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Promise and problems of emergy analysis

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Abstract

Solar Emergy is the available solar energy used up directly and indirectly to make a service or product. Although this basic concept is quite straightforward, its implications are potentially profound. H.T. Odum pioneered the development and use of emergy, and presented it as a way of understanding the behavior of self-organized systems, valuing ecological goods and services, and jointly analyzing ecological and economic systems. Unfortunately, like many groundbreaking ideas, emergy has encountered a lot of resistance and criticism, particularly from economists, physicists, and engineers. Some critics have focused on detailed practical aspects of the approach, while others have taken issue with specific parts of the theory and claims. This paper discusses the main features and criticisms of emergy and provides insight into the relationship between emergy and concepts from engineering thermodynamics, such as exergy and cumulative exergy consumption. This reveals the close link between emergy and ecological cumulative exergy consumption, and indicates that most of the criticisms of emergy are either common to all holistic approaches that account for ecosystems and other macrosystems within their systems boundaries, or a result of misunderstandings derived from a lack of communication between various disciplines, or are not relevant for engineering applications. By identifying the main points of criticisms of emergy, this paper attempts to clarify many of the common misconceptions about emergy, inform the community of emergy practitioners about the aspects that need to be communicated better or improved, and suggest solutions. Further research and interaction with other disciplines is essential to bring one of H.T. Odum's finest contributions into the mainstream to guide humanity on "the prosperous way down."

Keywords: Emergy analysis; Solar Emergy; Engineering thermodynamics

1. Introduction

Emergy analysis is perhaps H.T. Odum's masterpiece. It is "the most exciting, important, far-out, comprehensive, crazy, unsubstantiated, and/or necessary . . . " of all of the ideas of H.T. Odum (Hall, 1995a). *Emergy*, specifically *Solar Emergy*, is "the available solar energy used up directly and indirectly to make a service or product" (Odum, 1996). Emergy analysis considers all systems to be networks of energy flow and determines the emergy value of the streams and systems involved. "Emergy, spelled with an 'm,' is a universal measure of real wealth of the work of nature and society made on a common basis" (Odum et al., 2000). Emergy analysis presents an energetic basis for quantification or valuation of ecosystems goods and services. Valuation methods in environmental and ecological economics estimate the value of ecosystem inputs in terms that have been defined narrowly and anthropocentrically, while emergy tries to capture the ecocentric value. It attempts to assign the "correct" value to ecological and economic products and services based on a theory of energy flow in systems ecology and its relation to systems survival. A fundamental principle of emergy analysis is the *Maximum Empower*

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Principle. It states that "systems that will prevail in competition with others, develop the most useful work with inflowing emergy sources by reinforcing productive processes and overcoming limitations through system organization" (Brown and Herendeen, 1996). Odum (1996) states that this principle determines which systems, ecological and economic, will survive over time and hence contribute to future systems.

Since the early 1980s, emergy and emergy analysis have been used widely to analyze systems as diverse as ecological, industrial, economic, and astronomical (Odum, 1995a,b, 1996; Brown and Ulgiati, 1997, 2002; Lagerberg and Brown, 1999). Unfortunately, like many groundbreaking ideas, emergy has encountered a lot of resistance and criticism, particularly from economists, physicists, and engineers. Consequently, it has not been used much outside a small circle of researchers. This limited use of emergy analysis despite its broad relevance may be due to inadequate attention to details, poor communication of its potential importance, and lack of clear links with related concepts in other disciplines. The publication of Odum's "how to" book (Odum, 1996) and the more recent emergy folios (Odum et al., 2000; Odum, 2000; Brown and Bardi, 2001; Brandt-Williams, 2001) are important steps in making emergy more accessible. However, much more work is needed to connect emergy with concepts in other disciplines and to overcome a preconceived negative notion of emergy that is prevalent among many researchers outside of systems ecology.

2. Emergy analysis

2.1. Historical background

Emergy analysis is a part of a much larger theory developed by H.T. Odum about the functioning of ecological and other systems. This theory explains how systems survive and organize in hierarchies by using energy at the efficiency that generates the most power (Odum and Odum, 1981). As pointed out by Hall (1995b), the hypothesis about the role of energy in survival and evolution of systems "has roots in the 19th century and was first stated explicitly by the biologist Alfred Lotka (1922), who called the maximum power principle the fourth law of thermodynamics." Then, he adds that, "Odum has both used and expanded the maximum power concept as a general systems hypothesis throughout his career."

H.T. Odum started developing the roots of the concept of Emergy probably in the 1950s when he and E.P. Odum identified the importance of energetics to ecology (Odum, 1953). The brothers subsequently realized the importance of the quality of energy and the necessity of using a "common denominator for energy flows of different kinds" (Hall, 1995b). From this concept, H.T. Odum extended the original concept as the Maximum Empower Principle, and developed an energy systems language for the thermodynamics of open systems. Over the years, emergy became the dominant concept of this work. By the late 1970s, during the energy crisis, and as humankind became more aware of the negative impact of industrial activities on ecosystems, H.T. Odum had already recognized the critical role that ecosystems play in the global economy, and that economic activities were shaped not only by economic rules, but also by ecosystem constraints. He also developed the concept that emergy offered a common ground for integrating economic and ecosystems sciences.

2.2. Basic principles

Emergy is measured in solar embodied joules, abbreviated sej. Emergy analysis characterizes all products and services in equivalents of solar energy, that is, how much energy would be needed to do a particular task if solar radiation were the only input. It considers the Earth to be a closed system with solar energy, deep Earth heat and tidal energy as major constant energy inputs, and that all living systems sustain one another by participating in a network of energy flow by converting lower quality energy into both higher quality energy and degraded heat energy. Since solar energy is the main energy input to the Earth, all other energies are scaled to solar equivalents to give common units. Other kinds of energy existing on the Earth can be derived from these three main sources, through energy transformations. Even the economy can be incorporated to this energy flow network as, "wealth directly and indirectly comes from environmental resources measured by emergy" (Odum, 1996). Examples are elevated and purified water, timber and oil. Therefore, the circulation of money is related to the flow of emergy.

An important concept in emergy analysis is *Solar Transformity*, defined as “the Solar Emergy required to make 1 J of a service or product” (Odum, 1996). Solar Transformity is measured in sej/J. The Solar Transformity of a product is its Solar Emergy divided by its available energy, that is,

$$M = \tau \times B \tag{1}$$

where M is emergy, τ is transformity, and B is available energy. Since solar energy is the baseline of all emergy calculations, transformity of solar energy is unity.

Odum argues that the “energy flows of the universe are organized in an energy transformation hierarchy” and that “the position in the energy hierarchy is measured with transformities” (Odum, 1996). Therefore, transformity is regarded as a measure of energy quality. From a practical point of view, transformity is useful as a convenient way of determining the emergy of commonly used resources and commodities. Most case studies in the literature rely on the transformities calculated by Odum and co-workers to calculate the emergy of their inputs.

Most transformities are calculated from the yearly emergy flow to the Earth (Odum, 2000). The total emergy input to the Earth is the sum of the emergy of solar insolation, deep Earth heat and tidal energy. However, even these inputs are not added directly due to their different abilities to do work. The emergy of deep Earth heat and tidal energy are calculated by comparing their energy quality to that of solar insolation. The detailed calculations are based on energy balance equations for the Earth, and are described by Odum (2000). These global emergy inputs are the driving force for all planetary activities. Determining their contribution to ecological goods and services is essential for further analysis.

Odum and coworkers have determined the emergy of the Earth’s main processes, such as, the total surface wind, rain water in streams, Earth sedimentary cycle, and waves absorbed on shore, to be that of the total emergy input to the Earth (Odum, 1996). Each of these processes is assigned the total value because they are considered co-products of the global geological cycle and cannot be produced independently with less amount of the total emergy. Furthermore, detailed knowledge about the underlying network and all the outputs from these Earth processes is usually not available.

In the case of the Earth sedimentary cycle, Odum (1996) calculates the emergy per gram of sediment by estimating that a layer of nearly an inch of thickness of soil is removed from the continental land by erosion and replaced by Earth uplift in a period of a thousand years. The flux of sediments is calculated by taking the product of the annual replaced layer and the average density of rocks. The emergy per gram of sediment is the global emergy budget divided by the flux of sediments. In this case, emergy is allocated according to the mass of sediments.

Conceptually, determining the emergy of non-renewable resources, such as coal and petroleum, requires accounting for solar inputs over geological time scales. Odum suggests using the replacement time of such material to estimate their historic emergy. However, the transformity of non-renewable fuels used in most applications focuses only on the current emergy from the sedimentary cycle. For example, the transformity of coal is the emergy per gram of sediment from the Earth sedimentary cycle divided by the Gibbs free energy of a gram of coal (Odum, 1996). The transformity of other fuels are approximated based on their relative efficiency obtained in combustion chambers.

The emergy of economic inputs measured in terms of money is determined by multiplying the input in monetary units by the ratio of the nation’s total emergy to its economic gross national product, i.e.

$$M = F\left(\frac{M_{\text{nation}}}{F_{\text{nation}}}\right) \tag{2}$$

where F represents a particular economic input, M_{nation} is the total nation’s emergy, and F_{nation} is the gross national economic product.

Details about emergy algebra are described by Odum (1996). Matrix algebra techniques to partition emergy and calculate transformities have also been proposed (Patterson, 1993, 1998; Tennenbaum, 1988; Odum and Collins, 2003; Hau and Bakshi, 2003).

3. Characteristics and criticisms of emergy analysis

3.1. Attractive features

Emergy analysis overcomes the inability of many existing approaches to adequately consider the contribution of ecological processes to human progress and wealth. A large range of ecological products and services do not receive any value from conventional economic approaches despite the fact that they are used and spent for the making of economically valuable products, or indeed may be essential for life. The importance of accounting for nature's services is gaining wide acceptance (Daily, 1997; Holliday et al., 2002; Arrow et al., 1995), although the methods remain controversial. Through the last two decades, economists have developed techniques to assign monetary values to ecological products and services. However, this assignment typically relies on consensus of boards of experts, often with tenuous physical and biological foundations, and generally scaled to some market-derived values that may be, for example, highly skewed by advertising. In contrast, emergy analysis is meant to be independent of human valuation, but based on the principles of thermodynamics, system theory, systems ecology and, ultimately contribution to survival. Among the most attractive characteristics of emergy analysis are:

- It provides a bridge that connects economic and ecological systems. Since emergy can be quantified for any system, their economic and ecological aspects can be compared on an objective basis that is independent of their monetary perception.
- It compensates for the inability of money to value non-market inputs in an objective manner. Therefore, emergy analysis provides an ecocentric valuation method.
- It is scientifically sound and shares the rigor of thermodynamic methods.
- Its common unit allows all resources to be compared on a fair basis. Emergy analysis recognizes the different qualities of energy or abilities to do work. For example, emergy reflects the fact that electricity is energy of higher quality than solar insolation.
- Emergy analysis provides a more holistic alternative to many existing methods for environmentally conscious decision making. Most existing methods, such as life cycle assessment and exergy analysis, do expand the system boundary beyond the scope of a single process so that indirect effects of raw material consumption, energy use and pollutant emissions can be taken into account. However, these methods focus more on emissions and their impact, while ignoring the crucial contribution of ecosystems to human well being. The concept of critical natural capital and a framework to account for have been suggested recently (Ekins et al., 2003). Emergy analysis can quantify the contribution of natural capital for sustaining economic activity (Bakshi, 2002).

These features of emergy analysis are particularly impressive since emergy was developed many decades before the more recent engineering and corporate interest in life cycle assessment, industrial ecology, and sustainability. Partly due to being a theoretical concept whose application posed significant demands on data requirements, lack of adequate details about the underlying methodology, and sweeping generalizations that still remain unproven, emergy has encountered a lot of criticism, and has not been used much outside a small circle of researchers. However, there is no doubt that as an idea, it was truly revolutionary and is expected to have a huge impact.

3.2. *Criticisms*

Emergy theory has been characterized as simplistic, contradictory, misleading, and inaccurate (Ayres, 1998; Cleveland et al., 2000; Mansson and McGlade, 1993; Spreng, 1988). Rebuttals to many critiques have also been published (Patten, 1993; Odum, 1995a,b). However, much of the persistent skepticism seems to stem from the difficulty in obtaining details about the underlying computations, and a lack of formal links with related concepts in other disciplines. Odum's book (Odum, 1996), emergy folios (Odum et al., 2000; Odum, 2000; Brown and Bardi, 2001; Brandt-Williams, 2001), and plans for an emergy handbook are important and essential steps to provide greater insight and understanding about emergy.

The major criticisms of emergy analysis are discussed below. It is important to note that many criticisms are also valid for other methods that are popular for joint analysis of industrial and environmental systems, including, Life Cycle Assessment, Cumulative Exergy analysis, Exergetic Life Cycle Assessment, and Material Flow analysis.

3.2.1. *Emergy and economics*

Odum (1988) argues that "money cannot be used directly to measure environmental contributions to the public good, since money is paid only to people for their services, not to the environmental service generating resources or assimilating wastes. Price is often inversely related to the contribution of a resource, because it contributes most to the economy when it is easily available, requiring few services for delivery." Brown et al. (1995) also argue that price does not determine value, giving the example that "a gallon of gasoline will power a car the same distance no matter what its price; thus, its value to the driver is the number of miles (work) that can be driven." Since emergy does consider all contributions to the public good and truly measures value, it is suggested as a complete measure of wealth and a substitute for money (Odum, 1984). Moreover, Odum (1996) considers transformity of a product as an indicator of its economic usefulness as "transformity increases in ecological and economic energy transformation chains."

These claims are among the most controversial aspects of emergy analysis and have been most widely criticized (Ayres, 1998; Cleveland et al., 2000; Spreng, 1988). The emergy theory of value, as other theories of value based on energy and exergy (Cleveland et al., 2000; Spreng, 1988), focuses on the supply side and ignores human preference and demand. Modern economics, which is focused on humans and their values and not the biophysical world, has doubted the ability of all such theories to capture the value of products to humans. Some common arguments are that the emergy of a gallon of oil from whales has not changed, while its value to humans has. In addition, two paintings with similar emergies can have drastically different values, especially if one of them is by a renowned painter. Consequently, all of the thermodynamic theories of value have been rejected by economists over the last several decades. What most critiques about emergy-based valuation seem to miss is that emergy aims to provide an *ecocentric* value of ecological and industrial products and processes. This is in direct contrast to the economic view, which is anthropocentric. Clearly, the latter view is dominant today, but the emergy view can still provide invaluable information that can be used for sustainable development. Eventually, economic valuation will have to adopt a more ecocentric view if it intends to guide humanity to its survival.

In engineering analysis of industrial systems, thermodynamics-based methods, such as pinch analysis and exergy analysis (Seider et al., 1999; Bejan et al., 1996), are commonly used along with cost criteria. Although the final decision is based mainly on economic criteria, thermodynamic methods are crucial for constraining the search space and for directing the decisions. In the same way, emergy analysis of industrial systems may be able to coexist with economic analysis, with emergy providing the supply side information, and economics capturing human demand and values. Such approaches are very likely to direct decisions towards more sustainable industrial practices, making sustainable development more achievable and saving resources for the future.

3.2.2. Maximum Empower Principle

This optimizing principle is one of the most daring aspects of emergy analysis. Having its roots in work done by Boltzmann (1886) and Lotka (1922), the Maximum Empower Principle claims that all self-organizing systems tend to maximize their rate of emergy use or empower (Odum, 1988, 1996). That is, "ecosystems, Earth systems, astronomical systems, and possibly all systems are organized in hierarchies because this design maximizes useful energy processing." Thus, this principle can determine which species or ecosystems or any system will survive.

While some self-organizing systems have been shown to follow this principle (Odum, 1995b), claiming its general applicability to all systems implies that the Maximum Empower Principle can explain the order of the universe, and is akin to the unified theory that physicists have been piecing together. Not surprisingly, such broad, as yet unsubstantiated claims have made this principle extremely controversial (Ayres, 1998). Mansson and McGlade (1993) argue that the behavior of complex systems cannot be described with a one-dimensional optimizing principle categorizing this principle as misleadingly simplistic. They also claim to have invalidated this principle. However, the validity of their proof has been questioned (Odum, 1995a; Patten, 1993).

The Maximum Empower Principle seems to be one of Odum's contributions that may be ahead of its time. Consequently, it will continue to be a cause of arguments and further scientific exploration, until it is scientifically proven or unproven. Recent results on maximum entropy production in self-organized systems indicate that some systems do tend to maximize power (Lorenz, 2003; Dewar, 2003). In addition, Giannantoni (2003) proposes a mathematical formulation of the Maximum Empower Principle, which may be essential for addressing questions about the validity of this principle, and for providing a general proof.

For engineering applications, agreement or disagreement with the Maximum Empower Principle is *not* essential for using emergy analysis for gaining insight into the contribution of ecosystems. As discussed in the next paragraph, much of the jargon and numbers of emergy analysis are closely related to engineering thermodynamics. In fact, emergy analysis is equivalent to exergy analysis if the analysis boundary includes ecosystems (Hau and Bakshi, 2003). Thus, emergy analysis can still provide valuable information about the contribution of ecosystems to engineering design and assessment of industrial systems.

3.2.3. Relation with other thermodynamic quantities

There seems to be much confusion about the relationship between emergy and other thermodynamic properties, such as energy, exergy, enthalpy, etc. The qualitative difference, as pointed out by Odum and coworkers, is that unlike emergy, these thermodynamic quantities do not recognize the difference in quality of various energy sources. A common example is that “a joule of sunlight is not equivalent to a joule of fossil fuel . . . ” in the sense that they cannot do the same kind of work (Brown et al., 1995). However, formal quantitative links are missing. This leads to impressions that emergy analysis is a “very different approach” from exergy analysis (Emblemsvag and Bras, 2001). Similarly, Ayres (1998) questions the need for emergy as opposed to “standard variables of thermodynamics, namely, enthalpy and exergy.”

There is also some confusion about the exact definition of available energy, denoted B in Eq. (1). It is certainly not Gibbs free energy because not all of it is available for work. Odum (1995a,b) argues that neither is it exergy because “exergy is defined to include only energy flows of similar qualities, that of mechanical work,” while available energy as defined in emergy analysis also considers “important inflows, such as human services that require very large energy flows to maintain.” On the other hand, Odum (2000) and Campbell (2001) define available energy in emergy analysis as exergy or energy with the potential to do work. Scrutiny of transformity calculations indicates that available energy as used in emergy and exergy may indeed be equivalent. For example, for heat engines the available energy of the system is the same as exergy since it is obtained by multiplying its heat content or flow by the Carnot factor (Odum, 1996). The relationship of the transformities of fuels to their combustion efficiencies may be easily justified if available energy and exergy are equivalent. Odum uses the heat of combustion to determine available energy, which is shown to be close to exergy for fuels (Szargut et al., 1988). Moreover, the use of exergy justifies why dissipated heat carries no emergy value. This lack of formal links between emergy and other thermodynamics quantities is a significant cause of skepticism about emergy among engineers. Some efforts have been made to connect emergy with exergy (Ulgiati, 1999). Recently, Hau and Bakshi (2003) have derived the concept of emergy based on exergy as the starting point.

3.2.4. Combining disparate time scales

Conceptually, the calculation of emergy of some stored natural resources, such as metals, coal, and fossil fuels, would require knowing all the solar energy that was required to make it. Accounting for solar inputs over geological time scales is problematic since it is difficult, if not impossible to know the inputs and processes over such a long period (Ayres, 1998; Cleveland et al., 2000). Some common questions concern how to account for the emergy of metals that existed from the formation of the Earth and whether the emergy of fossil fuels includes the emergy of the living systems from where they are derived.

Odum does distinguish between the emergy of storage and the emergy necessary for making the storage available for human use. The emergy of stored resources, such as fresh water, glaciers on land, atmosphere, and continents, is calculated by multiplying the global emergy budget by their respective replacement or turnover time (Odum, 1996). The emergy for concentrating natural resources in the Earth’s crust so that they are available for human and other use is determined based on the Earth sedimentary cycle. In fact, the transformities of many resources, such as coal and oil, that are used in applications of emergy analysis consider only their *current* emergy required to concentrate these resources in the ore, and not that stored since prehistory. Ultimately this is a matter of selecting the appropriate temporal boundary for a given problem. Decisions about temporal and spatial boundaries are necessary for most holistic approaches, including life cycle assessment (LCA) (European Environment Agency, 1997). Therefore, this kind of criticism applies not only to emergy analysis but also to the other approaches. Greater interaction between emergy analysis and LCA may be useful for clarifying this issue.

3.2.5. Representing global energy flows in solar equivalents

Emergy analysis represents all energy flows in solar equivalents. This requires conversion of planetary energy inputs, such as tidal energy and crustal heat, into solar equivalents. Ayres (1998) questions such conversion since "there is no simple way to discover how much of any one form of energy might have been needed to produce another in the distant past." Calculation of the emergy of deep Earth heat and tidal energy inherently carries some assumptions regarding the efficiency with which they are carried to their point of application. Although not explicitly stated, this is derived from the Maximum Empower Principle. For example, the emergy of deep Earth heat is calculated by assuming that its transformity is equal to the transformity of the heat outflow contributed by the Earth sedimentary cycle that passes through the surface of the Earth. This assumption may be justified since the Maximum Empower Principle and evolutionary pressures may have caused both processes to operate in a similar manner to result in heat flows of identical quality.

Another way of looking at the transformity of global energy flows in solar equivalents is as algebraic coefficients based on a global energy balance of *current* flows. This view does not imply that solar energy is being converted into tidal energy or deep Earth heat. The primary benefit of this approach is that it allows a fair comparison of the concentration of different kinds of energy.

Such conversion factors are commonly used in many techniques. Transformity of fuels has been calculated by comparing their qualities based on their efficiencies in combustion chambers. LCA uses conversion factors to add the environmental impact of various substances, e.g. greenhouse gases are typically expressed in equivalents of carbon dioxide to quantify the impact by Global Warming. Calculation of chemical exergies requires defining reference reactions to convert substances absent in the surroundings into components of the reference state or state of the surroundings.

3.2.6. Problems of quantification

Emergy analysis has not considered the uncertainty in many of the numbers used to calculate the transformities. Averaged transformity of industrial and geological processes are frequently used in specific case studies with no knowledge of the degree of certainty of the resulting output. For example, the transformity of natural gas is calculated based on its average efficiency relative to coal in boilers (Odum, 1996), but this efficiency depends strongly on the type of coal and natural gas as well as the characteristics of the boiler. Similarly, calculating the emergy of economic inputs via the emergy to money ratio may also be inaccurate and may involve double counting (Ayres, 1998; Cleveland et al., 2000). This approach also seems to counter emergy analysis' argument that money is an incomplete measure of wealth.

H.T. Odum does recognize that there is no single transformity for any class of products or processes and that when viewed in greater detail, each production pathway for a given product (rain, wind, waves, oil, etc.) represents a unique transformation process that will result in a different transformity. Nevertheless, it has been assumed that generalized transformities do not differ significantly from any specific case.

This criticism is also shared by most other approaches. Exergy analysis uses an average reference state for the Earth's crust without addressing the resulting uncertainty. Similarly, LCA tends to ignore the effect of emissions in local environments and errors in inventory data. Efforts are being made in each approach to address these criticisms and more interaction and exchange of ideas between these fields can be helpful. For example, the use of the emergy-to-money ratio to account for economic inputs may be addressed via systematic methods to consider a larger boundary consisting of the main processes selected for emergy analysis (Ukidwe and Bakshi, 2003). Such techniques have been studied in other fields, including LCA (Lave et al., 1995), and may be adopted by emergy analysts. More research to verify the numbers used in emergy analysis and, their uncertainty and assumptions should also help. Techniques, such as sensitivity and uncertainty analysis, must also become an integral part of emergy analysis.

3.2.7. *Problems of allocation*

The method used for partitioning or allocating inputs between multiple outputs makes the emergy algebra quite challenging. Allocation is probably the most confusing aspect of emergy analysis, particularly to engineers who are used to conservation equations, even for systems with recycle. Emergy algebra can be very sensitive to the level of knowledge of the system under study. The decision of whether multiple outputs are co-products or splits may not always be obvious either. For example, the outputs of a crude oil distillation column may raise arguments about whether they should be treated as co-products or splits. Similarly, the results of considering different types of rocks as co-products (Odum et al., 2000) in the Earth sedimentary cycle are quite different from considering them to be splits (Odum, 1996).

Allocation is an important practical issue encountered by many techniques, including Cost Accounting, Cumulative Exergy Consumption, and Life Cycle Assessment. Current consensus in the LCA community is to avoid allocation as far as possible (ISO 14040, 1997). When avoiding allocation is not possible, the sensitivity of the results to the allocation procedure should be evaluated. Hau and Bakshi (2003) have proposed a formal algorithm based on network algebra that can be used for emergy analysis. Their approach prefers allocation that conserves emergy if information about the network and all its products is available. This is usually the case for industrial systems. However, if such information is not available, as it is usually the case for ecological systems, allocation is avoided by assigning the same emergy to all the outputs. In the latter case, double counting must be avoided.

4. Emergy and exergy

Improved understanding of the relationship between emergy and exergy is essential for constructive cross-fertilization between these areas. Such insight is essential for greater use of the data and concepts of emergy analysis in evaluating the life cycle of engineering products and processes. Engineering thermodynamic methods include exergy analysis (Szargut et al., 1988), thermoeconomics (Bejan et al., 1996), Cumulative Exergy Consumption (CEC) (Szargut et al., 1988), and Extended Exergy Analysis (Sciubba, 2001). An extension of these methods has been proposed by the authors to connect exergy with emergy. (Hau and Bakshi, 2003). The resulting concept of Ecological Cumulative Exergy Consumption (ECEC) starts with the basic premise discussed in Section 3 that available energy as used in emergy analysis and exergy are equivalent. ECEC expands CEC analysis to include ecological systems, and shows that the resulting ECEC can be equivalent to emergy if three conditions are satisfied.

- First, the analysis boundary for both methods should be identical. This means that the same processes or network should be analyzed.
- Second, the allocation method should be the same at each node for both methods.
- Finally, the same approach should be used for combining the global energy inputs that is, the global energy inputs may be combined via their transformities or some other approach.

These conditions are usually easy to satisfy, and indicate the exact relationship between exergy and emergy.

Further comparison of ECEC and emergy indicates that if the conditions for their equivalence are satisfied, then, transformities and cumulative degree of perfection have a reciprocal relationship. This indicates that transformities of ecological goods and services can be used to readily include their contribution in exergy analysis. The allocation approach used in ECEC partitions emergy in proportion to the exergy of the products, when knowledge about the network and products is available. This includes all industrial systems. However, for ecological systems, the input emergy is not partitioned since knowledge about the ecological network and its outputs is usually not available. This insight about the strong link between engineering thermodynamic concepts and emergy indicates that many criticisms of emergy, such as its connection with economic value or the Maximum Empower Principle, are not relevant to using emergy to capture the thermodynamic aspects of ecological goods and services. More importantly, it clearly shows the relation of emergy to other thermodynamic properties addressing one of the criticisms discussed in Section 3.2.

5. Summary and challenges for the future

Emergy is potentially one of the most groundbreaking contributions of H.T. Odum. It provides an ecocentric view of ecological and human activities, which can be used for evaluating and improving industrial activities. Such techniques are crucial for appreciating the contribution of ecosystems to all human activities and meeting the challenges of sustainable development. The Maximum Empower Principle attempts to explain the behavior of self-organized systems based on thermodynamics. These concepts were put forth many decades before the current interest in life cycle analysis, industrial ecology and sustainability, and before adequate data and techniques were available.

Like many new ideas, Odum's work on emergy has been controversial and is often criticized. Much of the criticism is directed towards the details of emergy analysis, or towards the link between emergy and money and the Maximum Empower Principle. Any new idea as profound as emergy requires much work to iron out the details before it can be widely accepted and used. Odum's book (Odum, 1996) and recent folios (Odum et al., 2000) are important steps in this direction. However, more needs to be done to link emergy with other thermodynamic concepts and with other related techniques. Criticisms pertaining to uncertainty, sensitivity, and quantification apply not just to emergy analysis but to all methods that focus on a holistic view of industrial activity. These include life cycle assessment, material flow analysis, and exergy analysis. Research in all these areas can greatly benefit from one another. For example, more interactions between emergy analysis and LCA may permit LCA to account for the contribution of ecosystems, and may permit emergy analysis to avoid allocation. An input–output framework has been used in many disciplines, including economics and LCA, and may provide a formal way of representing information about the ecological and industrial network.

Establishing the links between emergy analysis and other thermodynamic concepts (Hau and Bakshi, 2003; Sciubba, 2001; Ulgiati, 1999) is essential for widening the use of emergy analysis and for removing the resistance to emergy among many engineers, physicists, and economists. These efforts will not diminish the unique contribution of emergy, but will allow it to become more of a mainstream concept and have even greater impact. The complementary nature of emergy with other disciplines also needs to be explored. For example, human valuation of ecological goods and services requires information about the role of ecosystems, which may be provided via emergy analysis.

Controversy surrounding the Maximum Empower Principle reflects our limited understanding of the behavior of complex systems. Detailed studies of the Maximum Empower Principle and its connection with other concepts governing the behavior of self-organized systems is necessary. The recent book by Giannantoni (2003) may be an important step in this direction. However, as discussed in this article, the Maximum Empower Principle need not hinder the application of emergy analysis. Ultimately, the biggest challenge facing emergy analysis may be that of overcoming the preconceived misunderstandings about emergy to accept it as a legitimate and useful thermodynamic approach. These and many other challenges emanating from Odum's deep insight into the workings of complex systems, his creativity and limitless energy should keep researchers busy for many years to come, and will continue to play an important role in the evolution of human activity towards sustainability.

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References

Arrow, K., Bolin, B., Costanza, R., Dasgupta, P., Folke, C., Holling, C.S., Jansson, B.-O., Levin, S., Mäler, K.-G., Perrings, C., Pimentel, D., 1995. Economic growth, carrying capacity, and the environment. Science 268, 520–521.

Ayres, R.U., 1998. Ecology vs. Economics: Confusing Production and Consumption. Center of the Management of Environmental Resources, INSEAD, Fontainebleau, France.

Bakshi, B.R., 2002. A thermodynamic framework for ecologically conscious process systems engineering. Comput. Chem. Eng. 24, 1767–1773.

Bejan, A., Tsatsaronis, G., Moran, M., 1996. Thermal Design and Optimization. Wiley, New York, 543 pp.

Boltzmann, L., 1886. The second law of thermodynamics. In: Guiness, B. (Ed.), Theoretical Physics and Philosophical Problems. D. Reider, New York, 1974.

Brandt-Williams, S.L., 2001. Folio #4, Emergy of Florida Agriculture. Handbook of Emergy Evaluation. Center for Environmental Policy, Environmental Engineering Sciences, University of Florida, Gainesville.

Brown, M.T., Bardi, E., 2001. Folio #3, Emergy of Ecosystems. Handbook of Emergy Evaluation. Center for Environmental Policy, Environmental Engineering Sciences, University of Florida, Gainesville.

Brown, M.T., Herendeen, R.A., 1996. Embodied energy analysis and Emergy analysis: a comparative view. Ecol. Econ. 19, 219–235.

Brown, M.T., Ulgiati, S., 1997. Emergy-based indices and ratios to evaluate sustainability: monitoring economies and technology toward environmentally sound innovation. Ecol. Eng. 9, 51–69.

Brown, M.T., Ulgiati, S., 2002. Emergy evaluations and environmental loading of electricity production systems. J. Clean. Prod. 10, 321–334.

Brown, M.T., Odum, H.T., Murphy, R.C., Christianson, R.A., Doherty, S.J., McClanahan, T.R., Tennenbaum, S.E., 1995. In: Hall, C.A.S. (Ed.), Maximum Power—The Ideas and Applications of H.T. Odum. University Press of Colorado, Niwot, 393 pp.

Campbell, D.E., 2001. Proposal for including what is valuable to ecosystems in environmental assessments. Environ. Sci. Technol. 35, 2867–2873.

Cleveland, C.J., Kaufmann, R.K., Stern, D.I., 2000. Aggregation and the role of energy in the economy. Ecol. Econ. 32, 301–317.

Daily, G.C., 1997. Nature's Services: Societal Dependence on Natural Ecosystems. Ecosystem Services and Their Importance. Island Press, Washington, DC, 392 pp.

Dewar, R.L., 2003. Information theory explanation of the fluctuation theorem, maximum entropy production and self-organized criticality in non-equilibrium stationary states. J. Phys. A. Math. Gen. 36, 631–651.

Ekins, P., Simon, S., Deutch, L., Folke, C., De Groot, R., 2003. A framework for the practical application of the concepts of critical natural capital and strong sustainability. Ecol. Econ. 44, 165–185.

Emblemsvag, J., Bras, B., 2001. Activity-Based Cost and Environmental Management, A Different Approach to ISO 14000 Compliance. Kluwer Academic Publishers, Boston, 317 pp.

European Environment Agency, 1997. Life cycle assessment—a guide to approaches, experiences and information sources. Environ. Issues Ser. 6, 119 pp.

Giannantoni, C., 2003. The problem of the Initial Conditions and their Physical Meeting in Linear Differential Equations of Fractional Order. Appl. Math. Comput. 141, 87–102.

Hall, C.A.S., 1995a. Introduction: what is maximum power. In: Hall, C.A.S. (Ed.), Maximum Power—The Ideas and Applications of H.T. Odum. University Press of Colorado, Niwot, 393 pp.

Hall, C.A.S., 1995b. Emergy analysis. In: Hall, C.A.S. (Ed.), Maximum Power—The Ideas and Applications of H.T. Odum. University Press of Colorado, Niwot, 393 pp.

Hau, J.L., Bakshi, B.R., 2003. Expanding Exergy Analysis to Account for Ecological Inputs. Technical Report. Department of Chemical Engineering, Ohio State University (www.che.eng.ohio-state.edu/∼bakshi/ECEC.pdf).

Holliday Jr, C.O., Schmidheiny, S., Watts, P., 2002. Walking the Talk—The Business Case for Sustainable Development. Greenleaf Publishing, Sheffield, UK.

ISO 14040, 1997. Environmental Management—Life Cycle Assessment—Principles and Framework.

Lagerberg, C., Brown, M.T., 1999. Improving agricultural sustainability: the case of Swedish greenhouse tomatoes. J. Clean. Prod. 7 (6), 421–434.

Lave, L.B., Cobas-Flores, E., Hendrickson, C.T., McMichael, F.C., 1995. Using input–output analysis to estimate economy-wide discharges. Environ. Sci. Technol. 29 (9), 420A–426A.

Lorenz, R., 2003. Full steam ahead—probably. Science 299, 837–838.

Lotka, A., 1922. Contributions to the energetics of evolution. Proc. Natl. Acad. Sci. USA 8, 148–154.

Mansson, B.A., McGlade, J.M., 1993. Ecology, thermodynamics and H.T. Odum's conjectures. Oecologia 93, 582–596.

Odum, E.P., 1953. Fundamentals of Ecology. Saunders, Philadelphia.

Odum, H.T., 1984. Embodied energy, foreign trade and welfare of nations. In: Jansson, A.-M. (Ed.), Integration of Economy and Ecology—An Outlook for the Eighties. Proceedings of the Wallenberg Symposium. Asko Laboratory, University of Stockholm, Stockholm, pp. 185–199.

Odum, H.T., 1988. Self-organization, transformity, and information. Science 242, 1132–1139.

Odum, H.T., 1995a. Energy-systems concepts and self-organization—a rebuttal. Oecologia 104 (4), 518–522.

Odum, H.T., 1995b. Self-organization and maximum empower. In: Hall, C.A.S. (Ed.), Maximum Power—The Ideas and Applications of H.T. Odum. University Press of Colorado, Niwot, 393 pp.

Odum, H.T., 1996. Environmental Accounting: EMERGY and Environmental Decision Making. Wiley, New York, 370 pp.

Odum, H.T., 2000. Folio #2, Emergy of Global Processes. Handbook of Emergy Evaluation. Center for Environmental Policy, Environmental Engineering Sciences, University of Florida, Gainesville.

Odum, H.T., Collins, D., 2003. Transformities from ecosystem energy webs with the eigenvalue method. In: Brown, M.T., et al. (Eds.), Emergy Synthesis 2. Proceedings from the Second Biennial Emergy Conference. Center for Environmental Policy, University of Florida, Gainesville (in press).

Odum, H.T., Odum, E.C., 1981. Energy Basis for Man and Nature. McGraw-Hill, New York, 337 pp.

Odum, H.T., Brown, M.T., Brandt-Williams, S.L., 2000. Folio #1, Introduction and Global Budget. Handbook of Emergy Evaluation. Center for Environmental Policy, Environmental Engineering Sciences, University of Florida, Gainesville.

Patten, B.C., 1993. Toward a More Holistic Ecology, and Science—the Contribution of Odum, H.T., Oecologia 93(4) 597–602.

Patterson, M., 1993. Approaches to energy quality in energy analysis. Int. J. Global Energy Issues 19–28 (special issue on Energy Analysis).

Patterson, M., 1998. Understanding energy quality in ecological and economic systems: a brief explanation of QEM. In: Ulgiati, S. (Ed.), Advances in Energy Studies: Energy Flows in Ecology and Economy. Proceedings of the International Workshop, Porto Venere, Italy Musis, Rome, pp. 257–274 (642 pp.).

Sciubba, E., 2001. Beyond thermoeconomics? The concept of extended exergy accounting and its application to the analysis and design of thermal systems. Exergy Int. J. 1 (2), 68–84.

Seider, W.D., Seader, J.D., Lewin, D.R., 1999. Process Design Principles: Synthesis, Analysis, and Evaluation. Wiley, Inc., New York, 824 pp.

Spreng, D.T., 1988. Net-Energy Analysis and the Energy Requirements of Energy Systems. Praeger Publishers, New York, 289 pp.

Szargut, J., Morris, D.R., Steward, F.R, 1988. Exergy Analysis of Thermal, Chemical and Metallurgical Processes. Hemisphere Pubs., New York, 332 pp.

Tennenbaum, S.E., 1988. Network Energy Expenditures for Subsystem Production. MS Thesis. Environmental Engineering Sciences, University of Florida, Gainseville, 131 pp.

Ukidwe, N.U., Bakshi, B.R., 2003. Including Nature's Contribution in Input–Output Life Cycle Assessment; Part I: Approach. Technical Report. Department of Chemical Engineering, Ohio State University (www.che.eng.ohio-state.edu/∼bakshi/tio1.pdf).

Ulgiati, S., 1999. Energy, emergy and embodied exergy: diverging or converging approaches. In: Proceedings of the First Biennial Emergy Analysis Conference, Gainesville, Florida.