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SCALE: Software for CALculating Emergy based on life cycle inventories

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ABSTRACT

Emergy analysis is an environmental accounting approach which evaluates the memory of the geobiosphere exergy (environmental work) supporting economic systems, e.g. to make a product or service available via the use of natural resources.

This paper presents the software SCALE (Software for CALculating Emergy based on life cycle inventories), which allows a rigorous and replicable calculation of the emergy associated to any product or service. The software exploits an *ad hoc* algorithm, fulfilling the emergy algebra rules, which requires as input the matrix describing a given system of interconnected processes, containing the amount of natural resources used by the output product and its linked technological processes.

Starting from this matrix the algorithm performs a graph search across the corresponding network and records the output emergy associated with each of the explored paths linking the input nodes of the network (i.e. the emergy sources) to the output nodes (i.e. the studied products). The algorithm is specifically devised to be used with data coming (in matrix form) from any available life cycle inventory (LCI) database used in life cycle assessment (LCA) studies. Two case studies are presented to illustrate the features of the software: the first one deals with heat generation from grape marc pellets, the second with drinking water production.

The use of large LCI databases for emergy calculation using SCALE could contribute to extend the application of emergy systems evaluation in the practice of sustainability science. To our knowledge, this is the first software tool which allows exact calculation of the emergy of products using LCI databases, and therefore it achieves an operational integration between the well-known and standardized LCI methodology and emergy evaluation.

1. Introduction

Life cycle assessment (LCA) is a standardized methodology used to quantify the environmental impacts of products across their whole life cycle (ISO, 2006). Nowadays LCA is one of the most accepted and used tools for the environmental assessment of products and services (Curran, 2006; European Commission, 2010). Like most of the currently existing lifecycle-based impact assessment methods and related indicators, LCA takes an anthropocentric perspective, since the value of resources is related to their scarcity or to their usefulness in economic production systems.[1] Therefore, from the LCA point of view the resources to be protected are the ones requested by economic production activities (via market mechanisms) and whose stocks are scarce. Renewable resources and ecosystem services are often excluded from LCA, despite the fact that their support to human activities and their increasing depletion have been recognized (Hassan et al., 2005). Only recently some researchers attempted to formalize a consistent inclusion of ecosystem services in LCA (Zhang et al., 2010a,b) defining an ecologically based LCA approach (Eco-LCA).

Stemming from the work of Odum (1988, 1996), a new paradigm to quantify the value of resources from a *nature-centered* (or *donor-oriented*) point of view has emerged in the scientific community. This approach is based on the concept of *emergy* (spelled with an "m"). In its traditional definition emergy quantifies the amount of available energy (usually expressed as *solar* energy and measured in *solar emjoules* (sej), or its multiples) previously directly and indirectly required to generate a product and/or to support a system and its level of organization (Ridolfi and Bastianoni, 2008). A direct link has been claimed between the concept of emergy and the thermodynamic concept of exergy (Sciubba and Ulgiati, 2005; Bastianoni et al., 2007), although not universally accepted by

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[1] Within this paper the term "system" will occur several times. It will refer sometimes to the system meant as a set of interlinked processes (either natural or anthropic) and sometimes in a mathematical meaning, as the system of mathematical (energy and mass balance) equations describing a system meant in the first acceptation. Therefore, in order to avoid misinterpretations, hereafter we will use the word "system" in the first meaning and we will explicitly specify when we refer to the mathematical system of equations.

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the exergy community (Sciubba, 2010). As stated by Raugei (2011) "emergy may ultimately be interpreted for all practical intents and purposes as the 'memory' of the total exergy that was previously spent to make a product or service available to the end user". As a potential consequence, "for human-dominated systems [...] more emergy assigned to a process' yield should be interpreted" as "appropriation of more environmental work to produce the used resources and/or more work potentially required[2] to replace them" (Raugei, 2011). This definition appears to lend itself very well to establish a link between a formal explanation of emergy and a possible, more practical, interpretation of its "donor side value" (Dong et al., 2008).

LCA is based on realistic representations of anthropic production systems, described by models like the Ecoinvent database, which is conventionally used in LCA software. These kinds of models are very detailed, i.e. include thousands of processes connected together by mass and energy flows. The need to integrate the evaluation made with LCA, which ignores ecosystems good and services, and emergy evaluation (EME), which takes them into account, has emerged in different studies (Pizzigallo et al., 2008; Dong and Wang, 2009; Duan et al., 2011) but the attempts done so far have had the character of a synoptic assessment where the two approaches have been used as complementary tools, rather than the form of a structural integration.

The question of using LCI models to calculate the emergy associated to man-made goods therefore arises (Ness et al., 2007; Rugani et al., 2011; Rugani and Benetto, 2012) and poses the technical problem of applying the emergy algebra rules to very complicated systems.

The aim of this paper is to provide a tool for calculating emergy using life cycle inventory networks. More specifically, a software interface (Software for CALculating Emergy based on life cycle inventories – SCALE) using an *ad hoc* developed novel algorithm is presented. The software is able to quantify the sej value of every kind of life cycle product and process through a rigorous implementation of the emergy algebra rules.

2. Materials and methods

The rationale behind the concept of emergy is the consideration that all the different forms of energy can be sorted under a universal hierarchy of energy transformations and measured with the common metric of the *solar emjoule* (Odum, 1996; Ridolfi and Bastianoni, 2008; Brown and Cohen, 2008), which then becomes a yardstick by which all energy and material inputs and outputs can be compared with each other. To convert material and energy items in sej, EME uses a conversion factor called *transformity* (given in sej/j or multiples), or specific emergy (given in sej/g or multiples) – more in general *unit emergy value* (hereafter UEV) – which is the amount of emergy required to make one unit of a given product or service (Odum, 1996).

The methodological framework for EME calculation is represented by the set of algebraic rules known as "emergy algebra". These rules are completely different from those applied in LCA (Odum, 1996; Brown and Herendeen, 1996) and have been questioned by some authors (e.g. Sciubba, 2010). The rules, listed hereafter, are not discussed further in this paper and used as such:

(1) all source emergy to a process is assigned to the process output;
(2) co-products from a multi-output process have the total emergy assigned to each pathway;
(3) when a pathway splits, the emergy is assigned to each leg of the split based on its percentage of the total energy flow on the pathway;
(4) emergy cannot be counted twice within a system: (a) emergy in feedbacks cannot be double counted, and (b) co-products, when reunited, cannot be added yielding a sum greater than the emergy source from which they were derived. Thus, when adding emergy of inflows or outflows that are co-products, only the largest one should be considered.

Fig. 1 clarifies the meaning of these rules: an energy systems diagram drawn from a *conservation* perspective, typical of LCA is compared with an emergy systems diagram drawn from a *memorization* perspective. Numerical examples are provided to show the emergy calculation in the case of (a) splits & co-products, and (b) feedbacks. For the sake of clarity, *co-products* are "product items showing different physico-chemical characteristics, but which can only be produced jointly" (Sciubba and Ulgiati, 2005). They are assigned the same emergy (and different transformity) since each of them cannot be produced without providing the whole amount of emergy required for the process. On the other hand, *splits* are "originating flows showing the same physico-chemical characteristics" (Sciubba and Ulgiati, 2005). Therefore, the emergy of splits will be different, proportionally assigned on the basis of their respective quantities, while their transformity is the same. A better understanding of the fundamental differences between energy and emergy can be gained from (Brown and Herendeen, 1996), where parallel quantitative analyses of several simple systems are performed. The problem of flows allocation in EME is strictly related to the quality of the outputs. When the quality of two outputs is the same (e.g. electricity that can be used both to re-charge the battery of an electric vehicle and to run a hair dryer), EME considers this as a *split*, while *co-products* represent flows of different quality (e.g. soybean oil and glycerine obtained in the production of biodiesel from soybean).

A comprehensive description of the similarities and differences between the EME and LCA methodological frameworks is presented in (Rugani and Benetto, 2012), where the authors also propose the utilization of the matrix-based computational approach used in LCA (Heijungs and Suh, 2002) for a more consistent quantification of UEVs. This approach is, however, still at its infancy and therefore is not adopted in the present paper.

Some attempts have already been made to mathematically illustrate emergy and its properties in a more structured way and to propose emergy computational approaches fully or partially fulfilling the emergy algebra rules. From a conceptual perspective, the two most mathematically structured frameworks for emergy calculations proposed in the literature are the one proposed by Giannantoni (2006), who described an approach based on non-linear differential equations and on a variant of the functional derivatives concept and the one proposed by Bastianoni et al. (2011), who presented an approach based on the application of set theory. A further original and pioneering attempt, where the calculation steps of emergy algebra are structured into a formal and scientifically consistent framework, has been done by Tiruta-Barna and Benetto (submitted for publication). The authors demonstrate the emergy algebra rules starting from emergy's definition and using dynamic modeling applied to a simple network of processes. Interestingly enough, they observe that rule #4 has three different formulations depending on the relative magnitude of two characteristic time scales: one derived from the network's dynamics and one of observation (i.e. the integration time). They further infer that the conventional form of rule #4, usually found in the emergy literature, is valid only for the observation time, which is much higher than the network's characteristic time. These conceptual approaches do not, however, deal with the actual implementation

[2] By Nature (*ndr*).