Making Emergy Analysis More Popular for Environmentally Conscious Design and Manufacturing - Challenges and Opportunities

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ABSTRACT

As the need for changing the current non-sustainable industrial activities becomes increasingly obvious, engineers are being forced to consider more holistic techniques for design and assessment of industrial products and processes. As a result, techniques such as life cycle assessment (LCA) and material flow analysis (MFA) have been developed and are increasingly popular. Many of these techniques are similar to emergy analysis, but lack the thermodynamic basis and breadth of energy analysis. Although the need for including the contribution of ecosystems is widely recognized, and even though emergy analysis is able to meet this need, emergy analysis has still found relatively limited use in environmentally conscious design and manufacturing (ECDM) and LCA. Researchers in the ECDM and LCA society who are aware of emergy analysis seem to have a mostly negative view of the approach due to misunderstanding and inadequate access to details. This paper discusses the reasons why emergy analysis is not popular for engineering use and LCA. Most of the criticisms of emergy are either common to all holistic approaches that account for ecosystems within their systems boundaries, or a result of misunderstandings derived from a lack of communication between various disciplines. By identifying the main points of criticisms of emergy, this work 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, particularly engineering thermodynamics, is essential to bring emergy analysis into the mainstream of ECDM and LCA.

INTRODUCTION

Industrial society is increasingly recognizing the need for changing its current non-sustainable activities. For instance, DuPont’s former CEO, Holliday (1999) argues that to be competitive in the long term, industry will have to incorporate social and environmental aspects in its traditional decision-making objectives, and Elkington (1999), SustainAbility chairman, has described the triple bottom line as enhancing simultaneously economic prosperity, environmental protection and social equity. As a result, engineers are being forced to consider more holistic techniques for design and assessment of industrial products and processes, a practice referred to as Environmentally Conscious Design and Manufacture (ECDM).

Techniques such as life cycle assessment (LCA) and material flow analysis (MFA) attempt to quantify critical environmental variables. These methods seek to scientifically evaluate ecological variables, such as resource consumption and environmental impact, thus avoiding the arbitrariness in economic approaches. Further development of sustainability evaluation methods has driven the
engineering society into more thermodynamically founded techniques. For example, Energy flow analysis (Spreng, 1988) is based on the first law of Thermodynamics, while exergy analysis also considers the second law. According to this law, exergy or available energy is lost or consumed in all processes, making it the ultimate limiting resource for the functioning of all systems and a promising property for the joint analysis of industrial and ecological systems.

Exergy analysis only accounts for the exergy of material and energy streams flowing in the process. Extensions of exergy analysis have focused on incorporating exergy consumed in various inputs such as capital, labor, pollution remediation and natural resource utilization along the supply chain (Szargut et al., 1988; Ayres et al., 1998; Sciubba, 2001; Wall, 2002; Connelly and Koshland, 2000; Cornelissen and Hirs, 2002). It becomes clear that many of these techniques are similar to emergy analysis, but less developed and smaller in scope. Surprisingly, little attention has been paid to emergy analysis, even though it is also capable of meeting the challenges of sustainability evaluation and possibly more capable and holistic than most existing methods in ECDM. Most engineers are not aware that ecological processes have also been analyzed using the same thermodynamic principles common in engineering. Even those researchers who are aware of emergy analysis seem to have a mostly negative view of the approach due to inadequate attention to details, poor communication of its potential importance, and lack of clear links with related concepts in other disciplines.

This paper discusses the reasons why emergy analysis is not popular in ECDM. By identifying the main points of criticisms of emergy, this work 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. The new concept of Ecological Cumulative Exergy Consumption and its relation to emergy shows how such links can strengthen further interaction with other disciplines, particularly engineering thermodynamics. Cooperative research is crucial to the enhancement of ECDM and LCA and can bring emergy analysis to a higher level by expanding its practitioners’ opportunities to impact the industrial society and carry Odum’s legacy into a more sustainable future.

The paper is structured in four sections. The first section describes attractive features that make emergy analysis necessary in ECDM and LCA. The second section discusses the main sources of criticisms that have hindered its use in the ECDM and LCA society. The third section describes a work by Hau and Bakshi (2003a) and its implications in addressing most of the criticisms of emergy analysis. Finally, the last section presents solutions and challenges for clearing up negative perceptions about emergy analysis and setting it up as a model for ECDM methods.

EMERGY ANALYSIS AND SUSTAINABILITY

Sustainability evaluation demands tools that can deal with economic aspects, such as capital investment and operating and maintenance costs, as well as environmental aspects, such as natural resource consumption, water usage and environmental impact. Among the challenges that such demands pose are combining dissimilar streams or quantities, estimating values for ecological goods and services, and interpreting the variety of results. Existing approaches cope partially with these challenges; however, they ignore the contribution of ecological processes to human progress and wealth. Such processes not only create valuable natural resources and make them available to humans, but also provide services and other goods upon which industrial processes unconsciously rely. Ignoring them imposes a bias on the outcome of these evaluations since some processes may seem less resource demanding than others just because they rely more on these services.

Emergy analysis overcomes many of these challenges and considers the contribution of ecological goods and services. It provides a bridge that connects economic and ecological systems. Since emergy is scientifically sound and shares the rigor of thermodynamic methods, it can compare economic and ecological aspects on an objective basis that is independent of their perceived monetary value. Emergy compensates for the inability of money to value non-market inputs in an objective manner, providing an “ecocentric” valuation method. Its common unit allows all resources to be
compared on a fair basis and facilitates interpretation of results. Emergy analysis recognizes the
different qualities of energy or abilities to do work within a network. Summarizing, energy analysis
provides a more holistic alternative to many existing methods for ECDM. 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.

Despite the fact that emergy analysis provides a powerful framework for sustainability
evaluation, it has remained unexploited in the field. This is particularly surprising and unfortunate
because symbiosis could bring great advances and benefits in both fields. The lack of use of emergy
analysis is not caused by unawareness, but by a sort of rejection that originates from a long history of
criticism. As a matter of fact, the younger generations of engineers seem not to be familiar with the
approach itself but already have a negative preconceived notion of emergy analysis. The next section
discusses the main sources of criticism of emergy analysis and other causes that contribute to this
situation.

CRITICISMS OF EMERGY ANALYSIS

Emergy theory has been characterized as simplistic, contradictory, misleading and inaccurate
(Ayres, 1998; Cleveland et al., 2000; Mansson and McGlade, 1993; Spreng, 1988). Rebuttals of many
critiques have also been published (Patten, 1993; Odum, 1995). 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 (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 described below and discussed in more detail in
Hau and Bakshi (2003b). Although they may seem trifling or unjust, addressing them is essential to
undo this negative preconception about emergy analysis and boost its involvement in ECDM.

Emergy and Economics

Odum (1988) argues that “[m]oney 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
environment generating resources or assimilating wastes.” 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).

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 has doubted
the ability of all such theories to capture the value of products to humans. For instance, 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 of 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 eventually it will have to shift to a more ecocentric view if it intends to guide humanity to its
survival.
Maximum Empower Principle

The Maximum Empower Principle claims that all self-organizing systems tend to maximize their rate of emergy use or empower (Odum, 1996; Odum, 1988). This principle predicts which species, populations, or ecosystems (or systems of whatever kind) will survive. 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, 1995; Patten, 1993).

The Maximum Empower Principle seems to be one of Odum’s contributions that is ahead of its time. Consequently, it will continue to be a cause of arguments and further scientific exploration until it is scientifically proven or disproven. 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.

Relation with Other Thermodynamic Quantities

There seems to be much confusion about the relationship between emergy and other thermodynamic properties such as energy, exergy, and enthalpy. 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 (Odum 1988, Odum 1996). However, formal quantitative links are missing between emergy and these properties. 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. Sometimes, it is Gibbs free energy, exergy, kinetic energy or potential energy; but at other times it is implicitly identified in terms of a function of money and other physical inflows, as when estimating human services. This lack of formal links between emergy and other thermodynamic quantities is a significant cause of skepticism about emergy among engineers. Some efforts have been made to connect emergy with exergy (Ulgiati, 1999). As a starting point, Hau and Bakshi (2003a) have recently derived the concept of emergy based on exergy.

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 them. 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). 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 whence they are derived. A deep look into these questions reveals that the emergy of minerals and fossil fuels does not account for the emergy of their formation, but instead considers the emergy of concentrating them into ores and reservoirs, which is also the case for metals. Although such approximations can be justified by specifying temporal system boundaries, making some assumptions or reporting missing data, it is important to clearly communicate the approach taken so these approximations are not taken as discrepancies and do not raise unnecessary doubts.
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 conversions 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. These assumptions, which do not imply that solar energy is being converted into tidal energy or deep earth heat, may be explained with the maximum empower principle. However, they can also be justified as the means to determine conversion factors based on the observed effects of these disparate forms of energy. The primary benefit of this approach is that it allows a fair comparison of the concentration of different kinds of energy and does not inherit the criticism of the maximum empower principle.

Problems of Quantification

Emergy analysis has not considered the uncertainty in many of the numbers used to calculate the transformities. Averaged transformities of industrial and geological processes are frequently used in specific case studies without showing sensitivity of the data reported. This criticism is also shared by most other approaches; however, addressing it becomes crucial as the size and complexity of the system increases and information decreases, which is the case with emergy analysis.

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 pathways. 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. This issue can be made irrelevant by verifying the variability of the results due to different approaches for ambiguous outputs. Moreover, such allocation can be made more appealing to engineers by showing its practical benefits, rather than by justifying it theoretically.

Before drawing conclusions about the legitimacy and relevance of the criticisms discussed above, the next section discusses the link between emergy and exergy as derived by Hau and Bakshi (2003a). The significance of this section is that it addresses all of the criticisms by showing that they are either irrelevant for general purposes, 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.

LINKING 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, 2003a). The resulting concept of Ecological Cumulative Exergy Consumption (ECEC) starts with the basic premise that available energy as used in emergy
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analysis and exergy analysis 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, thus addressing the criticism about the relation of emergy with other thermodynamic quantities.

Since ECEC analysis derives from expanding exergy analysis’ system boundaries and is related to emergy analysis, it is made clear that exergy analysis is inevitably exposed to the same challenges faced by emergy and therefore to the same criticisms regarding disparate time scales, representation of dissimilar streams in equivalent units, and the same issues about quantification and reporting sensitivity. Moreover, the allocation approach used in ECEC analysis, which partitions ECEC in proportion to the exergy of the outputs and follows conservation law, is possible only if knowledge about the network and products is fully available. However, for ecological systems, this approach to allocation is virtually impossible. Emergy allocation proves convenient since it can deal with ecological systems, thus addressing the criticism about allocation.

SOLUTIONS AND CHALLENGES FOR THE FUTURE

Controversy surrounding the maximum empower principle reflects society’s 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. However, as shown above, the maximum empower principle need not hinder the application of emergy analysis by compromising every aspect of it. As for the criticism regarding emergy and economics, it can be addressed by using emergy and economic indicators as complementary, which provides a better estimator of value than the separate sets.

The other criticisms are not really attributable to emergy analysis, but to the nature of the systems studied by it and, therefore, are also shared by methods such as LCA, MFA, and ECEC. As a result, the negative preconceived notion of emergy analysis among ECDM practitioners can be eliminated by showing the analogies with ECDM methods, establishing formal links with common properties such as exergy and by focusing on the strengths of emergy while acknowledging unproven claims.

Educating the industrial and ECDM society about emergy analysis requires more accessible and comprehensive sources. Emergy folios are a great start, but more is needed. Projects for an emergy analysis handbook, a website for performing emergy analysis and accessing a concise and complete database of transformities are essential. The quality and uncertainty of the data used should be reported (e.g. tabulating the mean and variance of commonly used transformities). Finally, reorganizing emergy analysis by categorizing different inputs or aspects by levels of assumptions or different ranges of confidence should strengthen the rigor and improve understanding and interpretation of the analysis. Finally, implementing these solutions should not only clear up all misconceptions and negative perceptions of emergy analysis, but should also establish it as a model for ECDM and sustainability evaluation methods.
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