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Set theory applied to uniquely define the inputs to territorial systems in emergy analyses

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ABSTRACT

The language of set theory can be utilized to represent the emergy involved in all processes. In this paper we use set theory in an emergy evaluation to ensure an accurate representation of the inputs to territorial systems. We consider a generic territorial system and we describe how the emergy related to every flow in these systems can be uniquely determined through the operation of the union of sets. The aim of this paper is to propose a new way to evaluate the main emergy flows entering a system using set theory, which is a general scheme applicable to every system. Because this paper represents the first step in an emergy evaluation of hierarchically – organized systems, we consider a territorial system as an example, because in it we will always have at least two levels of organization. In this regard we consider the relationships between flows to and from as well as within the system and the respective flows of one of its subsystems in the process providing a definition using the mathematics of sets both for the flows and for the relationships between the respective flows that occur at the different scales.

1. Introduction

Emergy analysis, with the calculation of emergy indicators, is an appropriate methodology for analyzing the level of integration between humanity and the environment. The first task in evaluating emergy flows for a system is to determine the boundaries, forcing functions, components and processes that uniquely determine how the system works at each level of organization and how the various levels interact with each other. In this paper, we describe how the inflows, outflows, storages, etc. of territorial systems can be uniquely determined through the application of the mathematics of sets. The language of ingenuous set theory has been chosen, because it is a simple mathematical tool that is generally applicable to all systems and it helps make emergy easier to understand.

In the real world, in fact, there are no system boundaries, per se, because every system is within and exists in mutual relationship to a larger system that contains it. Also, each system is composed of various subsystems and it exists in mutual relationship with them extending down to atoms, which are composed of protons, neutrons and electrons, and within the proton and neutron the world of quarks, which are apparently the fundamental constituents of matter as is the electron, which is also not decomposable. Each system, in fact, is characterized by energy fluxes to and from the system that contains it, but the system's internal dynamics also may be influenced by changes in the management of its subsystems. In particular, this condition is verified by every territorial system that we might want to study. For example, productivity of a nation is dependent on the productivity of its constituent states: in fact, the union of all the productivities constitutes that of the nation. When we think of a territorial system we know that this system is located in space and that it is often a part of a larger political system or system of trade and we know also that it is invariably composed of several regions (or political and economic subsystems). The internal dynamics of a system at any level can be greatly influenced by policy changes in the management of its subsystems. An example is the European Union that is an economic and political union of 27 independent countries. If we look at monetary affairs or environmental policy, we can see that the European Union is similar to a federation of states, and in this way it is like a single system; but, at the same time, if we look at the internal affairs of the 27 nations, the European Union is closer to a confederation of states, because each country has its own fiscal policies and economy.

Often, when we perform an emergy evaluation of territorial systems we consider only that system without worrying about the fact that it is composed of subsystems or that it is a part of another larger system. There have been many emergy evaluations of territorial systems on various scales of organization, such as national systems (Ulgiati et al., 1994), sub-national systems, e.g., a state or province (Pulselli, 2010; Pulselli et al., 2008; Campbell, 1998;

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Campbell et al., 2005; Campbell and Ohrt, 2009, etc.), production or energy transformation systems (Bastianoni et al., 2001, 2005; Castellini et al., 2006) etc. but each of them is for all practical purposes a self-contained systems analysis, because in them we do not often find a dynamic relationship with systems on larger and smaller scales represented and analyzed. Despite the fact that it is often not the norm in practice, it is understood that a complete emergy analysis of a place would include at least three scales as described and illustrated in Odum (1996). In fact, several studies have been performed on multiple scales as evidenced by the following: (a) Odum et al. (1987) examined the state of Texas, including emergy evaluations of the USA, Texas and subsystems of the State, such as water resources, agriculture, mining, electricity production, and highways; (b) Odum and Arding (1991) evaluated shrimp mariculture in Ecuador including a consideration of the gains and losses from this activity for the nation, the region, and a local shrimp farm; (c) Odum et al. (1998) performed a multiple level study of the cumulative effects of environmental impacts on the Cache River watershed, its next larger system, the State of Arkansas, and the Black Swamp, a subsystem within the Cache River basin.

Analysis at three different levels is important especially when we want to combine data. In fact, to obtain data for a particular system, sometimes the only way is to aggregate data from the subsystems. We usually translate the word “aggregate” as the sum, but this is not always correct, because in some cases, we could count the same quantity twice. We tend to make this mistake, because in our mind sum is equal to the union of sets, but this is true only in particular cases: in set theory, in fact, the union is equal to the sum only when we consider independent sets, i.e., when the sets do not have any elements in common.

To make a correct analysis of a system at three different levels we can use a new description of emergy made by means of the language of sets (Bastianoni et al., 2011), i.e., the emergy of a product or service is the union of the sets of solar exergy required to obtain it. In this paper we illustrate the method with an analysis of two levels of organization: this choice is not restrictive, because the methods employed to analyze the two levels model can always be translated to the next level. Therefore the three, four, . . ., n levels of organization within a hierarchical system can be addressed by the method developed for the two level case study. Set theory was used based on the Bastianoni et al. earlier work and the fact that the union of sets completely eliminates double counting in cross boundary flows of hierarchical systems.

In accordance with the fact that emergy can be described by the set of available solar energy inputs that are directly and indirectly required to make a product, in this paper we also use set language to define the input that converges to obtain a product or service. In fact, we propose a new way to evaluate the main emergy flows using set theory and then a general scheme that can be applied to every territorial system when we consider it within a larger system and in relation to its subsystems. In particular we studied the relationships between the main flows in the system of concern, for example, the EU, and in one of its subsystems, for example, Italy.

2. Methods

2.1. Emergy evaluation of territorial systems

In general, when we evaluate the emergy of a system we identify three main flows of resources: Local Renewable (R), Local Non-Renewable (N) and External Flows (F) and from these flows we calculate indicators to estimate the sustainability of the use of resources. The union of these three flows is the total emergy of the necessary inputs required for the system (U).

According to Ulgiati and Brown (1998), we outline the distinction between these resources as follows:

The renewable flows (R) are: (i) flow limited (we cannot increase the rate they flow through the system); (ii) free (they are available at no cost); (iii) and locally available.

The non-renewable flows from within (N) are: (i) stock limited (we can increase the rate of exploitation, but the total available amount is finite within the time scale of the system); (ii) not always free (sometimes a cost is paid for their exploitation); (iii) locally available.

The feedback flows (F) may be: (i) stock limited (as above); (ii) never free; (iii) never locally available, always imported.

Renewable sources include all sources that are always available naturally like solar radiation, rain, wind, geothermal heat, waves and tides. Other environmental resources where the amount used in a year cannot be replaced within an annual cycle, like soil, groundwater and mineral and fuel extraction, are included in non-renewable sources. Examples of feedback flows from outside the system are all imported flows, and purchased resources, including fuels, minerals, machinery and all goods and services that the system needs.

Returning to our discussion of a typical emergy analysis of a territorial system, we have various examples in which we can see that in determining the emergy of each flow, the origin of the flow is not considered in determining its transformity and therefore the emergy inflow. Often because of problems in data retrieval the system under study (nation, state, region, or productive system) is most often considered as a single entity, enclosed within its borders, without dynamically linking it to the next larger systems and without considering the subsystems that could be inside it. Although this consideration may seem, at first, to not be very important for Renewable and Non-renewable sources that are derived from the biogeophysical characteristics of the system, we will see that it is very important to know the origin of the imported flows (F) that contribute greatly to the total emergy (U). Usually, we consider the origin of purchased inflows that come from the rest of the world, but also there may be interactions with neighboring systems within the same larger system and these interactions become important when we want to understand the real work done in the system under study. In fact, if we consider a generic subsystem X_i we can see (Fig. 1) that it has imports from the rest of the world, which are also part of the imports from the world to the larger system X. The system X_i, also has imports from the larger system that contains it. Thus, the total import to the larger system is different from the total of the imports to every subsystem, i.e., the sum of the imports to the subsystems is larger than the import to the larger system and this shows the complex internal workings of the system. Therefore, when we collect data for the subsystems to obtain data for the larger system, it is not always correct to take the sum, because we could be double counting some inputs.

2.2. Emergy and set theory

According to Bastianoni et al. (2011) we can use the language of set theory to clarify the emergy evaluation of a system. In particular we are using the operation of the union between sets as the fundamental operation, because this operation makes it impossible to have a sum greater than the source emergy.

In this paper, we use capital plain text letters without an index to refer to the main system X, while a letter in italics with an index will refer to a subsystem X_i. Let X be the main system that is constituted of several distinct subsystems X_i (for example we can consider X = the European Union that is constituted of 27 countries each of which is represented by an X_i); the system satisfies the following conditions:

$$X_i \subset X \quad \forall i \quad \text{and} \quad X_i \cap X_j = \varnothing, \quad \forall i \neq j$$

$$X = U_i X_i$$