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Exploration of Odum's dynamic emergy accounting rules for suggested refinements

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ABSTRACT

H.T. Odum suggested a set of rules for simulating the dynamics of emergy flow (Dynamic Emergy Accounting—DEA), which offers the capability to investigate how the emergy and transformity of a storage of energy increases and decreases over time according to inflows and outflows of emergy and energy. However, Odum's original rules are cumbersome and appear to violate fundamental emergy algebra. The aim of this paper is to advance DEA by simplifying the equations and rules needed to simultaneously simulate energy, material, emergy and transformity. Odum's statements, mini-models and computer programming code are reviewed to explore his intentions about how emergy and transformity of stored energy increased and decreased over time. Simplifications are proposed and compared to Odum's original rules using a single tank simulation model, EMTANK. The new, simplified rule for DEA is the change in emergy stored is a balance of emergy input and emergy output regardless of whether the stored energy is increasing, decreasing or not changing. The simplifications included (1) removing his logic statement that requires emergy accumulation to stop when a storage is near its climax, (2) disallowing emergy to be lost via the heat sink, and (3) requiring that some emergy be exported from the storage. One of most important aspects of the simplification is that it allows transformity of a storage to decline, which may be a significant philosophical shift for many emergy analysts. Streamlining the mathematics of DEA widens the opportunities for simulating emergy in various systems over a range of complexities, which will advance the science of emergy evaluation.

1. Introduction

For systems with dynamic emergy flows, Odum (1996) developed a set of rules that have been called "Dynamic Emergy Accounting" (DEA) (Tilley and Brown, 2006; Tilley, 2011). DEA offers the capability to investigate how the emergy and related transformity of an object increases and decreases over time, which forces consideration of the idea that emergy is gained and lost, and that transformity can decline. The loss of emergy has not commonly been dealt with in emergy evaluations, so a declining transformity has received little attention. Thus, these are novel ideas in emergy science. In addition DEA forces the emergy analyst to consider the evolution of a system's power intake, dissipation due to storing energy and build-up of energy in a storage, which is missing from conventional (i.e., tabular) emergy analyses.

While Odum's original DEA model provides a foundation for exploring the temporal changes in emergy, transformity, and empower, its potential for contributing to the theory of emergy synthesis has not been fully explored. Many of the current issues surrounding the emergy methodology, such as splits, co-products, recycling and partial transformities (Felix and Tilley, 2009; Li et al., 2013; Bastianoni and Marchettini, 2000; Tilley, 2011) should be explored in a dynamic framework because real systems operate in a dynamic world where inputs, coefficients, and outputs change.

There is a need to fully explore Odum's original rules for DEA to understand whether they are consistent with basic material and energy laws, and congruent with accepted emergy algebra (Brown and Herendeen, 1996). There have been a few attempts to utilize Odum's differential-logic equationsto simulate emergy (Tilley, 1999; Cohen, 2002; Tilley and Comar, 2006; Tilley and Brown, 2006; Tilley and Comar, 2006; Izursa, 2008), but there has been less consideration given to the limitations (Tilley, 2011; Winfrey, 2012; Winfrey and Tilley, 2013; Castro et al., 2013). Simultaneous to composing this paper, I interacted with R. Castro on his novel approach to use bond graphs to explore many of the same concerns I had

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about Odum's DEA. Castro et al. (2013) arrived at many of the same conclusions presented here. As emergy synthesis matures, there is a strong need to be able to analyze and synthesize the temporal dynamics of systems of interest. For example, human civilization and the Earth's ecosystems are undergoing a tremendous pulse of energy consumption and emergy production, but emergy syntheses are almost always conducted assuming linear, steady-state conditions. Tilley (2011) pointed out that although it has been known for decades that systems maximizing empower often develop material cycles in well-conserved loops as a strategy to relieve the impact of a limiting factor, there has been an insufficient amount of mathematical modeling to understand how emergy cycles. A better understanding of emergy cycling was accomplished by employing a "refined-DEA" (Tilley, 2011).

The goal of this paper is to advance dynamic emergy accounting by simplifying the equations and rules needed to simultaneously simulate energy, material, emergy and transformity. The paper reviews Odum's statements, mini-models and computer programming code to explore his intent about how the emergy and transformity of stored energy increased and decreased over time. Odum's rules are compared to the proposed simplifications by investigating a single tank simulation model, EMTANK, which was used by Odum (1996) to demonstrate the principles of emergy dynamics.

These simplifications allowed Tilley (2011), Winfrey (2012), and Winfrey and Tilley (2013) to integrate Brown's em-formation principle (Brown, 2005) into DEA, which lead to a mathematical framework for modeling emergy recycling. A better understanding of how to model emergy dynamics could also help explore questions such as:when a newly created product is destroyed, how much of its emergy remains? How and when does the emergy of an object disappear, if ever? If emergy is the memory of the energy dissipated, can the memory be "forgotten"?

For now, systems that involve co-production were not considered. See Giannantoni (2005) profound mathematical interpretations of Odum's emergy algebra to obtain a sense of how the emergy of co-production can be modeled.

2. Review of original rules of dynamic emergy accounting

H.T. Odum provided a foundation for simulating emergy accounting under temporally dynamic situations, whereby energy and material inputs and outputs did not necessarily balance, and energy and materials could accumulate during growth or be lost during decline. He left behind a modeling framework described in a set of differential equations with logic statements (Fig. 1) and a few computer mini-models with programming statements that demonstrate how the simulation of dynamic emergy and, consequently dynamic transformities, can be conducted (Odum, 2002; Odum and Odum, 2000; Odum and Peterson, 1996; Odum, 1996).

Odum demonstrated his framework for dynamic emergy accounting only for storages of energy and not for storages of material. In addition he focused solely on models where energy was increasing toward a steady state rather than declining from a maximum. He included the rules for simulating emergy in Chapter One of *Environmental Accounting* (Odum, 1996), emphasizing its importance to understanding emergy accounting. However, few emergy scientists have explored the philosophy behind DEA, and its implications for practicing emergy evaluations.

2.1. Emergy accumulation during growth (case 1)

Odum (1996) stated that the dynamics of an emergy storage could be described according to three situations based on the change in the energy of the storage. The first case was when the energy stored was increasing.

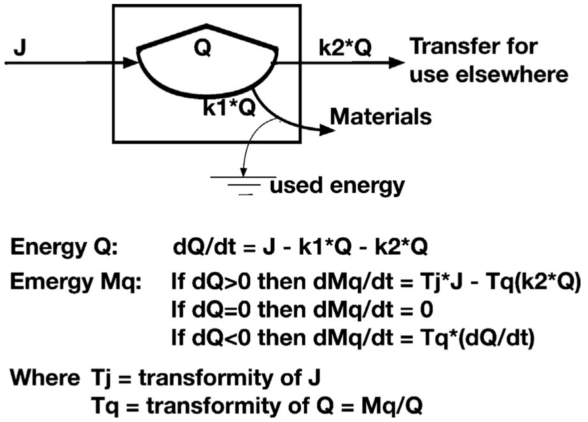

Fig. 1. Odum's (1996) EMTANK model with its original differential-logic equations for simulating temporally dynamic emergy and transformity of a single storage Q with three pathways: one input J, one useful export (k_2Q) and one loss to heat sink (k_1Q). (M_q is emergy of storage Q).

> "*The (emergy) storage receives and accumulates the* solar emergy required to develop the wood storage (of a forest). The solar emergy stored is that required to make the storage, in spite of the depreciation going on. Degraded energy going down the heat sink pathway is not available to do work, and thus has no emergy. The emergy accumulates as long as energy *is increasing*."(Odum, 1996, pp. 10–11)

> "*So long* as a storage is growing, the stored emergy is the sum of inflowing emergy minus that exported to other systems. But note that the energy drain (second law depreciation) is not included in the emergy equation since *that flow is necessary to the emergy storing process*."

The two important features highlighted in thequotes aboveare that (1) emergy accumulates in storages as the difference between emergy inputs and emergy exports and (2) energy lost (dissipated) to the heat sink does not remove emergy from the storage. These features are captured in Odum's EMTANK (Fig. 1) and elaborated in the following equations.

The single storage Q in Fig. 1 has an energy input J and two energy outputs, k_1Q and k_2Q, which gives Eq. (1).

$$\frac{dQ}{dt} = J - k_1Q - k_2Q \tag{1}$$

During the growth phase ($dQ/dt > 0$), Eq. (2) holds true according to Odum,

$$\frac{dM_q}{dt} = T_jJ - T_qk_2Q \tag{2}$$

implying that the change in emergy of the storage is a balance of useful input emergy (T_jJ) and exported emergy that is useful (T_qk_2Q), and that there is NO emergy associated with k_1Q the heat sink pathway (i.e., there is no T_qk_1Q term in Eq. (2)).

A profound implication of emergy accounting fromOdum's passage above, "Degraded energy going down the heat sink pathway is not available to do work, and thus has no emergy" and Eq. (2), is that any process that degraded 100% of its input energy, sending it all down the heat sink, would leave no energy to carry forward the memory of how much energy was used (i.e., its emergy), which would completely break the chain of energy transformations and destroy that emergy forever. In other words, this is a case when emergy is forgotten or lost. Since emergy is the *memory* of the