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Short communication

Odum–Tennenbaum–Brown calculus vs emergy and co-emergy analysis: A reply

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ABSTRACT

In a recent communication, Le Corre et al. (2015) criticize the method of calculating emergy using the co-emergy/emergy formulation given in Tennenbaum (2014). I will attempt to show that this method conforms to both the definition and the "rules of emergy algebra" laid out by Brown and Herendeen (1996). The note does raise some interesting points that should be open to discussion.

1. Introduction

The purpose of this note is to address the concerns and objections to the method of calculating emergy proposed in Tennenbaum (1988, 2014) expressed by Le Corre, Truffet, and Lahiou in a recent communication to this journal (Le Corre et al., 2015). The proposed aims of that communication were (1) to "clarify the Odum–Tennenbaum–Brown approach", and (2) "show that emergy/co-emergy analysis of systems with splits and feedbacks based on linear algebra cannot be exact. And to give the correct values of emergy. . .on the example of Tennenbaum (2014, subsection 2.2.1)" (Le Corre et al., 2015). The reasons they give as to the inexactness of the emergy/co-emergy method are purported violations of Brown's "four rules of emergy algebra" Brown and Herendeen (1996). In this response I will show that *none* of the four rules are violated. I will also make some observations and comments both abstract and practical.

For reference, Odum's definition of source emergy (Odum, 1988) is reproduced here.

> "In order to put the contributions of different kinds of energy on the same basis, we express all resources in terms of the equivalent energy of one type required to replace them. A new name is defined: EMERGY (spelled with an "M") is defined as the energy of one type required in transformations to generate a flow or storage."

Brown's four rules of "emergy algebra" are also reproduced (Brown and Herendeen, 1996).

> First rule: All source emergy to a process is assigned to the processes' output.
> Second rule: By-products from a process have the total emergy assigned to each pathway.
> Third rule: When a pathway splits, the emergy is assigned to each 'leg' of the split based on its percent of total energy flow on the pathway.
> Fourth rule: Emergy cannot be counted twice within a system.
> (a) Emergy in feedbacks cannot be double counted;
> (b) By-products, when reunited, cannot be added to equal a sum greater than the source emergy from which they were derived.

Finally the definition of co-emergy given in Tennenbaum (2014) is, "The total system use of energy of one type, upstream of and including that used by a particular unit j is denoted M_j and is called the *emergy* of unit *j*. And. . .the flow passing through an intermediate unit k enroute to the target unit j is called *co-emergy*, and is denoted $C_{k,[j]}$." Co-emergy calculations are specific to the emergy assessment of a particular target compartment. And, for the purposes of the emergy assessment of that target, one unit of co-emergy is indistinguishable from any other unit of co-emergy, that is, units of co-emergy attendant to a particular target are commensurate and summable.

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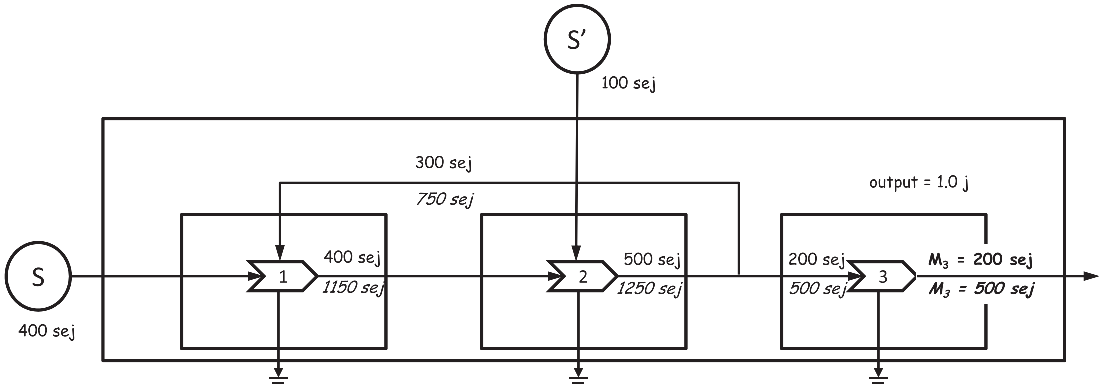

Fig. 1. A simple 3 compartment system. Co-emergy flows and emergy are for the 3rd compartment only. Labels above the flows in Roman are calculated using the OTB method. Labels below the flows in Italics are calculated using the EC method. Only the output of compartment 3 is emergy. All other amounts are co-emergy.

Given these definitions, what is the form of emergy, and what is the form of co-emergy? Do they exist in the physical world or are they just accounting tools? First, emergy is not some physical thing at the target compartment. There is no instrument, scale, or meter that one can apply to the target to get a reading of emergy. This means there is no direct material way to check the emergy of a component of a complex system. In that sense, emergy is an accounting entity. However, we can, through careful redefinition of the spatial, temporal, and structural boundaries of the system that contain the target compartment, expand that system so that all the energy inputs to that system are of a single type and similar power density (this type is usually taken to be solar energy). In this sense emergy is a physical entity, though consisting of (solar) energy inputs from multiple places and times. Some inputs, such as fossil fuels require moving the boundaries back, in theory at least, millions of years and to places that are completely restructured and transformed.

Co-emergy, on the other hand, is an accounting entity entirely. It is a valuation assigned to physical flows in a system in order to track the paths and weights of transactions leading from the sources to the target compartment. It is ***not*** emergy. When using co-emergy to calculate emergy, the emergy of one compartment's output is not used to calculate the emergy (or co-emergy) of another compartment's output. The one exception is when the flow is the base type, typically solar energy. It may be that other flows correspond in emergy and co-emergy values. This will typically happen with other raw inputs, such as crude oil, tides, wind, rain, mineral ores, and so on, when there are no or negligible feedbacks from human or natural processes. However, current human impacts on local and global climate, weather patterns, and alterations to coastal and inland geography are having their impact in this respect as well.

2. Cycling vs double counting

In their communication, LeCorre, Truffet and Lahlou (Le Corre et al., 2015) claim that the co-emergy method violates the fourth rule of Brown's four rules of emergy algebra and give a simple example modified from Figure 8b of Brown and Herendeen (1996). I have reproduced the system, as depicted in Le Corre et al. (2015), in Fig. 1, and labeled the flows with emergy and co-emergy calculated both by the *"Odum–Tennenbaum–Brown approach"* (hereafter referred to as OTB), and by the *"emergy/co-emergy method"* (hereafter referred to as EC). This diagram illustrates the emergy calculations for *compartment 3 only*, and, except for those flows emanating from compartment 3, all the flows labeled in this diagram are co-emergy. The quantities in Roman font above the flows are computed using the OTB method. In Tennenbaum (1988) these quantities are called "acyclic source requirements". The quantities in Italic font below the flows are computed using the EC method. In Tennenbaum (1988) these quantities are called "total source requirements". The EC method has two possible sinks, or absorbing states for source inputs: the target compartment output, and exports when present. The OTB method has three possible sinks, or absorbing states, for source inputs: the target compartment and exports as before, and all closed circuits of any length that exist en route from source input to target compartment.[1] The split in output from compartment 2 has 40% of output going to compartment 3 and 60% cycling back to compartment 1, Thus, as stated in Le Corre et al. (2015), the emergy of the output of unit 3 is given below for each method.

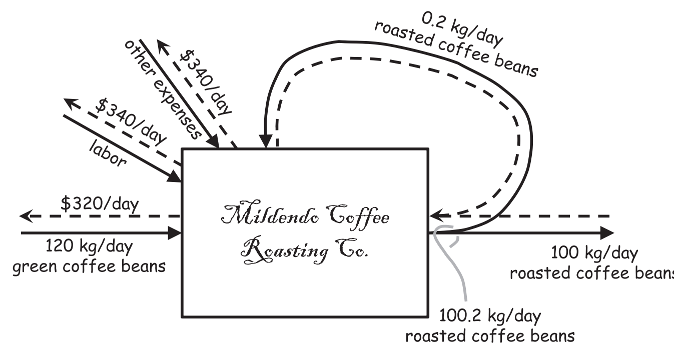

Fig. 2. A hypothetical coffee roasting company. Physical inputs and output are shown with solid lines, money flows are shown with dashed lines.

OTB yields : $M_3 = 400 \times 0.4 + 100 \times 0.4 = 200$

EC yields : $M_3 = 400 + 100 = 500.$

The paper then goes on to demonstrate, via series expansion of a general output structure matrix (the inverse of the difference between the identity matrix and the fractional outflow matrix), that cycles of all lengths potentially exist in the EC method. The diagonal elements of the powers of the fractional outflow matrix $(\mathbf{F}^n)$ represent the fraction of flow (co-emergy) that cycle back to that unit in exactly n steps. While this is true, the argument that this is an example of double counting is not.

As an example, I will use the case of a hypothetical small coffee roasting business (see Fig. 2). This company roasts 120 kg of green coffee beans per day to yield 100.2 kg of roasted coffee per day. The company sells 100 kg of roasted coffee per day and the staff of the company consume 200 g per day of their own product. The daily operating budget consists of $320 for the 120 kg of green

[1] A brief description of the EC and OTB calculation methods are given in Appendix B. For more detailed explanations the reader is referred to Tennenbaum (2014, 1988).