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Using the language of sets to describe nested systems in emergy evaluations

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ABSTRACT

The language of set theory has been recently used to describe the emergy evaluation of a process. In this paper this mathematical language is used as a guide to evaluate the emergy of nested systems. We analyze a territorial system on multiple scales as an example of hierarchically nested systems. In this regard, we consider two levels of organization of a territorial system with particular attention to defining the relationships between the flows at each level and between the levels. Our method is designed to make quantifying the interactions among levels easier and more accurate.

1. Introduction

In this paper we developed a schematic model to describe emergy evaluation of nested systems. To accomplish this we used the language of set theory because it is a simple mathematical language that helps us understand the role of each flow in an emergy evaluation of a system and, at the same time, it completely respects the rules of emergy algebra (Bastianoni et al., 2011). We focused on nested territorial systems, because there is often a question of how to avoid double counting when the usual methods of emergy evaluation are applied to such systems, especially when energy and materials are passed from the level of the system under evaluation to higher (or lower) levels of organization.

This category of systems brings to light the problem of scale better than others, because in the definition of the "system window" (Fig. 1) we can arbitrarily define processes inside the system and inputs to the system without considering whether the sources from outside the system are independent (Odum, 1996). For example, we can consider a system either as a single entity (Fig. 1a) or as a subsystem inside the larger system that contains it (Fig. 1b). In the first case we have a system with two independent external sources (indicated with S and F) and three components (A, B and E). In the second case, when the system is considered inside the larger system, we can see that S and F are not entirely independent because the flow F is also the result of flows deriving from S.

There are many past studies concerning emergy evaluations at different levels of organization but often the level under study is considered as a single system (Pulselli, 2010; Campbell and Ohrt, 2009; Pulselli et al., 2008; Campbell et al., 2005; Ulgiati et al., 1994) and only in some of them (Odum et al., 1987, 1998; Odum and Arding, 1991) is the relationship with the larger system that contains it explicitly considered.

In this work we propose a method to perform a complete emergy evaluation for hierarchically nested system. The model we will present is an improvement on the general model that used set theory to apply emergy methods to the analysis of territorial systems presented in a recent work (Morandi et al., 2013): here a detailed description of all a model's components necessary to represent the interactions within a hierarchically nested system will be described. We start by describing an emergy evaluation of a generic territorial system at one level of organization and, in particular, we illustrate how each flow contributes to the development of the system's structure and function. After this general description of the generic model, we continue by illustrating the application of the method to the simplest example of a nested system: a system organized in three levels (the system, its subsystems, and the next larger system), which considered together explain the role of each flow at every level. As recommended by Odum (1996) a system examined at three levels of organization is the best overall model to understand the structure of real systems but, for the purpose of illustrating the method as simply as possible, we limited our

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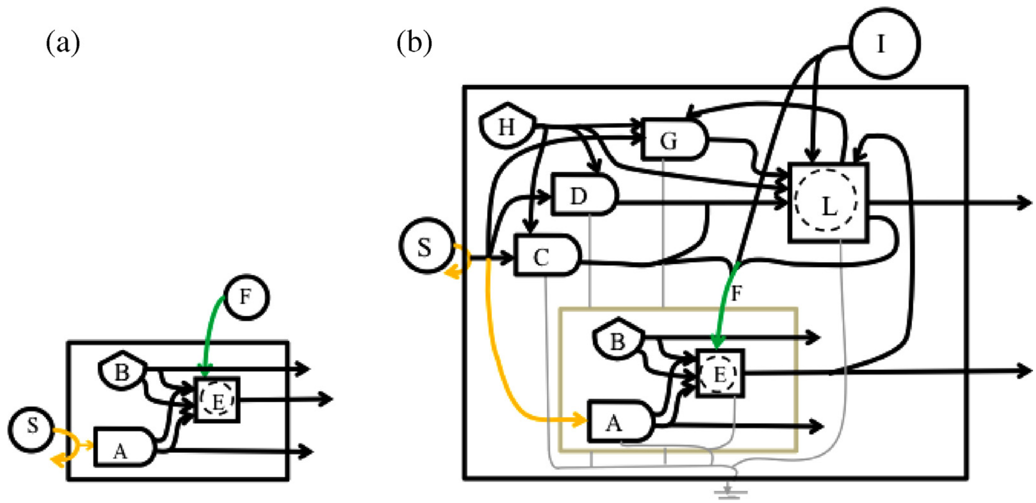

Fig. 1. (a) General diagram for a system with an arbitrary boundary and (b) the system considered inside the larger system that contains it.

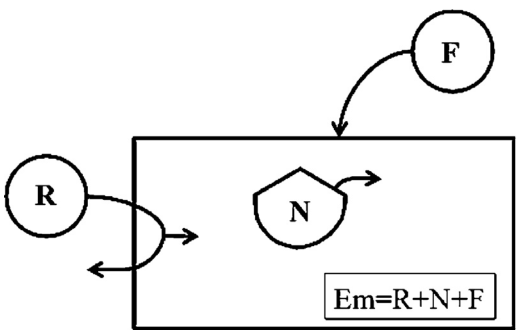

Fig. 2. Main emergy flows entering a generic system.

description to a model with only two levels, because mathematically we can consider any nested system as a successive iteration of this basic configuration.

2. Method

2.1. Emergy evaluation of a territorial system

When we analyze a territorial system, we have three main categories of emergy flows[1]:

- local renewable sources (**R**) that are generated most often by planetary processes outside the system and then concentrated within the area of the system,
- local non-renewable sources (**N**) that flow from internal storages of the system, and
- imported flows (**F**), usually defined as feedback flows because they are purchased and originate from outside the system.

The total emergy flow (Em) to the system can be considered as the emergy flow received by the system ($\bar{\mathbf{U}}$) or the emergy flow absorbed by the system (**U**) (Campbell et al., 2005). In both cases, we can show that the total emergy flow (Em), received or absorbed, is given by the union of the sets of inputs regardless of whether we consider them as received or absorbed (Fig. 2).

[1] Note that a flow of emergy is always associated with an underlying flow of available energy, matter or information, upon which it depends.

Following Bastianoni et al. (2011), we can represent a category of flows with a set, so we have:

R = {emergy flow of renewable sources}
N = {emergy flow of local non-renewable sources}
F = {emergy flow of imported goods and services}
U = {total emergy flow used in (i.e., absorbed by) the system}
$\bar{\mathbf{U}}$ = {total emergy flow received by the system}

Let us note that the total emergy used can also be considered in terms of concentrated use (C_{use}) and dispersed use (D_{use}) of resources (Odum et al., 1987). Sometimes, in fact, it is useful to distinguish between the emergy that is supplied to a territorial system in a concentrated form and that which is supplied in a dispersed form. Emergy supplied to the system in a dispersed form is generated and used over broad areas of the landscape, e.g., soil, timber, fish, groundwater. In general, these resources are renewable, if they are used at a rate less than or equal to their natural replacement rates, which are generally on the order of 1–500 years (Hilbert and Wiensczyk, 2007; Jenny, 1982; Uhlig et al., 2001). If one or more of these resources is used faster than its natural replacement rate, the emergy consumed is added to the emergy required for the territorial system. In contrast, emergy that enters the system as fuels, minerals and electricity can support the concentrated uses required for economic and social systems, e.g., construction, manufacturing, and information processing, which are essential to building and operating urban systems of all sizes. Resources that can support concentrated uses are most often fuels and minerals, which have long replacement times (on the order of millions of years) and are often used at a rate much faster than they can be replaced. Concentrated use also includes electricity that can be from sources other than fossil fuel. Thus, there can be a renewable component (R_E) of concentrated use, e.g., electricity generated from solar, wind, and geothermal energy, as well as hydropower (Fig. 3).

To elaborate our model, the division between concentrated and dispersed use of resources is not fundamental, so we will not use it in the demonstration below, but at the end of the paper, we will show how we can use it in an emergy evaluation of nested systems.

2.2. Set theory

In this section we recall the main concepts of set theory that will be used through the paper. A quick reference guide to the mathematical symbols used in this explanation can be found listed