial supply chains via aggregated cumulative exergy and emergy indicators. Their work forms the basis of the proposed Eco-LCA approach at the economy scale.

The result of the IO model is resource consumption per dollar of economic product for each economic sector, which can be expressed as g/$ for mass, J/$ for energy and exergy, and sej/$ for emergy. This calculation produced new and useful information for traditional emergy analysis. Emergy analysis usually uses a single emergy to money ratio. Sectoral emergy to money ratios (sej/$) provide more reliable emergy per unit data for inputs from the economy. Secondly, information on renewable and non-renewable resources is retained by the model. Thus, purchased products need not to be treated as equivalent to non-renewable resources in emergy analyses.

Although the Input-Output Model can represent the whole economy with all products sold on the market, the model is still too aggregated: the whole economy is broken into only 488 sectors while the economy produces thousands of products. A better approach is the Hybrid model, which combines the process and IO models. It first uses the methods of the process model to study critical processes, and then it connects the other so-called unimportant processes by using IO data. Therefore, the hybrid LCA can improve the accuracy of the result while maintaining the overall precision. The process model, the IO model and the hybrid model can all be used to do Eco-LCA studies. In this work, we will show one case study based on IO model. The use of the hybrid technique can be found at Baral and Bakshi’s work (2006).

Figure 1 shows a diagram of hybrid emergy analysis. The left side gives information on renewable and nonrenewable inputs to the process in the studied system, while the right side shows that the system takes inputs from the economic system. The circle outside the box presents solar, tidal and
wind energy ($R_3$), which are the three major renewable energy sources driving the entire ecosystem on the Earth. Renewable ($R_i$) and non-renewable ($N$) goods and services from the ecosystem flow to the studied system directly and indirectly via the economy. The IO model is used to track resources entering the economy ($V_{ph}$) and calculate cumulative consumption for each economic product. Renewable and nonrenewable resources flowed through economy can be represented by $FR_1$, $FR_2$, and $FN$. Human beings work in the economy and also buy goods and services from it. National economy usually interacts with other countries by imports and exports.

**Quantification Methods**

Environmental LCA has made significant advances in classification, characterization and assessment of the impact of emissions. Impact analysis is important to understand the potential human health and environmental damage from inventory data on emissions. In analogy, we propose the following steps to understand the overall and individual impact of resource consumption.

**Normalization**

Comparing resource use encounters a big challenge because the resources are expressed in different units and their availability in nature is diverse. Normalized metrics are unitless, which enables comparison across resources. Normalized metrics are calculated by comparing cumulative consumption of a resource with its total flow at the national level. It can not only be applied to individual resources, but also to aggregated metrics. Normalization can help identify the limiting resources, especially when comparing products with similar functionality. The choice of using national level resource consumption was made because of the data availability, but the denominator can also be based on policies and regulations, or based on the scarcity of the resources (Bare and Gloria 2006).

**Classification**

Natural resources can be classified using multiple criteria. The most important distinction is renewable and non-renewable. Renewable resources can be living (e.g., fish, forest) and non-living (e.g., water, soil). Another kind of renewable resources is flows, such as solar radiation, wind, and tides. Flows are abundant, and need not to be regenerated. Non-renewable resources are fossil fuels, minerals, etc. Minerals can be further segregated as metallic and nonmetallic minerals. Resources can also be classified on the basis of their origin as biotic and abiotic. Biotic resources are derived from
animals and plants, abiotic resources are derived from the non-living world (e.g., land, water, and minerals). Also resources can be distinguished as energy or materials. Another classification is to consider their form when entering the economy, which is the concept of ecosystem goods or services.

**Aggregation**

Resources in the same category have similar properties and functionality, and sometimes they are exchangeable. Aggregating resources according to classes can reduce the complexity of a problem without losing much useful insight. By applying multiple criteria, many hierarchical aggregation structures can be built. The input streams when expressed in mass, energy and ICEC are additive. The aggregation to emergy follows the distinction of additive and non-additive. This is quite unique and challenging. For example, rain and wind are co-products of the global ecosystem, but complete knowledge about ecological networks and all interactions between ecosystem components is seldom available. Consequently, the allocation is avoided by assigning the same emergy to all the outputs. The resource whose emergy is defined by this method is classified as non-additive. On the other hand, when a process consumes several non-additive resources, the maximum emergy among these input streams is assigned to the product to avoid double counting.

**Sustainability Indicators**

Sustainable development requires meaningful, practical and scientifically sound metrics. These metrics serve as indicators to assess the sustainability of the studied process. Metrics can be defined based on the information about material and energy inputs and/or emissions for a product in its life cycle (Yi et al. 2004). The indicators used in Eco-LCA are based on thermodynamic methods (Odum 1996, Ukidwe and Bakshi 2007). The definition of metrics is based on the characterization of resources inputs (Ulgiati and Brown 1998). Industrial processes consume 1) direct renewable resources ($R$), such as agricultural sectors and wind-based power generation; 2) direct non-renewable resources ($N$), such as minerals and fossil fuels; 3) input from economy ($F$). Economic inputs represent goods and services bought from other processes, and valued in monetary units. The embodied resource consumption of economic inputs can be calculated by the process-based model or the IO model. Use of IO model can retain the renewable portion ($FR$) and nonrenewable portion ($FN$) of economic inputs. The embodied resource consumption of the studied process ($Y$) is the summation of the previous three inputs.

\[ F = F_R + F_N \]  
(1)
\[ REN = R + FR \]  
(2)
\[ NR = N + FN \]  
(3)
\[ Y = R + N + F \]  
(4)

Equation 2 can be applied to mass, energy, and ICEC calculation. However, for the emergy calculation, the total renewable emergy is the maximum instead of summation of renewable resources. If the process consumes a total of $n$ types of renewable resources, equation 5 should be applied.

\[ REN = \max(R_1 + FR_1, R_2 + FR_2, ..., R_n + FR_n) \]  
(5)

The above characterizations of resource flows make it possible to calculate different indices that can be used to assess the process’s behavior. The three indicators used in Eco-LCA are yield ratio ($YR$), loading ratio ($LR$) and sustainability index ($SI$).

\[ YR = Y/F \]  
(6)
\[ LR = NR/REN \]  
(7)
\[ SI = YR/LR \]  
(8)

The Yield Ratio is the ratio of total resources requirement to the bought resources from the economy. In other words, this indicator is a measure of the ability of the process to directly exploit local resources. The Loading Ratio indicates the relative reliance of the product on non-renewable
resources. Since the renewable and non-renewable portion of the bought goods and services can be distinguished, the underlining assumption made by emery analysis that all bought goods and services are non-renewable is not necessary. The ratio of $YR$ to $LR$ is called yield-to-loading ratio and is considered in emery analysis as the index of sustainability. If a process uses more direct and renewable resources, the ratio is bigger, meaning the process is more sustainable.

**CASE STUDY**

Eco-LCA method has been applied to the 1997 U.S. economy, considering 46 resources and emissions. The cumulative mass, energy, exergy and emery consumption of each industrial sector and their ratio with economic activity of the corresponding sector were calculated. Such ratios can help determine the resource consumption of any product or service provided its price is known. The Eco-LCA can be used for determining and interpreting the resource vulnerabilities and intensities of the supply and demand chains of industrial sectors so that strategies for reducing these intensities may be devised.

A preliminary case study demonstrating this tool is to compare cups, made of ceramic and glass. The industrial sector corresponding to these cups are 327112 (ceramic), and 327213 (glass). They are compared on a per cup basis. Figure 2(a) displays the normalized cumulative consumption of resources for the two kinds of cups. The normalization factors are annual consumption of resources in U.S. economy. Several bars for specific minerals and some services are not shown here for maintaining clarity, and because they show similar normalized values due to their entering the economy via the same sector. Fossil fuel consumption of one glass cup is 3.75 MJ, bigger than the consumption of a ceramic cup, 2.73 MJ. While, ceramic cups dominate the use of minerals, including metallic and non-metallic. Within then, sand is the biggest contributor because it is the main material. Minerals come from mining industries. Mining causes the destruction of natural ecosystems through complete removal of soil, plants and animals. The impact of mining is generally more severe than most other kinds of disturbance to land. Without proper soils but the disposal of rock, overburden, etc. presents extreme challenges to restore any kind of self-sustaining ecosystem (Cooke, 2002). Regarding renewable resources on the right side of the figure, the normalized consumption is very small for both cups. Figure 2(b) is normalized emission data. The emission rates for both cups are close, and it is hard to declare a winner.

Subfigures c, d, e, and f show the aggregated results in terms of cumulative mass, energy, ICEC and ECEC. Two criteria are used for the hierarchical structure. The resources are first grouped according to the classification of ecological products and services. The ecological products are further disaggregated to their four sources: lithosphere, biosphere, hydrosphere, and atmosphere. Such classification assists categorization of a vast number of ecological resources into smaller groups, but it is by no means critical to the applicability of Eco-LCA. The second is renewable and nonrenewable. The last unitary value is the total amount of all resources. Loading ratios are also plotted with the total consumption at the top level. Yield ratios are not applicable because no process model is built for this case. Note that the y-axis is log scale in these subfigures, and the ranges of y-axis in the four subfigures vary.

Using the unit of mass, water use for power generation dominates. Although the discharged water from power plants is not polluted by chemicals, it is still harmful to fish and algae due to temperature rise. In terms of energy, only fossil fuels from the lithosphere, wood and grass use from the biosphere, and renewable energy (sunlight, wind, etc.) as ecosystem services are counted. Aggregation by mass cannot capture resource quality and impact. Aggregation by energy cannot take material streams into account. Although fossil fuels are usually the emphasis of conventional LCA, the biggest energy contributor is sunlight. Solar energy is abundant, but has a lower quality. This implies that CEnC ignores the quality difference between different kinds of energy. ICEC captures the exergy flows in industrial systems, and it also captures the exergy quality difference between resources, but it lacks the ability of to capture ecological work. One interesting observation is that more renewable resources are consumed than nonrenewable resources in terms of mass, energy and ICEC due to the large amount of
water and sunlight used, also resulting in near zero loading ratios. But ECEC reversed this relation by extending the boundary of ICEC to include the ecosystems, which gives a fair standard for comparing renewable and nonrenewable resources based on the ecological work. The loading ratios based on ECEC are more than 100. This study finds that one ceramic cup consume similar amount of renewable resources to, but several times more non-renewable resources than one glass cup. Hence, glass cups should be recommended for use.

Figure 2. Eco-LCA comparison of ceramic and glass cups.
CONCLUSIONS

Natural capital is important for sustainable development, but it is often ignored in traditional Life Cycle Assessments and other materials and energy flow analyses. Emergy analysis and Ecological footprint analysis are the only methods quantifying the contribution of ecosystem goods and services to industrial activities. However, they usually represent the impact in highly aggregated results without presenting details. This work describes a fundamentally different approach. This “Ecologically-Based LCA” or Eco-LCA accounts for inputs from nature such as water use from different sources, soil erosion, land use, pollination services, fish, wind, sunlight and bio-geo-chemical cycles. Such information is available in diverse units of mass, quantity or energy, which are difficult to combine and highly multivariate. A hierarchical structure is used to represent them systematically. The raw data with their original units form the finest scale. These data are normalized by national consumption. Normalization can be performed for any resources even for those which have no transformities, and it is an important step for identifying limiting resources. Methods are proposed for characterizing and categorizing this basic information into a few categories such as ecosystem goods, ecosystem services, renewable, nonrenewable etc. Multiple units are recommended for aggregation, which can help decision-makers at various levels. Among them, exergy, or useful energy, are recommended due to its ability of quantifying resource quality and accounting for both material and energy flows. An input-output model of the United States was developed based on the proposed approach. Software for using this model is being developed and was demonstrated via the comparison of ceramic, and glass cups. This study found glass cups are the better choice based on the resource consumption.

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