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Environmental accounting methodologies: an overview

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Abstract

The assessment of sustainability requires alternative and integrated approaches for a deeper understanding of the complex network of interactions occurring between humans and the environment. In the present publication we will present an overview of some of the more interesting environmental accounting indicators (methodologies).

The *ecological footprint*, as proposed by Wackernagel and Rees, quantifies the intensity of resources used and the waste discharge activity in a specified area in relation to the area's capacity to provide for that activity.

Emergy analysis is an holistic methodology which can evaluate both the contribution of economics and environmental work on a common basis. Odum defines emergy as the solar energy directly and indirectly required to generate a specific flow or a product. This quantity represents the memory of all energy, matter and time that the biosphere used to make a product available.

The indicator *exergy* is a more effective way to verify if and how much a system is efficient, whether in a single productive process or on a territorial level because it includes both quantity and quality aspects.

Life Cycle Analysis (LCA) permits a systematic analysis of the effects of a particular human activity on the environment. This method allows an environmental diagnosis of the whole story of a product, from its production until the exhaustion of its functions and effects: a cycle called "cradle to grave".

All this methodologies are focusing only on particular aspects of the overall, so the integration is recommended, in order to have a global and more accurate vision of the problem.

1 Introduction

Since the introduction of the Sustainable Development issue and related topics, numerous attempts to quantify this elusive concept have been made.

Herman Daly [1] proposed two principles of sustainability: the first one states that harvest rates should equal regeneration rates, and the second one states that waste emission rates should equal the natural assimilative capacities of the ecosystems into which the wastes are emitted.

To implement and measure the degree of sustainability at ecological, economic and social level, we need integrated indicators built up on well-founded scientific bases. In other words, we need interdisciplinary tools of analysis able to reveal more than one aspect of the overall.

The aim of this paper is briefly to describe some of the most interesting methodologies for the assessment of sustainability problems such as ecological footprint assessment, emergy analysis, exergy analysis and life cycle analysis.

2 Ecological footprint assessment

In the early 1990's, William Rees and Mathis Wackernagel, from the British Columbia University of Vancouver, Canada, developed the original concept of the ecological footprint (Wackernagel [2]). This environmental accounting methodology is recognized as one of the more interesting tool that attempts such an integrated resource accounting.

The ecological footprint (E.F.) of any defined population (from a single individual to that of a whole city or a country) is defined as the total area of ecologically productive land (forests, arable land, pasture, built-up area,...) and water ecosystem required to:

a) produce the resources and services consumed,
b) assimilate wastes generated by that population,

wherever on the Earth that land and water may be located.

E.F. is based on the assumption that most of the energy and material flows can be converted into the biologically productive area that is required to maintain these flows. It is measured in “area units”; one “area unit” is equivalent to one hectare of biologically productive space with world average productivity. Land itself is a powerful indicator because it is understood by everyone.

Assessing human use of natural capital by comparing resources consumption and wastes production to the regenerative capacity of the Earth, the ecological footprint is a conservative estimate of human pressure on global ecosystems, and so it can be defined as the portion of carrying capacity necessary to that population (Wackernagel [3]).

Carrying capacity is the quantity of population or activity that an ecosystem can support without compromising its intrinsic integrity. Human impact is a function of the population and its activities which should include both the number of individuals as well as their individual consumption level.

Since areas are scaled according to their capacity to produce biomass, area units allow the comparison of the E.F. of different countries and with the world average biological capacity available per person. The minimum requirement for global sustainability is that humanity's footprint must be smaller than the biosphere's biological capacity.

Rough (under)estimates confirm that globally humanity's present an overshoot: i.e. if everyone enjoyed a North American standard of living this would require three earths. Since we have only one earth, we are living beyond our biophysical means.

The analysis also defines a bio-productive capacity of a certain region (local, national or global) and compares its E.F. with this capacity, to determine the so-called ecological deficits or surpluses. The ecological deficit indicates whether a region, in principle, is able to supply itself with local resources or it has to rely on "net imports of land".

One of the most important strength of the ecological footprint concept over some other indicators like environmental space is the E.F. gives a clear, unambiguous message often in an easily form. The simplicity and the clarity of the communication are fundamental properties of any indicator for both policy makers and the general public.

The E.F. indicator has stimulated a great interest of public although there are ongoing debates about specific methods for the calculation. Ecological Economics [4] has kept all a volume to collect commentaries (comments) and to stimulate discussion on this topical issue.

3 Emergy analysis

The methodology was developed by H.T. Odum [5] of the University of Florida, (USA) in the early 1980's. The solar emergy (from now on simply emergy) of a flow or storage is defined as the solar energy directly or indirectly required to generate that flow or storage. It is an extensive quantity and its units are solar emergy joules, sej. In order to convert all the flows involved in the process, into this common base a conversion factor is used: the (solar) transformity, defined as the emergy per unit flow or unit product. It is an intensive quantity measured in sej/J.

Emergy can be considered as an energy memory because it takes into account all the energy, past and present, needed to produce that product or flow.

As the emergy analysis is useful to check applications of the first Daly's rule (sustained yield) it is recognized as an important tool to define the sustainability in the long run and measure the human impact on nature.

This environmental accounting methodology can be used to assess the complex relationships between the economic system and its supporting environment because the work of both is expressed in equivalent terms. In this way we are able to consider also the energy flows that are "free" and generally neglected in the traditional energy and material balances.

A set of emergy-based indicators is also proposed to evaluate different scenarios comparing their emergy inputs (Odum [6]). The total emergy of the output (Y) is divided into the renewable (R) and the non renewable (N) part, and the local (L) (natural) and imported from outside inputs (F).

Here some of the most important ones are presented:

The *emergy yield ratio* (EYR) is the emergy of an output (Y) divided by the emergy of those inputs to the process that are fedback from the economy (F):

$$EYR = \frac{R+N+F}{F} = \frac{Y}{F} \tag{1}$$

This ratio indicates whether the process can compete in supplying a primary energy source for an economy. If the ratio is lower than alternatives, less return is expected to be obtained per unit of emergy invested.

The *emergy investment ratio* (EIR) is the ratio of the emergy fedback from the economy (F) to the indigenous (renewable R and non renewable N) emergy inputs:

$$EIR = \frac{F}{N+R} \tag{2}$$

This ratio indicates if the process is economic as utilizer of the economy's investments in comparison to alternatives. The physical meaning of this index is to evaluate the emergy input from the economy needed to exploit a unit of indigenous local resources.

The *environmental loading ratio* (ELR) is the ratio of purchased and non renewable indigenous emergy to renewable (free) environmental emergy:

$$ELR = \frac{N+F}{R} \tag{3}$$

A high ratio suggests a high technological level in emergy use and/or a high level of environmental stress. It is like an alarm-bell for a state of non-equilibrium which in the long run could become irreversible.

Emergy use per person suggests a measure of the standard of life in a country intended as availability of resources and goods.

The *empower density*, the emergy flow per unit area, is a measure of spatial concentration of emergy flow within a process or system. A high empower density can be found in processes in which emergy use is large if compared to available area and suggests that land is a limiting factor for the future economic growth.

4 Exergy analysis

Exergy (Ex) is a thermodynamic potential that can be derived from Gibbs Free Energy. It can be defined as the maximum work that can be obtained from a system when this is brought from its present state to the so called "thermodynamic equilibrium", that is, to a state in thermal, mechanical and chemical equilibrium with the surrounding environment (Jørgensen [7]). One of the most used thermodynamic relation of exergy is proposed in eqn (4):

$$Ex = S(T - T_0) - V(p - p_0) + \sum_i N_i(\mu_i - \mu_{i0}) \tag{4}$$

where the extensive parameters (i.e. quantities that increase with the size of the system) are entropy (S), volume (V) and number of moles of substance i (N_i) and the intensive parameters (i.e. quantities which are independent of the size of the system) are temperature (T), pressure (p) and chemical potential of substance i (μ_i) for the system. The subscript 0 relates to the reference environment. Its units are Joules. Since exergy approaches zero as the system approaches equilibrium, its value shows how far the system is from the equilibrium.

Exergy is related to the degree of organization and its value is very important in the evolutive thermodynamics for the state far from equilibrium.

The exergy content in a material can be determined by the formula in eqn (5)

$$Ex = \sum_i N_i(\mu_i^o - \mu_{io}^o) + RT_o \sum_i N_i \, ln\left(\frac{c_i}{c_{io}}\right) \tag{5}$$

where μ_i^0 is the chemical potential for the matter i in its reference state (a state to which all values of the chemical potential for a certain matter are related) and c_i is the concentration of the component i. In this way it is possible to determinate the exergy content in each type of material theoretically.

This methodology has been widely used to assess industrial processes and energy production (Szargut [8]). It has recently also been applied to the study of ecosystems (Jørgensen [9]). On a larger scale, early studies of the Swedish and Japanese society (Wall [10]) showed inconsistencies with other types of analysis, usually based on energy, which gave more optimistic results. The main difference is that since energy is conserved (while exergy is used and dissipated), it is purely quantitative neglecting the quality factor, the real potential for performing work.

Recently the Exergy/Emergy ratio as a measure of the level of organization of systems was proposed (Bastianoni [11]). It measures the efficiency with which an ecosystem transforms its inputs (in emergy terms) in order to auto-organize. Jørgensen showed that emergy and exergy have a strong correlation in the development of natural selection. This ratio can be useful to determinate the level of evolution of an analyzed ecosystem and compare different natural and artificial ecosystems.

5 Life cycle assessment

Life Cycle Analysis (LCA) is a very important tool for environmental policy that provides a systematic framework which helps to identify, quantify, interpret and evaluate the environmental impact of a product, function or service in an orderly way. During the LCA of a product (or of a process or an activity), the environmental impacts of the whole productive cycle are studied, from the identification and quantification of emission and material and energy consumptions to the management of the waste produced [12].

LCA is an iterative process until the final goal is achieved, from the data collection to their processing. The structure-type of a LCA is:

- definition of boundaries, goals and scopes of the study;
- data collection concerning the different stages of the life cycle (inventory);
- data processing and evaluation of the environmental impacts (assessment);
- results interpretation (interpretation).

This method allows an environmental diagnosis of the whole story of a product, an approach called "cradle to grave" i.e., from the initial extraction and processing of raw material until the exhaustion of the functions and effects.

Until now LCA has only been used by experts and scientists mainly due to the complex nature of the analysis, but gradually should become a more generally applicable tool.

LCA is a diagnostic tool which can be used to compare existing products or services with each other or with a standard, which may indicates promising areas for improvement in existing products and which may aid in the design of new products.

LCA represents a technical and multidisciplinary approach to environmental problems, whose results are connected with the practitioners' capacity of composing, identifying and measuring the meaningful phases of the processes.

6 Discussion

In this paper a set of tools was presented each of which gives some insight into the complex issue of sustainable development. No tool for sustainability is complete and none will satisfy everyone. To implement and measure the degree of sustainability at ecological, economic and social level, we need an integrated set of indicators in order to have a global and more accurate vision of the problem.

LCA is quite complete according to the concept of sustainability, it responds both the first and second Daly's principles, since it takes into consideration all the products and by-products of a process. As in any weighted matrix, it has the problem of subjectivity in the assessment phase. As a weak point, we can say that LCA is a more reductionist approach with respect to the others presented here that uses a holistic viewpoint.

Emergy analysis is a flexible tool, giving much other information about actions and policies with respect to sustainability such as efficiency, correct use of local resources and their degree of renewability. On the other hand it is unlike to be fully understood by the public.

Ecological footprint analysis is an interesting approach, which can be immediately understood by the public and policy makers. Early analysis shows that there may be a good correlation between its results and those of emergy analysis, in particular with the empower density or emergy per person.

Exergy is a thermodynamic indicator that was introduced and proposed in ecological models, where it was successfully applied for the development of structural models. Now it is becoming an important tool because of its various increasing applications in several fields.

Furthermore the development of analytical methods to determine the carbon balance of a process or a spatial area becomes a fundamental tool to better organize the policies for the reduction of gas emissions.

In our opinion a good strategy is to consider all these approaches, together with others such as the procedure for accounting the value of the world's ecosystem services and natural capital as suggested in Costanza et al. [13]. To

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have a more complete understanding of the system, some of the indices can be used as real indicators of sustainability. The effort of the scientists should be to make the use of such indicators easier for policy makers. Policy makers should be open minded to scientifically based approaches, that are more likely to give reliable indications for a good planning.

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