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A semantic study of the Emergy Sustainability Index in the hybrid lifecycle-emergy framework

Damien Arbault[a,b,c,d], Benedetto Rugani[a], Ligia Tiruta-Barna[b,c,d,*], Enrico Benetto[a]

[a] *Public Research Centre Henri Tudor/Resource Centre for Environmental Technologies, 6A avenue des Hauts-Fourneaux, L-4362 Esch-sur-Alzette, Luxembourg*
[b] *Université de Toulouse, INSA, UPS, INP, LISBP, 135 Avenue de Rangueil, F-31077 Toulouse, France*
[c] *INRA, UMR792, Laboratoire d'Ingénierie des Systèmes Biologiques et des Procédés, F-31400 Toulouse, France*
[d] *CNRS, UMR5504, F-31400 Toulouse, France*

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ABSTRACT

Emergy-based indicators are claimed to be useful outcomes of the emergy evaluation framework, which aims at guiding decision-makers toward environmental sustainability. The calculation of the Emergy Sustainability Index (ESI), in particular, seems widely consensual among emergy scholars, but several variants actually exist in the scientific literature, which may lead to different interpretations or misunderstanding of the ESI result. This paper proposes a semantic study of two variants in both components of the ESI (the Emergy Yield Ratio and the Environmental Loading Ratio, respectively EYR and ELR), to enhance standardization and reproducibility in the calculation of emergy indicators. It is shown that ESI can be consistently defined at the level of the production site as well as from a lifecycle perspective, although several case studies in the literature use an intermediary version with inconsistent system boundaries. A recent definition of lifecycle-oriented EYR is made operational by the development of an algorithm to be implemented in the emergy accounting software SCALE. However, the classification of foreground inputs needs further precision. ESI is also decomposed using partial derivatives, in order to analyze the influence of each input category and retrieve generic recommendations. These multiple outcomes demonstrate the added value of hybrid lifecycle-emergy evaluation to identify specific potential actions toward enhancing ESI of human activities.

1. Introduction

Decision-makers need operational environmental sustainability indicators in order to monitor territorial policies and assess businesses' performance. On the one hand, national or regional environmental policies are often evaluated using composite indicators, i.e. synthetic aggregations of independent parameters, reflecting stakeholder values and expert weighting (e.g. Sébastien and Bauler, 2013; Spangenberg and Bonniot, 1998). On the other hand, business- and product-oriented indicators are usually derived by adopting a Life Cycle Assessment (LCA) perspective of the production chain, in order to identify the best improvement opportunities and to avoid pollution transfer from one step to another of the lifecycle (European Commission, 2010).

With regard to the assessment of resource depletion, one set of indicators is based on the notion of scarcity (e.g. Frischknecht et al., 2006; Goedkoop et al., 2009), using data on consumption rates and remaining stocks. Alternative indicators are based on exergy, i.e. the maximum potential useful energy that can be retrieved from a resource (Bösch et al., 2007; Dewulf et al., 2007; Szargut, 2005). Exergy accounting assesses the thermodynamic efficiency of an activity in converting the useful work embodied within resources. Moreover, the concept can be extended beyond the traditional boundaries of LCA to include the resource costs of labor, capital and environmental remediation (Sciubba, 2013). Despite their pertinence, these approaches do not necessarily take into consideration that the physical limits of human exploitation of the planet may have been reached already (Rockström et al., 2009), due to the increasing global population and technological improvements (Moldan et al., 2012). The comparison of the relative importance among resources (i.e. the potential impact of their shortage) essentially reflects their utility values, which potentially deviate from the planet's physical limits. However, prominent studies demonstrate the effectiveness of exergy accounting in modeling what is

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* Corresponding author at: Université de Toulouse, INSA, LISBP, 135 Avenue de Rangueil, F-31077 Toulouse, France Tel.: +33 05 61 55 97 88;
fax: +33 05 61 55 97 60.
E-mail address: ligia.barna@insa-toulouse.fr (L. Tiruta-Barna).

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potentially lost at Earth scale, suggesting novel approaches to study the physical limits of the globe and the efficiency of production processes, especially those that consume exhaustible resources (Chen, 2006; Chen et al., 2006; Hermann, 2006; Liao et al., 2012; Szargut, 2005; Wall and Gong, 2001). In any case, the effects on the ability of the geobiosphere processes to (re)generate scarce and non-renewable resources after human intervention cannot be assessed, i.e. the contribution of natural processes and ecosystems in the formation of renewable resources is systematically omitted, which makes these indicators more adapted to account for the depletion of non-renewable resources from a user-oriented perspective.

The study of energy and exergy flows in systems ecology (Fath et al., 2004; Jorgensen and Nielsen, 2007; Kleidon and Lorenz, 2005; Lotka, 1922; Puzachenko et al., 2011; Schneider, 1994; Skene, 2013) aim at relating the energy used up by natural systems to the amount of renewable resources they deliver, providing scientific indications on the maximum consumption rate of renewable resources that human systems can afford in the long run. Odum (1996, 1988) proposed the concept of emergy for comprehensive environmental accounting. Emergy was defined as the total direct and indirect (solar) energy used up to deliver a product. Therefore, emergy encompasses in its definition the contribution of both geological and biological processes, as well as transformation steps by human activities. The novelty in the emergy concept is the nature-centered perspective to the evaluation of human activities, which are considered as embedded within and dependent on the surrounding natural environment. Although the mathematical framework of emergy and its relationship with thermodynamics remain debated (e.g. Amponsah et al., 2011; Bastianoni et al., 2011, 2007; Brown and Herendeen, 1996; Lazzaretto, 2009; Le Corre and Truffet, 2012; Li et al., 2010; Morandi et al., 2013; Patterson, 2012; Sciubba and Ulgiati, 2005; Tiruta-Barna and Benetto, 2013), hybrid emergy-LCA models were proposed, either using emergy as an indicator for resources in LCA (Ingwersen, 2011; Raugei et al., 2012; Rugani et al., 2011, 2013; Zhang et al., 2010), or using detailed datasets from LCA to enhance the resolution of emergy evaluations (Arbault et al., 2013a, 2014; Marvuglia et al., 2013a; Rugani and Benetto, 2012) and to calculate Unit Emergy Values (UEVs), i.e. emergy per product unit.

Commonly adopted but less discussed achievements of the emergy evaluation framework are emergy-based indicators. In his emergy masterpiece (Odum, 1996), Odum first considered the calculation of ‘investment ratios’ as the ultimate step of the emergy evaluation of a human system. To this end, he classified the system's inputs into four categories: free, renewable (R) and non-renewable (N) resources, which are those retrieved directly from the natural environment by the activity under evaluation, and ‘imported’ materials (M) and services (S), i.e. those purchased from the larger economy. As argued in the literature (Campbell and Garmestani, 2012; Odum and Odum, 2001; Odum, 1988; Ulgiati and Brown, 1998), natural systems do not operate at steady-state conditions but rather follow cycling and oscillating patterns. Therefore, according to the emergy rationale, an activity cannot be defined as ‘sustainable’ by referring to a particular value to minimize in order to reach a steady ‘sustainable level’ of resource consumption, because it depends on the oscillating patterns of resource production by natural systems. Instead, an activity is estimated ‘environmentally sustainable’ when it anticipates and adapts to the changes in the surrounding environment (Ulgiati and Brown, 1998). Hence, this assumption would be better reflected by ratios that consider a human system within its economic and environmental context.

Among the most widely used emergy-based indicators, the Emergy Yield Ratio (EYR) evaluates the level of integration of the activity within its surrounding human context, while the Environmental Loading Ratio (ELR) reflects the intensity of human development around the exploitation of environmental resources (see e.g. Brown and Ulgiati, 2004, 1997; Raugei et al., 2005; Ridolfi and Bastianoni, 2008). The Emergy Sustainability Index (ESI) was introduced by Brown and Ulgiati (1997) as the ratio of EYR by ELR. Accordingly, the authors defined sustainability as ‘*a function of yield, renewability, and load on the environment*’. A sustainable process should be both environmentally and economically sound, i.e. operate with a low dependence on non-renewables and provide a suitable yield to society. ESI is thus a ratio of two ratios, which evaluate both environmental and economic compatibility of a system ‘*according to changes in its driving forces*’ (Ulgiati and Brown, 1998), i.e. the human and natural context. Therefore, it seems that ESI provides emergy evaluation scores with a clear directionality, i.e. a higher ESI refers to a more sustainable system (Brown and Ulgiati, 1997). However, the sustainability assessment through ESI is subjected to different interpretations and potential misunderstandings, because several variants of EYR and ELR have been recently proposed (Agostinho et al., 2010; Brown and Ulgiati, 2004; Brown et al., 2012; Campbell and Garmestani, 2012; Duan et al., 2011; Lima et al., 2012; Lu et al., 2009; Ortega et al., 2002; Raugei et al., 2005; Ridolfi and Bastianoni, 2008; Tao et al., 2013; Wilfart et al., 2013; Yang et al., 2010; Zhang et al., 2012), while other authors have suggested new indicators to enhance the emergy sustainability evaluation framework (Li et al., 2013; Lu et al., 2003, 2007, 2009; Mu et al., 2011; Ortega et al., 2002; Reza et al., 2013; Song et al., 2012, 2013; Zhang et al., 2011).

The aim of this study is to further analyze the implications of the diversity of definitions and formulations of EYR and ELR proposed in the emergy methodology, with regard to the mathematical decomposition of ESI. Six case studies of water treatment plants are used to illustrate the results. Two variants of ELR and EYR are selected, covering both the production site and the whole chain of production (lifecycle perspective) as system boundaries. In addition, the operational definition of the lifecycle-based EYR proposed by Brown et al. (2012) is tested by developing and using a specific algorithm. Consequently, four variants of ESI are described, with explicit meanings and covering different system boundaries. A sensitivity analysis of the 4 ESIs with respect to each type of input (local, foreground, background, renewable or non-renewable) is further performed, from which generic trends are derived to enhance the characterization of ESI.

2. Critical review of EYR and ELR

The Emergy Yield Ratio (EYR) is defined as the total emergy of inputs to a system divided by the imports from the larger economy: $\mathrm{EYR} = (\mathrm{N} + \mathrm{R} + \mathrm{M} + \mathrm{S})/(\mathrm{M} + \mathrm{S})$ (Brown and Ulgiati, 2004, 1997; Raugei et al., 2005; Ridolfi and Bastianoni, 2008). This index is interpreted as the ability of the local system to exploit local resources in order to deliver ‘real’ wealth to the larger economy. More details on the evolution of its definition in the literature and interpretation are provided in Supplementary Information material, section S1 (SI1). When applied to an activity, EYR reflects its ‘efficiency’ in processing local resources: the smaller the emergy of imports (M + S), the higher the EYR, the more ‘efficient’ is the activity. Recently, Brown et al. (2012) argued that this definition is misleading for the evaluation of technological systems (i.e. chains of processes), because typically they do not have a specific location in the global economy. The authors rather proposed switching from ‘local vs. imported’ to ‘foreground vs. background’ inputs by adopting a lifecycle perspective when calculating EYR for an industrial process. Foreground input flows were defined as ‘*flows that are directly input to the process expressed in the emergy of the raw resources from which they are derived*’ and background inputs as ‘*the investments required previously to extract, refine, and deliver foreground input*