C. R. Mecanique 343 (2015) 13–17

Contents lists available at ScienceDirect

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eMergy: A holistic paradigm for sustainability

éMergie : Un paradigme holistique pour le développement durable

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A R T I C L E   I N F O

Article history:
Received 4 July 2014
Accepted 17 September 2014
Available online 4 November 2014

Keywords:
Embodied energy
Recycling
Max-plus algebra
Complex systems
Sustainability
Path-finding problem

Mots-clés :
Empreinte énergétique
Recyclage
Mathématiques tropicales
Systèmes complexes
Développement durable
Recherche de chemin

A B S T R A C T

The aim of this paper is to present a new approach for evaluating the sustainability by crossing two scientific barriers within the concept of eMergy. The emergy analysis of steady-state complex systems presents the first barrier. As the second barrier, the emergy analysis of recycling process can be identified.

R É S U M É

Le but de cet article est de solutionner deux *difficultés* scientifiques du concept d'éMergie, une mesure utilisée dans le cadre du développement durable. Reformuler les règles de calcul de l'analyse émergétique sur des systèmes complexes en régime permanent résout *la première difficulté*. Introduire des retards dans le cas du recyclage est une réponse à *la seconde difficulté*.

Version française abrégée

En 1987, Bruntland [1] définissait le concept de développement durable : « préserver les ressources pour les générations futures tout en satisfaisant les besoins actuels. » Trois secteurs d'activités sont identifiés comme primordiaux : les économies d'énergie et de matières premières, la production propre et le recyclage. L'analyse du cycle de vie (analyse multicritère à pondération), l'empreinte CO_2 et aussi l'analyse énergétique et exergétique sont utilisées pour quantifier l'impact sur l'environnement.

Les ressources fossiles sont issues de la végétation s'étant décomposée et ayant séjourné près du magma pendant des millénaires. Or, cet historique n'est pas caractérisé par les grandeurs thermodynamiques, comme le pouvoir calorifique. Le caractère intrinsèque de « réservoir d'énergie solaire » de ces ressources est à la base de l'empreinte énergétique, *embodied energy*, ayant donné le néologisme de eMergie. Odum [2] définit l'émergie comme étant la somme de l'énergie solaire équivalente utilisée sur l'ensemble des *entrants* pour obtenir un produit, un bien ou un service. Ainsi, comparer l'efficacité d'un

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http://dx.doi.org/10.1016/j.crme.2014.09.007
1631-0721/

système renouvelable (photovoltaïque, éolien) et celui d'un système conventionnel (moteur ou turbine à combustion, cycle à vapeur) en considérant l'origine des ressources est l'objet de l'empreinte énergétique. En partant du bilan de la géobiosphère, Brown et Ulgiati [3] ont estimé l'émergie unitaire du vent et des marées. Considérant les différentes périodes géologiques, Brown et al. [4] ont estimé l'émergie spécifique des combustibles fossiles, en tenant compte de leur composition chimique. De nombreuses analyses émergétiques ont été menées dans divers domaines (production d'électricité, production d'hydrogène, traitement de l'eau, pisciculture, etc.). Une base de données d'émergies unitaires est régulièrement mise à jour [5].

Dans cet article, deux verrous de l'analyse émergétique sont levés. Le premier concerne l'application de l'émergie pour des systèmes complexes en régime permanent et le second s'intéresse au recyclage.

1. Introduction

In 1987, Bruntland [1] defined the concept of sustainability as: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." Three major sectors are highlighted in order to preserve resources: energy saving, clean energy, and recycling. Thus, a major issue is to quantify or compare technical solutions in terms of environmental performance. Some of the most commonly used approaches are the life cycle analysis, ecological footprint and the approaches based on the two principles of thermodynamics. Energy and exergy are two thermodynamic state functions and consequently are independent from the type of the process. Therefore, fossil fuels are characterised by their physical properties, such as low heating value, for example. Considering that hard fossil fuels are time-derivatives of wood decomposition (carbonisation during a long period of exposure to high pressures and temperatures beneath the surface), they can be considered as "solar energy tanks".

Based on this idea, Odum [2] introduced the concept of emergy and defined it as the total solar equivalent energy (or exergy) of one form of energy that was used up directly or indirectly in the work of creating a product/good/service. The unitary emergy of a product is the ratio of the total solar equivalent energy to one unit of a product. A unitary emergy is more or less a reverse of a holistic time-process efficiency.

The annual emergy flow of the geobiosphere is considered to be the baseline reference from which all other emergy flows units are directly or indirectly derived (see Brown and Ulgiati [3]). Renewable resources (wind and tide) are then evaluated under the convention that the unitary emergy of the solar energy is equal to 1 [seJ/J]. Brown et al. [4] estimated the specific emergy of coal, depending on the age of formation (Triassic, Cretaceous, etc.) and its composition (anthracite, lignite, bituminous, sub-bituminous). For example, the specific emergy for anthracite is $1.07 \cdot 10^5$ seJ/J. Hence, if an electric production with PV-cells (efficiency around 15%) is compared to a coal-fueled steam cycle (efficiency around 30%), an emergy assessment (taking into account all inputs for these two electric productions) could conclude that PV-cell involves less emergy. Or, as another example, the environmental impact of using biomass depends mostly on the transportation process. Jamali-Zghal et al. [6] defined the notion of maximum supply distance, beyond which biomass transportation becomes too environmentally intensive compared to a fossil fuel fired heating system. Moreover, this analysis shows that CO_2 footprint overestimates the maximum supply distance.

For a multi-input single-output system, the emergy assessment is comprised of three steps. The first step is the definition and categorisation of elementary inputs, assuming that they originate from *independent sources*. The second step is to convert those inputs to their emergy contents by using an open database [5]. Finally, the third step is to estimate the exergy of the output (to calculate the unitary emergy of the output). Additionally, emergy inputs are classified into renewable, nonrenewable, and purchased resources. Using this classification, Brown and Ulgiati [7] defined different ratios, one of which is the emergy yield ratio: a measure of the potential contribution of the process to the main economy, due to the exploitation of the local resources. Numerous emergy assessments have been published concerning different applications (electricity production, H_2 production, water treatment, fish production, etc.).

In this paper, two current scientific barriers within emergy assessment are addressed. The first one is emergy assessment for complex systems in steady-state conditions, and the second one is emergy assessment applied to recycling.

2. eMergy assessment for complex systems in steady-state conditions

Similar to a thermodynamic analysis, emergy evaluation requires first the definition of the system borders and the period considered (often the life duration), and so the crossing-emergy flows coming from the so-called sources. Thus, as for the well-known Kirchoff law, Odum [2] stated four rules to allocate emergy inputs in the case of the complex systems.

- Rule 1: When only one product is obtained from a process (i.e. a process with only one output), all of the source emergy assigned to it.

The following rules apply to processes with more than one output.

- Rule 2: When a mass flow separates, the total emergy splits accordingly to the mass fraction of each branch.
- Rule 3: When two or more co-products are generated in a process, the total source-emergy is assigned to each of them.

Finally, a fourth rule describes how emergy is assigned within a system of interconnected processes.

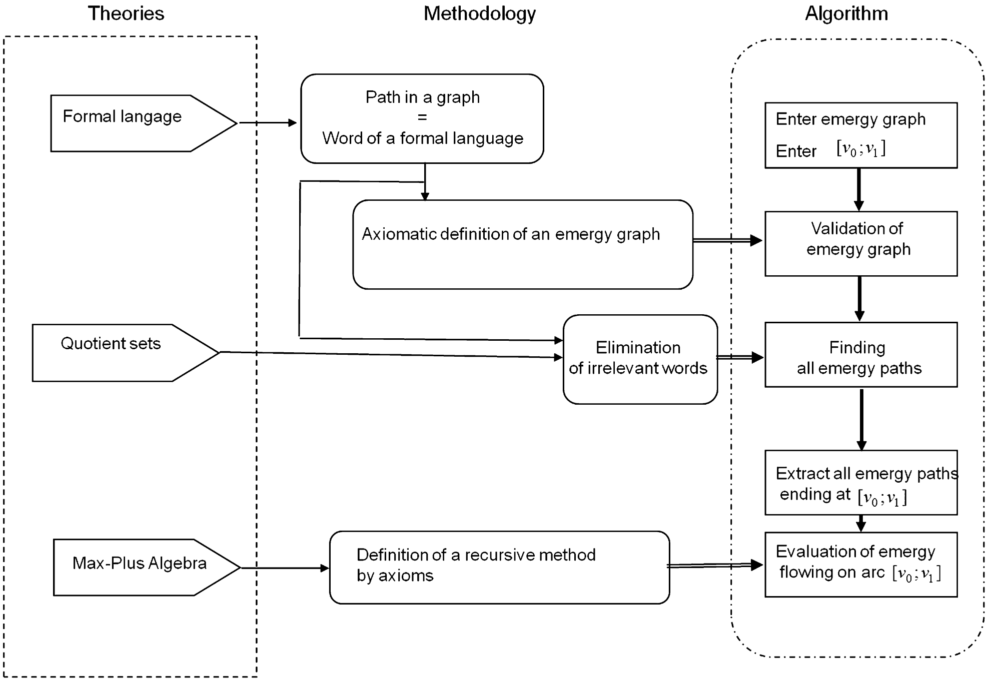

Fig. 1. eMergy assessment for a complex system in the steady state.

- Rule 4: Emergy cannot be counted twice within a system.
  - Rule 4.1: Emergy in feedbacks cannot be double-counted.
  - Rule 4.2: Co-products, when reunited, cannot be summed. Only the emergy of the largest co-product flow is accounted for.

Such rules are *not inter-consistent*. Le Corre and Truffet [8] rewrote these rules into two steps. The first step is the emergy flow enumeration, where paths from an emergy source to the input of a given process are enumerated, avoiding the double counting of emergy assignation. This step is a path-finding problem, see [9], which is a slight modification of *a null square Gerbier approach* to find elementary/simple paths in a graph. The second step evaluates the emergy flow between two components of the system. It is a quantitative part in which the problem of avoiding double-counting splits and co-product flows are dealt with by introducing a way to mark splits and co-products flows. The method is partially parallelizable. They introduced a semiring, see [10–12], equipped with an idempotent addition for path-finding and emergy calculation (rules application). Emergy is expressed as a function of the sources in the max-plus algebra (see [13]). To describe paths in the emergy graph, some formal language formalism is used. Additionally, the irrelevant paths are eliminated by introducing two equivalence relations. The set of emergy paths is then obtained as a quotient set of all paths of the emergy graph. This set is computed step by step (see Fig. 1 for the whole method).

3. eMergy assessment applied to recycling

A conceptual recycling process usually consists of four main steps (from “cradle to grave” according to the common expression): mining exploitation, transformation, use, recycling (collection and separation), see Fig. 2. Here, the use duration corresponds to the life duration of the product. As an example, if the automotive application of aluminium is considered, the usual life span is near 12–15 years. For the whole recycling process, this life duration is viewed as a time delay. Moreover, the recycling process receives its inputs from different parts and stores and mixes all recycled matter. In the following description, the product is considered at the output of the transformation process, e_p, the sampling time is the previous time delay and the discrete time is its index n. An inventory of inputs gives the mining exploitation, with its unitary emergy e_i, the transformation, with its unitary emergy e_t, and the recycling, with its unitary emergy e_c. Each input could be the sum of renewable, non-renewable and purchased resources. The mass fraction collection is denoted by q. Here, two mass losses are considered: ϵ_t at the transformation process and ϵ_c at the recycling process. The time-discrete specific emergy of the product is given in Eq. (1) under the assumption that the mass losses, the unitary emergies of the sources, and the mass fraction collection are time independent.

$$\begin{cases} e_\mathrm{p}(n) = \big(1+\epsilon_\mathrm{t} - q(1-\epsilon_\mathrm{c})\big)e_\mathrm{i} + q\big(\bar{e}_\mathrm{s}(n) + e_\mathrm{c}\big) + (1+\epsilon_\mathrm{t})e_\mathrm{t} \\ e_\mathrm{p}(0) = e_\mathrm{i} + e_\mathrm{t} \end{cases} \tag{1}$$

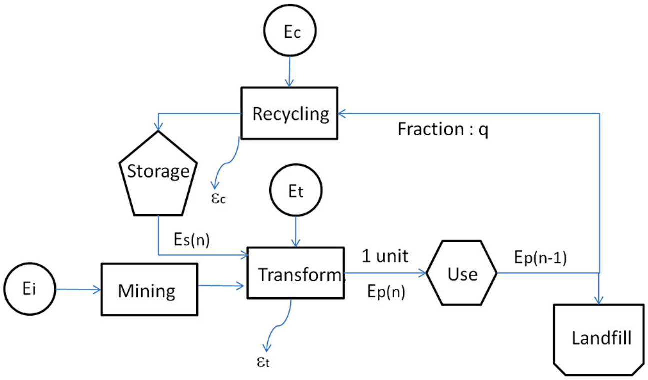

Fig. 2. Recycling scheme.

The specific average emergy of the recycled material at step n coming from the storage $\bar{e}_s$ is the mass blend of previous recycled material $\bar{e}_s(n) = \sum_{i=1}^{n-1} x_{i,n} e_s^{cl}(i)$, where $x_{i,n}$ is the mass fraction of the ith recycling at step n. Considering the superposition of emergy (cumulative embodied energy), the unitary emergy $e_s^{cl}(i)$ of the ith recycled matter is the solution of a "closed-loop" recycling. A "closed-loop" recycling corresponds to a Lagrangian approach: the raw material is followed during the ith consecutive recycling, see Eq. (2).

$$\begin{cases} m_p^{cl}(i) = \dfrac{q}{(1+\epsilon_t)(1+\epsilon_c)} m_p^{cl}(i-1) \\ E_p^{cl}(i) = m_p^{cl}(i)(1+\epsilon_t)\left[e_s^{cl}(i) + e_t\right] \\ e_s^{cl}(i) = (1+\epsilon_c)\left(e_c + e_p^{cl}(i-1)\right) \end{cases} \tag{2}$$

The initial condition of Eq. (2) is derived from the original pathway of the raw material, see Eq. (3).

$$\begin{cases} m_p^{cl}(0) = 1 \\ E_s^{cl}(0) = (1+\epsilon_t)(e_i + e_t) \end{cases} \tag{3}$$

Under the previous assumptions, Eq. (4) can be derived:

$$\begin{cases} m_p^{cl}(i) = \left(\dfrac{q}{(1+\epsilon_t)(1+\epsilon_c)}\right)^i \\ e_p^{cl}(i) = \left[(1+\epsilon_t)e_t + \alpha e_c\right]\dfrac{\alpha^i - 1}{\alpha - 1} + \alpha^i (1+\epsilon_t)(e_i + e_t) \end{cases} \tag{4}$$

where $\alpha = (1+\epsilon_t)(1+\epsilon_c)$. The cumulative aspect on e_t and e_c at each cycle is in the first term and the original value (without recycling) that is contained in the second term.

For example, Bertram et al. [14] proposed the evolution of the percentage of aluminium recycling. Since the share is around 30%, the asymptotic behaviour is reached in less than five cycles. So, an estimation the mass fraction $x_{i,n}$ is possible (whatever the use: building, automotive, etc.).

4. Conclusion

The purpose of this paper was to present propositions for crossing the two current barriers within the concept of emergy itself and emergy evaluation of the recycling. The first obstacle is within emergy analysis in case of complex systems. The four rules of emergy assessment are not inter-consistent. By using formal language, quotient set and max-plus algebra, a general methodology is proposed. The second obstacle concerns emergy assessment in case of recycling. By introducing a time delay (life duration of a product) during the material use (as a transformed product), it is possible to highlight the cumulative effect of emergy on the recycled material. This cumulative effect is counterintuitive due to the fact that recycling is considered as an environmentally friendly solution.

References

[1] G.H. Bruntland, Our Common Future: The World Commission on Environment and Development, Oxford University Press, Oxford, UK, 1987.
[2] H.T. Odum, Environmental Accounting, EMERGY and Decision Making, John Wiley, 1996.
[3] M.T. Brown, S. Ulgiati, Updated evaluation of exergy and emergy driving the geo-biosphere: a review and refinement of the emergy baseline, Ecol. Model. 221 (20) (2010) 2501–2508, http://dx.doi.org/10.1016/j.ecolmodel.2010.06.027.

[4] M.T. Brown, G. Protano, S. Ulgiati, Assessing geobiosphere work of generating global reserves of coal, crude oil, and natural gas, Ecol. Model. 222 (3) (2011) 879–887, http://dx.doi.org/10.1016/j.ecolmodel.2010.11.006.
[5] http://emergydatabase.org/.
[6] N. Jamali-Zghal, N.Y. Amponsah, B. Lacarrière, O. Le Corre, M. Feidt, J. Clean. Prod. 47 (2013) 446–456, http://dx.doi.org/10.1016/j.jclepro.2012.09.025.
[7] M.T. Brown, S. Ulgiati, Emergy analysis and environmental accounting, in: C.J. Cleveland (Ed.), Encyclopedia of Energy, vol. 2, Elsevier, 2004, pp. 329–354.
[8] O. Le Corre, L. Truffet, A rigourous mathematical framework for computing a sustainability ratio: the emergy, J. Environ. Inform. 20 (2) (2012) 74–88.
[9] R.C. Backhouse, B.A. Carré, Regular algebra applied to path-finding problems, IMA J. Appl. Math. 15 (2) (1975) 161–186, http://dx.doi.org/10.1093/imamat/15.2.161.
[10] N. Bourbaki, Eléments de Mathématiques : Algèbre, Chapitres 1 à 3, Springer, 2006.
[11] M. Gondran, M. Minoux, Graphs, Dioids and Semirings, Springer, 2008.
[12] K. Glazek, A Guide to the Literature on Semirings and Their Applications, Mathematics and Information Sciences with Complete Bibliography, Kluwer Academic Publishers, 2002.
[13] F. Baccelli, G. Cohen, G.J. Olsder, J.-P. Quadrat, Synchronization and Linearity, John Wiley and Sons, 1992.
[14] M. Bertram, K.J. Martchek, G. Rombach, Material flow analysis in the aluminium industry, J. Ind. Ecol. 13 (5) (2009) 650–654, http://dx.doi.org/10.1111/j.1530-9290.2009.00158.x.