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Recycling flows in emergy evaluation: A mathematical paradox?

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ABSTRACT

This paper is a contribution to the emergy evaluation of systems involving recycling or reuse of waste. If waste exergy (its residual usefulness) is not negligible, wastes could serve as input to another process or be recycled. In cases of continuous waste recycle or reuse, what then is the role of emergy? Emergy is carried by matter and its value is shown to be the product of specific energy with mass flow rate and its transformity. This transformity (τ) given as the ratio of the total emergy input and the useful available energy in the product (exergy) is commonly calculated over a specific period of time (usually yearly) which makes transformity a time dependent factor. Assuming a process in which a part of the non-renewable input is an output (waste) from a previous system, for the waste to be reused, an emergy investment is needed. The transformity of the reused or recycled material should be calculated based on the pathway of the reused material at a certain time (T) which results in a specific transformity value (τ). In case of a second recycle of the same material that had undergone the previous recycle, the material pathway has a new time ($T+T_1$) which results in a transformity value (τ_1). Recycling flows as in the case of feedback is a dynamic process and as such the process introduces its own time period depending on its pathway which has to be considered in emergy evaluations. Through the inspiration of previous emergy studies, authors have tried to develop formulae which could be used in such cases of continuous recycling of material in this paper. The developed approach is then applied to a case study to give the reader a better understanding of the concept. As a result, a 'factor' is introduced which could be included on emergy evaluation tables to account for subsequent transformity changes in multiple recycling. This factor can be used to solve the difficulties in evaluating aggregated systems, serve as a correction factor to up-level such models keeping the correct evaluation and also solve problems of memory loss in emergy evaluation. The discussion deals with the questions; is it a pure mathematical paradox in the rules of emergy? Is it consistent with previous work? What were the previous solutions to avoid the cumulative problem in a reuse? What are the consequences?

1. Introduction

Emergy synthesis has been widely applied in the evaluation of ecological systems, energy systems, and environmental impacts of processes and a large number of studies. Most studies have applied the emergy theory to eco-economic systems in recent years. Brown and Ulgiati (2002) proposed an emergy-based method to quantitatively study the function of the environment in absorbing and diluting by-products generated by a process. Bakshi (2000) introduced an emergy analysis method for industrial systems, where waste treatment was considered. The wastes are not only handled by an end-of-pipe treatment approach and ecosystem dilution, but also by waste reuse techniques. Yang et al. (2003) also proposed a new emergy analysis method for waste treatment, reuse and recycle. Recycling is a major concept in completing the ecological life cycle of materials, where waste or production output from one system is an input to another system. Recycling serves to amplify and reinforce production processes, and provides a multiplier to the input resources. Systems that do not develop a complete cycle of materials will not be long continued (Odum, 1996; Buranakarn, 1998). Recycling is a common vocabulary when dealing with waste. Ulgiati et al. (2004) observe that emergy indeed has a role in this terminal part of the process chain and propose ways of accounting for its emergy amounts to avoid mistakes when recycling waste. If the wastes are released into the environment, the input provided by nature for their abatement via natural processes should be accounted for and assigned to the main product. However if wastes are treated and re-enter a production process as a substitute material or resource, only the emergy invested in the treatment and recycling process should be assigned to the recycled resources. A set of indices based on emergy for the evaluation of such sustainable processes and economics (Brown and Ulgiati, 1997), is used in evaluating the recycling value of solid wastes. The concept of

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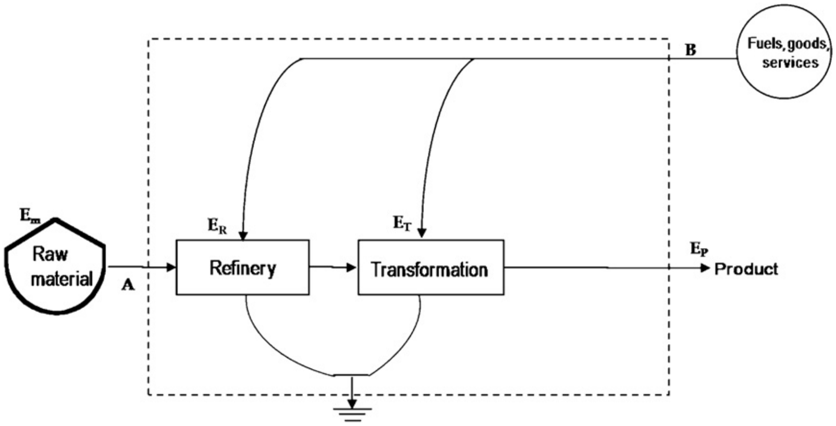

Fig. 1. Aggregated system with no internal recycle flows.

emergy has been also applied to building construction and recycle of building materials and several environmental indicators have been proposed (Buranakarn, 1998; Brown and Buranakarn, 2003; Huang and Hsu, 2003; Meillaud et al., 2005; Pulselli et al., 2008; Yuang and Li, 2008). For example, Buranakarn (1998) made emergy calculations for recycling matter in building applications where he studied 4 material flows and recycling patterns based on emergy evaluation:

(1) conventional material flow where material is discarded after use
(2) material recycle where material is recycled back to a stage in the transformation process and re-transformed
(3) use of a by-product waste from another production process in place of some material
(4) reuse of a material for some other purpose

In this case study (Buranakarn, 1998) the author considered the effect of material recycle in calculating its transformity for a first recycle. Most studies usually consider solid wastes recycling as one system with a single output (Marchettini et al., 2007; Feng and Cao, 2007; Brown and Buranakarn, 2003). Some studies however, consider the recycling system as a multi-product system (Yang et al., 2003). Solid wastes could either be beneficial or not depending on the process under study. Two different kinds of wastes are normally observed in eco-economic systems. One serves as a potential resource to produce new goods whilst the other is the real waste with no potential for any resource recovery (Yuang and Li, 2008). When the wastes are fully degraded so that the useful value of whatever their physical characteristics (concentration, pressure, chemical potential, temperature) is zero in relation to the reference level of the environment, they are no longer a resource (Ulgiati et al., 2004). These real wastes need resources and services to render them harmless. When comparing recycling pathways with traditional waste treatment, it is important to consider these two kinds of wastes at the same time (Yuang and Li, 2008). However, some researchers focus on the harmful waste (Bastianoni et al., 2002; Yang et al., 2003; Lou, 2004) and neglect the resourceful waste which could be a resource for new products and accounted for as emergy inflows.

This work contributes to a better accounting of emergy for recycling processes. A set of equations are proposed with a correction factor and used in some examples (metallic products – steel and aluminium recycling processes and non metallic products – glass and plastic recycling processes).

2. Emergy evaluation for systems involving recycling flows

Consider an aggregated system as in Fig. 1. With a raw material flow (source A), into the system, not all internal processes might be known within the different process units (Brown and Ulgiati, 2004). In this example, raw materials are refined, transformed, used and discarded. Source (B) represents the flow from other services, goods and fuel. As such, the process of refining requires an emergy input (E_R). The process of transforming the refined material into a finished product also requires emergy inputs of fuels, goods and services (E_T). If the emergy in the raw material is E_M then the emergy in the product (E_P) is the sum of the emergy in the raw materials and the emergy inputs for refining and transformation i.e. $E_P = E_M + E_R + E_T$.

Considering a similar system which involves recycling, additional emergy through services, goods and fuel inputs would be required for recycling (E_c) from source (C) as shown in Fig. 2. The emergy in the product (E_P) is then the sum of the emergy in the raw materials and all the emergy inputs required to maintain the cycle of the material system i.e. $E_P = E_M + E_R + E_T + E_C$ (note: though E_M remains the same notation for both the conventional process and the recycling process, they vary in terms of real quantities i.e. E_M decreases since E_c is a substitute in the recycling scenario).

The transformity of the product is given as: $\tau_P = \sum_{source} E_i/Q$ which takes into account the individual emergy flows (E_M, E_R, E_T, and E_c) over a year and the product output (Q). Transformity (of raw material, fuels, goods, services, and so on) is undoubtedly an important concept in emergy studies. There is still an on going research in developing the use of transformity values and its use in emergy evaluation (Ingwersen, 2010; Baral and Bakshi, 2010; Amponsah and Le Corre, 2010; Ulgiati et al., 2010, etc.).

Systems with recycling flows as mentioned above have a rather peculiar nature. The additional emergy (E_c) needed by a system involving recycling or material reuse obviously increases the output or final emergy compared to that of a conventional system. As such, a new transformity would be defined by this system involving recycle.

3. Analysis method

In Fig. 3 the method of configuring a general equation for systems with recycling flows, is described for a unitary product. As such, the kind or units of material input is not significant.

E_i is the total emergy inputs (emergy of raw material, fuel, goods and services, etc. without recycle, from source (A) and (B)), E_c is the specific additional emergy needed for recycling from source (C), (E_c is calculated from the emergy of the additional activities needed before a material is successfully recycled or reused (e.g. sorting and