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A thermodynamic framework for ecologically conscious process systems engineering

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Abstract

Making process systems engineering decisions that are ecologically conscious requires analysis of both industrial and ecological processes. Traditional methods in process engineering usually fall short of meeting this requirement due to considering the environment as secondary to economic objectives. Life cycle assessment and design methods have broadened the scope of traditional methods by considering the environmental impact in the entire life cycle of a product or process. These methods focus primarily on the environmental impact of emissions and ignore the contribution of ecological products and services. This paper presents a thermodynamic approach for including the input from both ecological and economic resources, and for analyzing industrial and ecological processes together. This approach is based on the fact that growth and sustenance of both industrial and ecological processes are limited by the available energy and its conversion to useful work. Thus, the embodied energy (emergy), that is, the energy used directly or indirectly to make a product or service is a measure of ecological cost. Emergy analysis of industrial and ecological processes provides insight into the environmental performance and sustainability of the industrial process or product. Emergy-based life cycle assessment is developed to combine the benefits of both methods. The proposed framework is broadly applicable and is illustrated by the emergy based life cycle assessment of soy bean growth.

Keywords: Life cycle assessment; Product assessment; Process design; Ecosystem services; Exergy; Emergy

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1. Introduction

Increasing awareness of the impact of human actions on the environment has motivated the development of techniques for incorporating environmental considerations in process engineering. Popular approaches focus on maximizing the economic potential while posing environmental and safety regulations or cost of waste treatment as constraints. These approaches have been successful in modifying processes to prevent pollution and minimize waste at the scale of the process. Unfortunately, such an approach of considering the environment to be ancillary to economic objectives, and of minimizing waste only at the scale of the process is too narrow in scope, and often causes the environmental impact to shift from one domain or process to another without truly reducing or eliminating it (Cano-Ruiz & McRae, 1998; Allenby, 1999). Consequently, making environmentally conscious process engineering decisions requires expansion beyond the scale of the process, and techniques for considering both economic and ecological aspects.

The technique of life cycle assessment (LCA) (Heijungs, Huppes, Udo de Haes, Van den Berg & Dutlith, 1996; Curran, 1996) considers the impact of all the industrial processes in the life cycle of a product from extracting the natural resources to using and disposing the product. Life cycle methods for process design have posed the life cycle impact considerations as a constraint while maximizing the economic potential (Cabezas, Bare & Mallick, 1999), or as part of the objective function (Azapagic, 1999).

Despite its many benefits and popularity, LCA suffers from several shortcomings. It focuses primarily on the environmental impact of emissions and nonrenewable and energy inputs, while ignoring ecosystem services and products such as, rainfall and pollination. Ignoring these inputs can lead to significant error in the analysis and misleading results, since ecological services

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are estimated to be twice as valuable as the global gross national product (Costanza et al., 1997). Furthermore, the final result of LCA depends on the highly subjective step of valuation. Finally, LCA does not consider environmental sustainability of products or processes.

Techniques for measuring ecological products and services, and ecosystem health have been developed by systems ecologists. These techniques are based on the fact that the development and sustenance of natural systems is limited by the available energy and their ability to use the energy for themselves and other systems that they depend on. Since solar energy is the main source of energy for the planet, the ecological input in any product or service may be measured by the equivalent solar energy embodied in it. Methods based on analyzing thermodynamic properties such as the embodied solar energy and the exergy content provide information about the health and sustainability of ecosystems (Jorgensen, 1997).

This paper presents a thermodynamic framework for incorporating the cost of ecological materials and services in the analysis of industrial systems, and for combining it with the cost of economic materials and services. The approach is adapted from techniques in systems ecology and exploits the fact that industrial systems also follow the same laws of nature as ecological systems. Since all materials and services are transformed and stored forms of solar energy, the amount of solar energy used directly or indirectly to make any product or service is used as a measure of the ecological input or investment in that product or service. Thus, solar embodied energy or solar emergy is used as a common currency for the analysis of industrial and ecological systems (Odum, 1988).

The rest of this paper is structured as follows. A brief introduction to the principles of life cycle assessment and design is provided in Section 2. This is followed by an introduction to the relevant thermodynamic concepts for the analysis of industrial and ecological systems in Section 3. The principles of emergy analysis are discussed in Section 4. The emergy-based approach for product assessment and process design is presented in Section 5. Finally, a brief overview of the emergy-based LCA of soy bean oil is in Section 6.

2. Life cycle assessment and design

LCA is a systematic approach for considering the environmental impact of a product or design throughout its life cycle (Curran, 1996; Heijungs et al., 1996). The steps in LCA have been standardized and include, goal definition and scope, inventory analysis, impact assessment, and improvement assessment. Inventory analysis collects information about the inputs and emissions in each stage of the product's life-cycle. Large databases have been compiled for obtaining this information (Curran, 1996). One of the important contributions of LCA is the standardization of impact assessment of a broad variety of emissions. Life cycle impact assessment (LCIA) involves classification of the emissions into various impact categories such as, abiotic depletion potential, energy depletion potential, global warming, ozone depletion, human toxicity, ecotoxicity, etc. Different emissions are converted into equivalents of selected reference substances such as, equivalents of CO_2 for global warming, and equivalents of SO_2 for acidification. The quantified contribution in each impact category is then normalized by the size of the local or global problem. The next step requires determining the relative importance of various impact categories, that is, the importance of global warming versus eutrophication versus human toxicity versus depletion of nonrenewable resources. These important but difficult decisions are typically left to the valuation of the users and other parties concerned.

In life cycle process design, environmental considerations have been included as constraints or as a part of the objective function. If environmental concerns are posed as inequality constraints, the bounds for these constraints are determined from regulatory requirements, or from life-cycle considerations (Pistikopoulos, Stefanis & Livingston, 1994). Environmental considerations have been included in the objective function as the cost of waste treatment and disposal, or by combining the economic objective with life cycle impact considerations (Azapagic, 1999; Cabezas et al., 1999). Several techniques are available for solving the resulting multiobjective optimization problem.

The systematic consideration of emissions and environmental impact beyond the scale of the process is an important advance in environmentally conscious process engineering. Databases are being developed for providing the large amounts of information about various industrial processes. But, existing approaches for environmentally conscious process engineering still face many shortcomings. The most significant deficiency is that existing methods ignore the need for ecosystem services and products such as, sunlight, soil formation, and photosynthesis in the analysis. The importance of including nature's products and services in the analysis is indicated by Costanza et al. (1997), who estimate that the value of these services is almost twice that of the global gross national product. Furthermore, many ecosystem services are irreplaceable. Consequently, any approach for environmentally conscious process engineering that does not account for ecosystem services is likely to grossly underestimate the true cost of a product or process. This limitation also makes it difficult for LCA and related methods to determine the environmental sustainability of products and processes, and to analyze ecological and industrial systems together. The approach developed in this paper overcomes many of these disadvantages.

3. Energy, exergy, and emergy

The thermodynamic concepts of energy, exergy and emergy are useful for the analysis of industrial and ecological systems, and are discussed in this section. *Energy* is a commonly used state variable that is easy to calculate, but often misunderstood to be a measure of the ability to do work. As indicated by the second law of thermodynamics, for 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 environment. It may be defined as,

$$B = \left(U - TS + PV + \sum \mu_i N_i + v^2/2 + zg \right) - \left(U - TS + PV + \sum \mu_i N_i + v^2/2 + zg \right)_0 \qquad (1)$$

where the subscript 0 indicates the reference state. Exergy is not a state variable, since its value depends on the selected reference state. The reference state may be selected to be that of the system at equilibrium or of the natural environment, which is far from equilibrium (Szargut, Morris & Steward, 1988). The value of exergy is independent of the path taken to produce the product.

Exergy analysis has been used extensively for identifying inefficiencies and opportunities for saving energy in industrial systems (Szargut et al., 1988). It has also been suggested to be a measure of the potential for emissions to cause environmental degradation (Ayres, Ayres & Martinas, 1998). The exergy of an ecosystem is an indicator of its health (Jorgensen, 1997).

Although exergy is a more useful concept than energy, it only provides information about the current state of the system, and its future ability to do work. It does not provide any information about the quality of the available energy. Thus, the concept of exergy does not highlight the fact that electrical exergy can do more types of work than the same amount of solar exergy. Furthermore, exergy provides no information about the thermodynamic or energy history of the product or service at a global scale. These shortcomings are overcome by the concept of emergy.

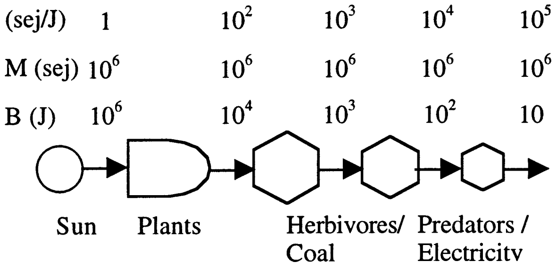

Fig. 1. Energy transformation in a food/industrial chain.

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 (Odum, 1988). Since the ability to do work can be different for different kinds of energy, it is essential to convert all types of energies into a common unit before combining them. For convenience, units of solar energy are usually selected as the common unit. Thus, solar emergy is the amount of solar energy used directly or indirectly to make a service or product. Solar emergy is measured in solar emergy Joules or solar emjoules (sej). For the energy flow diagram shown in Fig. 1, the emergy of each product remains unchanged. As depicted in Fig. 1, as solar energy moves to higher quality or more concentrated forms, the actual exergy content decreases. The relationship between emergy, M, and the exergy contained in an item is given via the transformity, τ, as,

$$M = \tau B \qquad (2)$$

The units of solar transformity are sej J^{-1}. The transformity of solar energy is defined to be unity. For the process in Fig. 1, the transformity increases as the energy becomes more concentrated and of higher quality. Thus, transformity is a measure of energy quality.

The values of emergy and transformity depend on the path taken to reach the state. This path dependence makes it more challenging to determine these variables, since their values may change with the efficiency of the transformation processes. The transformities of ecological products and services vary over a very narrow range since these processes have evolved to be very efficient. These transformities have been computed by Odum (1996). In contrast, the transformity of industrial products and services varies according to the selected raw materials, and the production efficiency. The emergy of economic inputs measured in terms of money may be determined as,

$$M = M_{\text{total}} \times \$/\text{GEP} \qquad (3)$$

where, \$ is the amount of money to be converted to emergy, M_{total} is the total emergy of the regional or national system including natural and economic inputs, and GEP is the region or nation's gross economic product.

4. Emergy analysis of industrial and ecological systems

Both, ecological and economic systems are examples of self-organized systems (Jorgensen, 1997; Krugman,

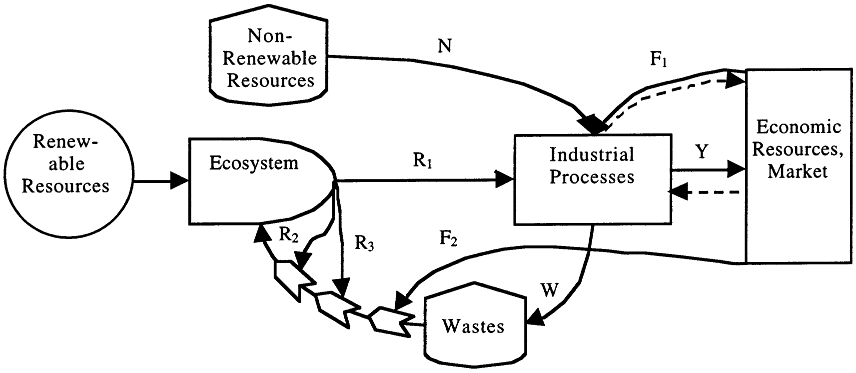

Fig. 2. Emergy flow chart. Dashed lines denote flow of money.

1996), and are governed by the same laws of thermodynamics (Ayres, 1994). Consequently, a common thermodynamic framework for analyzing ecological and economic systems may be developed, as described in this section.

The development and survival of ecosystems is known to be limited by the available energy, and by their ability to convert it to useful energy for themselves and the surrounding systems that they depend on (Lotka, 1925; Odum, 1988). Self-organizing systems strive to use the available energy to maintain themselves at a low level of entropy, and far from equilibrium. That is, these systems try to maximize their exergy and rate of emergy consumption. If such a system is perturbed by a disturbance such as, the introduction of pollutants, it tends to move closer to equilibrium, causing a reduction in its exergy. The pollutants increase the emergy of the ecosystem, but emergy is also needed to dissipate or absorb the impact.

Based on this insight, systems ecologists have developed thermodynamic methods for assessing ecosystem health and for modeling their behavior. The approach of analyzing the energy or emergy flow through the components of an ecosystem can be extended to study the behavior of both industrial and ecological systems. Such an approach based on emergy analysis has been developed by Odum (1996) and forms the framework for ecologically conscious process systems engineering proposed in this paper. This section presents the basic principles of emergy analysis. Some deficiencies in the existing approach are also identified, with solutions proposed in Section 5.

4.1. Emergy flow chart

A typical energy or emergy flow diagram for an industrial process is shown in Figure 2. This diagram uses the language for energy flow analysis developed by Odum (1996), and shows the flow of energy or emergy through renewable and nonrenewable resources, the ecosystem, the industrial systems being studied, and the economy. For simplification, all the ecological and industrial processes are lumped together in their respective block. The direct inputs to the industry block include nonrenewable resources, N, renewable ecosystem services and products, R_1, and inputs from the economy, F_1. The economic inputs represent things that are valued by the economy and are part of the market. The outputs include the main products that are sold in the market, Y, and emissions that return to the environment, W.

Most existing applications of emergy analysis ignore the impact of emissions on the environment and economy. This implicit assumption that the emissions are benign is okay for the analysis of ecological systems, but can cause large errors in the analysis of industrial systems. This paper proposes an approach for including the impact of emissions in emergy analysis by including the emergy flows, R_2, R_3, and F_2 in Fig. 2. The approach for determining the values of these emergy streams is outlined in Section 5.

The flow of money, shown by dashed lines in Fig. 2, indicates that the economy does not pay money for environmental services and products. Clearly, money is an incomplete measure of the true cost. The renewable and local nonrenewable inputs are economically free, and are readily available in the ecosystem. These are nature's products and services that are usually overlooked by the market as well as by most existing pollution prevention and life cycle management methods. In contrast, emergy accounts for both, ecological and economic costs making it a more complete measure of wealth and reflects the true cost of products and services.

4.2. Emergy metrics

Metrics similar to those used in economic analysis can be defined to determine the ecological feasibility, environmental loading and sustainability of a product or process. The net emergy is the emergy gained by the economy in exchange for providing its services. It is defined as (Odum, 1996),

$$M_{\mathrm{net}} = Y - F_1 \tag{4}$$

and is analogous to the economic potential or profit from a process, but in terms of emergy. For any process to be 'emergetically profitable' for the economy, the net emergy must be positive. That is, the product must contribute more emergy to the economy than the emergy in the economic inputs needed to make it. The emergy yield ratio,

$$\mathrm{EYR} = \mathrm{Y}/F_1 \tag{5}$$

is the emergetic return on investment. Since money is an incomplete measure of ecological goods and services, the net emergy and emergy yield ratio provide a better estimate of whether the process is feasible. Other emergy-based metrics have also be defined to assess the environmental loading and sustainability of the process (Brown & Ulgiati, 1997). The environmental loading ratio is defined as,

$$\mathrm{ELR} = (F_1 + N)/R_1 \tag{6}$$

The ELR is an indicator of the stress on the local environment. Since it is desirable to have a higher emergy yield per unit of environmental loading, the sustainability index is defined as,

$$\mathrm{SI} = \mathrm{EYR}/\mathrm{ELR} \tag{7}$$

Determining the ELR and SI requires information about the emergy flow from renewable and nonrenewable sources. This information is not required for determining the net emergy and EYR.

5. Ecologically conscious PSE

The framework presented in Section 4 can be used for incorporating ecological considerations in any process systems engineering task. Practical application of emergy analysis to industrial systems requires techniques for including the impact of emissions in the analysis, as well as knowledge about the relevant materials and processes. This section describes the approach for including the impact of emissions in emergy analysis, and emergy-based methods for life cycle product assessment.

5.1. Impact of emissions

Emissions to the environment may require emergy to render them harmless, or to suffer the harmful impact. This emergy to absorb impact may be derived from both ecological and economic sources. Many emissions are rendered harmless due to services provided by the ecosystem which dilute or degrade the emissions to an acceptable concentration or state. Examples of such services include wind and ocean currents to dilute air and water emissions, photosynthesis to absorb CO_2, and bacteria to degrade biodegradable materials. The emergy for these ecological services, denoted as R_2 in Fig. 2, may be determined from knowledge of the concentration and nature of the emissions, and the transformity of the relevant ecological services. For example, the emergy required to dissipate NO_x emissions in air may be determined with information about the concentration of the emissions, the acceptable dilution, and the transformity of wind (Brown, 1999).

Some emissions may harm the ecological or economic system by causing a fish kill or lake eutrophication. Such effects are represented in Fig. 2 as R_3 and F_2, and may be quantified as the emergy contained in the ecological and economic loss.

Many studies have estimated the monetary loss of environmental impact. This may be easily converted to emergy via Equation (3). For example, the economic impact of global warming by 3°C due to CO_2 doubling by 2090 from pre-industrial levels is estimated to be $\$50.3 \times 10^9$ for the US in 1988 US dollars (Nordhaus, 1994). Using the emergy to money ratio for 1988 US dollars of 1.75×10^{12} sej $\$^{-1}$ (Odum, 1996), the emergy cost of global warming is 88×10^{21} sej. Dividing this emergy cost by the total kilograms of CO_2 equivalent emitted that is, 590 billion metric tons of C equivalent results in a transformity of 1.5×10^8 sej kg^{-1} of C equivalent.

Quantifying the ecological impact in terms of emergy requires knowledge about the loss of ecosystem components and self-organization caused by the emissions. Unfortunately, such studies are not yet readily available for most ecological impacts (Jorgensen, 1997).

5.2. Emergy-based life cycle assessment

Combining emergy analysis with LCA exploits the complementary features of both methods. The resulting approach, called EmLCA, is better suited for ecologically conscious PSE than either method alone, as described in the sequel.

The steps in EmLCA include, defining the goal of the analysis; developing the emergy flow chart; defining the analysis boundary; collecting information and data about the relevant industrial, economic and ecological processes and products; computing the emergy of the inputs, outputs and impacts; analyzing the results based on selected emergy metrics. These steps are similar to those standardized in LCA (Heijungs et al., 1996), but enhance the existing LCA approach.

In defining the analysis boundary, it is important to include processes that are critical in terms of their consumption of ecological and economic inputs, and emissions. Most economic materials and services contain emergy from renewable, non-renewable and economic sources. These sources are considered separately only for products inside the analysis boundary. For economic sources outside the boundary, these sources are lumped together and approximated as input from the economy.

Information about the materials used and emissions in each process may be obtained from the existing databases use in LCA. Emergy analysis requires additional information about the transformities of ecosystem services and products. Such information has been tabulated by Odum (1996). If the transformity of a resource is available, Eq. (2) can be used to determine its total emergy. The emergy breakdown into renewable, non-renewable and economic sources requires separate transformities for each category of input, or a more detailed analysis.

Most of the previous work on emergy analysis has ignored the impact of emissions. This is in contrast to the approach for LCA, which focuses primarily on the analysis of emissions, and ignores contributions from the ecosystem. This complementary nature of emergy analysis and LCA is exploited in the proposed approach. The approach for determining the emergy of ecological services, R_2 is described in Section 5.1. To determine the emergy flows, R_3 and F_2 the emissions are characterized and classified according to the method of LCIA. The emergy of the emissions in each category may then be determined based on knowledge about the emergy of impact per unit of emission, as illustrated in Section 5.1.

An important advantage of EmLCA is that if the appropriate data are available, emergy based impact assessment provides an ecological alternative to the valuation step in LCIA for combining the impact of various emissions. Once the emergy flow sheet and values are determined, metrics such as those defined in Section 4.2 may be used to compare the ecological viability and sustainability of various products.

Table 1
Selected emergies for EmLCA of soy bean growth

#	Item	Amount	Emergy (sej)
1	Sunlight	5.0E+13 J	5.0E+13
2	Rain	4.5E+10 J	4.7E+14
3	Surface water	2.3E+10 J	1.1E+15
	Renewable inputs, R_1		1.6E+15
4	Soil erosion	1.7E+11 J	1.3E+16
	Non-renewable inputs, N		1.3E+16
5	Labor	5.2E+07 J	4.6E+14
6	Nitrogen fertiliser	99 kg	4.2E+14
7	Phosphates fertiliser	28 kg	1.9E+14
8	Potassium oxide fertiliser	56 kg	1.7E+14
9	Insecticides	12 kg	1.8E+14
10	Herbicides	1.65 kg	2.4E+13
11	Diesel fuel	5.8E+08 J	3.8E+13
	Economic inputs, F_1		1.5E+15
12	Impact due to GWP	45.3 kg C	7.2E+09
	Emissions impact, F_2		7.2E+09
	Product emergy, Y		1.6E+16

6. Case study: EmLCA of soy bean oil

The features of the thermodynamic approach developed in this paper are demonstrated by the EmLCA of the soy bean growth phase. This small part of the EmLCA of soy bean oil is based on tentative data, and is presented primarily for illustrative purposes. The detailed example will be presented in the future. The emissions data are taken from Heijungs et al. (1996), and the data for ecological inputs are adapted from similar data for sugarcane growth (Bastianoni & Marchettini, 1996). The emergy values for selected inputs, and economic impact due to the global warming potential (GWP) are shown in Table 1.

These numbers indicate that the emergy contributed by ecological inputs is at least as important as that from economic inputs. Including the emergy of the impact of other emissions is expected to increase the magnitude of this term. It is important to note that conventional LCA ignores the ecological and economic inputs, and focuses primarily on the impact of the emissions.

7. Conclusions

A new approach for ecologically conscious process systems engineering is described. This approach includes the contribution of ecological products and services along with economic inputs in process analysis. Examples of ecological products and services include, sunlight, rain, and soil formation. These inputs are at least as important as the economic inputs, but are usually not measured by money, and are ignored by most existing environmentally conscious engineering methods.

The approach for ecologically conscious PSE is based on considering energy to be the common driving resource for the development and sustenance of both industrial and ecological systems. Since all renewable and nonrenewable resources as well as products and services are created directly or indirectly from solar energy, the approach developed in this paper analyzes processes and products based on the embodied solar energy. This embodied energy is called emergy, and has been used by systems ecologists for analyzing, assessing and modeling ecological systems. Emergy based metrics may be used to assess the economic and ecological feasibility and sustainability of processes.

An emergy based LCA (EmLCA) is developed by combining the features of emergy analysis with LCA. The resulting method accounts for both ecological and economic inputs in terms of their emergy. The features of EmLCA are illustrated via a simple case study on the growth of soy beans.

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