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Individual based emergy analysis: A Lagrangian model of energy memory

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ABSTRACT

Three new emergy computational methods are developed with identical outcomes to substantiate and in some cases improve the conventional emergy algebra, particularly with regard to the computations associated with system cycling. The power series, the algebraic method, and the individual-based methods are derived and presented by example. Considering energy flow and its accumulation from an individual quanta or energy particle perspective, the discrete individual-based approach that we present is constructed from a single, reasonably simple, agent-based rule of interaction. As such, emergy calculations are the result of a simulated agent-based method where discrete packets of available energy are labeled and tracked in time as they flow through system processes. To quantify energy memory, each particle has a transformity attribute derived from process inefficiencies. This agent- (or individual-) based method provides a way to compute emergy for complex multiple input, output, or even cycling systems, without assuming additional rules. We compare the outcomes from the power series, the algebraic, and the agent-based methods with the current algebra rules of conventional emergy computation. We also point out that the conventional emergy algebra, the power series, the algebraic, and the individual-based methods all need additional research and corresponding reconciliation with regard to the emergy of by-products.

1. Introduction

Using an individual based simulation to verify our theoretical development, we propose an alternative to the theoretical algebra and associated mathematics of the concept of emergy. The word “emergy” is correctly spelled with an “m”, which may be thought of as a mnemonic for energy memory, is all the available energy of one kind (usually solar energy for environmental systems) used up both directly and indirectly in the past to make a product or service that exists in the present (Odum, 1986, 1988, 1996). Emergy units are emjoules (eJ), connoting joules of energy of one particular kind used in the past (energy memory joules), which purposefully distinguishes them from energy joules (J). That is, the solar energy used in the past (seJ, solar equivalent joules, or solar emjoules) to make a joule of available energy in the present is called the *transformity* (seJ/J) of the product where the transformity of solar radiation is assumed equal to one by definition (1.0 seJ/J). Therefore, emergy, energy, and transformity satisfy the following formula:

$$\text{Emergy (seJ)} = \text{Transformity (seJ/J)} \times \text{Energy (J)} \qquad (1)$$

The advantage of using emergy is that environmental, social, and economic quantities expressed in solar emjoules can be compared on the same accounting ledger subsequently serving as a common measure of often disparate system attributes. Emergy permits a quantification of the environmental work contributed to a specific social or economic activity where the accounting balance (emergy assets versus emergy liabilities) quantifies sustainability with regard to nature’s value (Campbell et al., 2004; Campbell, 2005). It is important because maximizing emergy flows is hypothesized to be the criterion that determines success in evolutionary competition (Odum, 1988; Campbell, 2001, 2008). Although the emergy methodology is not completely developed and the approach is not accepted by everyone in the scientific community, its results and corresponding insights are significant and growing (Brown and Herendeen, 1996; Li, 2009). Substantial emergy studies include but are not limited to the states of West Virginia (Campbell et al., 2005), Minnesota (Campbell and Ohrt, 2009), and the San Luis Basin in southern Colorado (Campbell and Garmestani, 2012) funded by the U.S. EPA, Puerto Rico and its Luquillo National Forest (Scatena et al., 2002) funded by the USDA Forest Service, and the Mississippi delta marsh system (Martin, 2002) funded by the National Oceanic and Atmospheric Administration through the Louisiana Sea Grant Program. Emergy was used as the basis for the environmental certification ISO14001 of the Province of Siena, Italy (Ridolfi et al., 2008). The National Natural Science Foundation of China’s funding of emergy analyses of

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economically important sectors of the Chinese economy is growing (Li and Wang, 2009; Hu et al., 2009; Ren et al., 2010; Lei et al., 2010, 2011).

Brown and Herendeen (1996) and Odum (1996) articulate four rules of emergy algebra using various models with increasing complexity to aid their demonstration:

1. All source EMERGY to a process is assigned to the processes' output.
2. Process by-products have the total EMERGY assigned to each by-product pathway.
3. When a pathway splits, the EMERGY is assigned to each 'leg' of the split based on the fraction of total energy on each leg.
4. EMERGY cannot be counted twice within a system.
   a. EMERGY in feedbacks cannot be double counted.
   b. Process by-products, when reunited, cannot be added to equal a sum greater than the source EMERGY from which they were derived.

Regardless of system size and complexity, emergy computation for any system is expected to obey these four rules, which we subsequently refer to as the Eulerian emergy rules or simply emergy algebra rules for short. As such, for a given system, computing all emergy values may not be a trivial task. This is especially the case if a system involves feedbacks and or multiple inputs with different transformities. For ease of introduction, Fig. 1 depicts a two-compartment system with a single feedback and two inputs with different transformities (1 for S and 10 for F) from Brown and Herendeen (1996). Emergy flow from A to B is correctly computed as 460 because A receives 400 units of emergy from outside and only 60% of the 100 units of emergy that B receives from outside (adhering to rule 3, 3/5 = 0.6), totaling 460 units. Also, consider that the emergy output of B is 500 units because this accounts for all the emergy received into B that is not double counted (adhering to rule 4a).

Although these computations are reasonable, note that the total emergy input from the outside to the combined system of A and B together (400 + 100 = 500) does not equal the total emergy from the combined system released back to the outside (200). In this paper, we provide three alternative computation methods that resolve this nontrivial issue and provide a means for the emergy algebra rules to work at all hierarchical groupings. The results of our computation for this same system are shown in Fig. 7. For this relatively simple system, computations simultaneously satisfying rules 1 and 4a are not easy. To understand the reason for this difficulty, we focus on the energy flow from process A to process B. This flow contains both new energy that entered the system from S and F and existing energy recycling between A and B. Therefore, the energy flow from A to B is not of a single homogeneous transformity. Instead, transformities of individual energy quanta will have different transformities due to their pathway history. Therefore, this suggests that the amalgamated transformity of all energy flow from A to B can also be computed as the mean of a distribution of transformities of all the energy quanta flowing from A to B.

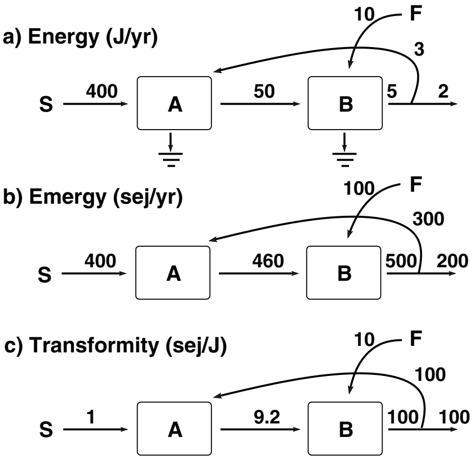

Fig. 1. Energy, emergy flows, and transformities in a 2-compartment system with feedback, from Brown and Herendeen (1996).

These considerations motivate a Lagrangian or individual-based emergy computation simulating individual energy quanta flowing within the system. Each individual energy quanta maintains a transformity, which depends on the processes it has experienced. In theory, such a simulation should enable a computation of the average transformity for all energy flows within the system. Accurate emergy computation regardless of system size and complexity should result, which inherently satisfies all emergy algebra rules.

Although the methodology is based on a simple idea, for complex systems the execution is rather involved. Therefore, we will demonstrate various aspects of the methodology on three example systems:

1. *One compartment system with single input, output, and dissipation.* We use this example to define and demonstrate the individual-based emergy rule. This single Lagrangian emergy rule effectively reproduces all Eulerian emergy rules except rule 2. This exception is discussed later.
2. *One compartment system with two inputs each with a different transformity, output, and dissipation.* This example shows that the individual-based emergy computation agrees with the conventional Eulerian methodology for systems with multiple inputs but different transformities, with the exception of rule 2.
3. *Two compartment system with single input, feedback, output, and dissipation.* We will use an individual-based method to simulate the energy flow within the system. We then compute the emergy values based on the transformities of individual energy quanta. These values satisfy all emergy algebra rules except rule 2 discussed later.

2. Individual-based methodology

Individual-based emergy analysis works by discretizing energy into identical agents, which we refer to as quanta, or energy particles. For clarity and consistency, we use the term *particle* to refer to a discrete quantity of available energy, thus a particle, quantum, agent, or individual. The size of a particle is defined by its energy content, which is user selectable. Particle size is constant for all particles throughout the simulation, and should be small enough that any energy flow within the system can be represented by an integer number of particles. For example, if particle size is 2 J, then 100 J/day of energy flow can be represented by the movement of 50 particles over one day. Individual-based modeling software simulates the movement of particles. From Eq. (1), emergy is computed by multiplying the amount of energy with the appropriate transformity. For individual-based emergy analysis to be successful, we need an individual-based rule that governs how the transformity of a particle is modified by a process. Given the Eulerian emergy algebra rules, emergy values for a system are generally computed with knowledge of both the energy input and energy output of all processes and all associated transformities. However, a particle acquires or maintains no knowledge of the entire system. The only information a particle possesses is its own transformity. For example, it has no knowledge of the transformity