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Review

Advancing quantification methods of sustainability: A critical examination emergy, exergy, ecological footprint, and ecological information-based approaches

Ali Kharrazi[a,*], Steven Kraines[b], Lan Hoang[c], Masaru Yarime[a]

[a] Graduate School of Public Policy, The University of Tokyo, Tokyo, Japan
[b] Future Center Initiative, The University of Tokyo, Tokyo, Japan
[c] Centre for Sustainable Development, University of Cambridge, Cambridge, United Kingdom

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ABSTRACT

Sustainability is increasingly used to describe a paradigm for shaping the social and economic future of mankind. While the concept of sustainability remains elusive, various attempts to construct a framework towards the quantification of sustainability have been made. In this paper, we review the attempts of emergy, exergy, ecological footprint, and the ecological information-based approach towards quantifying the concept of sustainability. Specifically, we review these methods based on their ability to address three criteria namely, the integration of ecological and economic dimensions, the long term resilience of a system, and the consideration of both extensive and intensive properties, e.g. properties that depend on system size and properties that do not. This paper is intended to provide a base for advancing the development of better methods for quantifying sustainability.

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1. Introduction

Sustainability is widely recognized as a paradigm upon which future policies must be based. However, a universally accepted definition for sustainability still has not been established, making it hard to systematically compare alternative policies. We suggest that a holistic approach that addresses the interactions between the dimensions of the concept of sustainability while providing a common ground for policy assessment is critically needed.

To achieve such a holistic approach to sustainability, a method must be developed for measuring sustainability as a holistic metric at the system level. For example, most existing conceptual tools for quantifying sustainability are based on identifying quantitative indicators along ecological and economic dimensions, which are quantified separately or aggregated into a single numerical value (Lopez-Ridaura et al., 2002). This reductionist approach leads to a fragmented assessment which treats sustainability dimensions as uncorrelated factors. While a holistic approach may result in loss of information about details of each of the individual dimensions, creating a holistic system-level image of the interactions between the dimensions is critical for quantifying sustainability. The challenge then is to construct tools that can quantitatively integrate both dimensions.

* Corresponding author. Tel.: +81471364877.
E-mail address: alik@sustainability.k.u-tokyo.ac.jp (A. Kharrazi).

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A quantifiable definition for the concept of sustainability must be able to distinguish between intensive and extensive properties relevant to the sustainability of a system. An extensive property of a system fluctuates according to the size of a system, for example how much of natural resources are available and how much is being consumed. An intensive property however depends not on the size of a system and is concerned for example on measurements of efficiency and resiliency in a system.

The earliest attempts to quantify sustainability emerged from the use of thermodynamic principles within the field of ecology to measure the sustainability of ecological systems. Emergy analysis was one of the first, followed by other conceptual tools such as exergy analysis, and ecological footprint analysis. These methods, which have been widely discussed and employed in the literature, attempt to evaluate the sustainability of a system in terms of emergy, exergy, and/or ecological footprint analysis from an accounting perspective. The primary concerns of the accounting perspective are the overconsumption or yield inefficiency of resources. As a result, these approaches only consider factors related to the long term availability of resources or what one may describe as extensive dimensions to sustainability. They ignore intensive dimensions of sustainability, such as the effect the topological structure of the connections and distribution of resources among the entities of a system. For example, intensive dimensions such as the resiliency of the system in response to stress or disturbances. The ecological information-based approach is a less researched method that attempts to address the topological characteristics of a system. Consequently, this approach can quantify a system's robustness to stress—which arguably is an aspect of resiliency.

We aim to identify the principal contributions and the major assumptions of four different approaches in the quantification of sustainability based on the following three criteria: (1) their ability to consider holistically the interactions between the ecological and environmental dimensions of sustainability, (2) the degree to which the long-term resilience of the system is considered, and (3) the degree to which both extensive and intensive properties pertaining the sustainability of a system are addressed. The paper is organized as follows. Sections 1–4 critically review the approaches of emergy, exergy, ecological footprint, and ecological information-based approach towards the quantification of sustainability. Section 5 provides a synthesis of the approaches and compares them using the three criteria. Section 6 concludes with suggestions for future research directions.

2. Emergy

The emergy analytical method is the measurement of all previous solar energy inputs that have been used in creating a service or product. Emergy analysis can be utilized to account for the natural capital required to deliver services and products. It provides researchers with various index-based tools to investigate and evaluate systems from an eco-centric perspective where it is aimed to bridge both economic and ecological parameters. Studies across various disciplines have employed the emergy analytical approach, such as regional and national sustainability (Ulgiati and Brown, 1998; Yang et al., 2010); natural ecosystems (Morandi et al., 2013; Odum and Odum, 2000) and urban sustainability (Liu et al., 2009; Zhao et al., 2013). These studies have been successful in comparing systems and have provided policy makers with insights into the efficiency of the economic output of a system relative to its emergy inputs as well as the risks of over-dependence on nonrenewable local emergy inputs.

Emergy analysis views any given environment as a complex web of energy flows. Starting from sunlight, the primal energy source, energy is concentrated and transferred to higher trophic levels. However, from the second law of thermodynamics, it is argued that all energies cannot be considered to maintain an equal quality and therefore the values must be transformed to a unified unit in order to account for the quality of energy transformations. Using the common unit of solar emjoules as a reference base, all chained solar energy inputs to a particular process are modified by the solar transformity of each input flow and aggregated to give the specific output of the process (Odum, 1996, p. 8).

The solar emergy P_K of the flow k of the products and/or services from a given process is:

$$P_k = \sum_i Tr_i E_i \quad i = 1, \ldots, n$$

where Tr_i and E_i are the solar transformity and usable energy, respectively, of the ith input flow to the process. The solar transformity of a given outflow of a process, i.e., Tr_k, is defined as:

$$Tr_i = \frac{B_i}{E_k} = \frac{\sum Tr_i E_i}{E_k}$$

where B_i is the total solar emergy underlying the ith inflow into the process and where E_k is the usable energy of the product k from the process. Solar emergy is measured in solar emergy joules (sej) and solar transformity is measured as the ratio of solar emergy joules over the joules of a product or service. Through a complex measurement process, researchers calculate various transformations for products and services thus allowing for the computation of various emergy flow values. For a comprehensive description of the methodologies used to derive the transformity coefficients of various processes, see Odum (1996, Chapters 2–4). The transformity coefficients permit the unification of all flows represented in a system, whereby units of energy/mass are converted to equivalent units of emergy.

After obtaining the values of various emergy flows, various emergy indicators are constructed to describe the system at the system-level. The emergy-based indicators are mostly based on functions of renewable (R), non-renewable (N), purchased emergy inflows (F), and emergy yield output of a process (Y). From these functions, the following emergy indices relevant towards a quantified definition of sustainability are constructed:

- *Environmental loading ratio (ELR):* It is the ratio of purchased emergy inflows (F) and non-renewable (N) to renewable emergy flows (R); it is calculated as $F+N/R$. This ratio indicates the load or pressure on ecosystems. A large ratio suggests a high level of emergy usage typical of an advanced system and also high level of stress on local environmental resources (Brown and Ulgiati, 1997).
- *Environmental yield ratio (EYR):* It is the ratio of the emergy yield of a process over the purchased emergy inflows from outside of the system used to convert raw materials to a product. It is calculated as Y/F. The EYR is a measurement of the total emergy used per unit of invested emergy inflows (F). A high EYR value is always desired where yield should be high while the imported investment should be low.

From the above indices of ELR and EYR, a quantified definition of sustainability, termed as the sustainability index (SI), is derived as $SI = EYR/ELR$. The SI index can be described as a measurement of the contribution of resources or processes, per unit of environment loading, to the system (Ulgiati and Brown, 1998). This index can be used to evaluate relationships between human–ecological systems, for example, to compare different processes which have the same yield output. Furthermore, this index can be used to evaluate the