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Emergy-based indicators to measure circularity: promises and problems

Abstract: In the constant pursue of the sustainability of socio-industrial systems, the definition of useful, reliable and informative, and at the same time simple and transparent, indicators is an important step for the evaluation of the circularity of the assessed systems. In the circular economy (CE) context, scientific literature has already identified the lack of overarching indicators (social, urban, prevention-oriented, etc.), pointing out that mono-dimensional indicators are not able to grasp the complexity of the systemic, closed-loop, feedback features of CE. In this respect, Emergy accounting is one of the approaches that have been identified as holding the potential to capture both resource generation and product delivery dimensions and therefore to provide an enhanced systems' evaluation in a CE perspective.

Because of Emergy's intrinsic definition and its calculation structure, Emergy-based indicators conceptually lend themselves very well to the evaluation and monitoring of circular processes. Additionally, Emergy has the unique feature of enabling the evaluation of systems that are not necessarily only technosphere systems, but also of technological systems which embed nature (techno-ecological systems).

The present paper gives a perspective on a set of Emergy-based indicators that we have identified as suitable to evaluate circular systems, and outlines the different perspective compared to the circularity indicators defined in the "Circularity Indicators Project" launched by the Ellen MacArthur Foundation.

Keywords: Emergy-based indicators, boost circularity, circular economy

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Introduction

The concept of circular economy (CE), which has become very popular in the last decade and is now part of recent strategies of the European Union (EU) (EC 2014, 2015), is not a sudden revolution, but in reality it builds on several schools of thought that have grown across several years. It considers the concepts of Cradle to Cradle design philosophy (McDonough and Braungart 2002), the Laws of Ecology (Commoner 1971), the Looped and Functional Service (Performance Economy) concepts (Stahel 2010), Regenerative Design (Lyle 1994), Industrial Ecology (Graedel et al. 1995; Lifset and Graedel 2002), Biomimicry (Benyus 2002), Natural Capitalism (Hawken et al. 1999), and the Blue Economy approach (Pauli 2010).

Apart from the conceptual paradigm, which is now recognized and whose value is almost self -evident, the challenge now resides in finding operational schemes and putting them into practice to fully implement the CE paradigm via suitable business models and sustainable supply chain management schemes (Bocken et al. 2016; Geissdoerfer et al. 2018). However, putting them into practice is not the final step. Progress needs to be measured, and reliable ways to compare the state of a system before and after the implementation of a CE model need to be applied.

In this respect, the development of suitable indicators to assess the circularity of alleged CE models is still an important subject worthy of further investigation. Apart from the material circularity indicators developed in the framework of the Circularity Indicators project launched by the MacArthur Foundation (Ellen MacArthur Foundation & Granta Design 2015), which, in principlem is supply-chain-wide, some other similar indicators have been developed at the micro-level (products, companies) (Ardente and Mathieux 2014; Huysman et al. 2015). However, in the CE context the scientific literature has already identified the lack of overarching indicators (social, urban, prevention-oriented, etc.), pointing out that mono-dimensional indicators are not able to grasp the complexity of the systemic, closed-loop, feedback features of CE (Geng et al. 2012).

Accordingly, an alternative possibility is represented by the application of an Emergy Accounting (EMA) approach. Emergy-based indicators will probably not tackle all the elements that need to be taken into account to assess CE systems. However, they may offer a new or complementary perspective to allow accounting even for resources (also including services offered by ecosystems) that would be disregarded using other approaches, like the ones mentioned above (i.e. those approaches that are basically based on material balances).

The concept of Emergy, initially developed by American ecologist H.T. Odum in the 1980's (Odum 1986, 1996), is defined as the total available energy (exergy) of one kind that was required (used up) directly or indirectly in the work of making a product or a service (Brown and Ulgiati 2016a,b). Emergy can therefore aggregate energy and matter flows of a different nature into a common unit, using conversion factors called unit emergy values (UEVs), which express the amount of equivalent solar energy invested in the production of a unit quantity of a delivered resource (usually measured in solar emjoules per gram, sej/g). If the delivered resource is energy, the UEVs are called *transformities* (usually measured in solar emjoules per joule, sej/J).

By definition, Emergy is based on a holistic and donor-side (i.e. nature-oriented) perspective. This means that EMA estimates the value of resources based not just on their scarcity and consequent cost of extraction for humans, but also on the global effort done by nature (geo-biosphere work) to make those resources available. Additionally, EMA allows to evaluate the capability to absorb, dilute and recycle the emissions released by human activities when using those resources to produce commodities (Ulgiati and Brown 2002; Reza et al. 2014). In this way, EMA can account both for moneyed resources used by the technosphere (such as fossil fuel and minerals) and for non-moneyed and free environmental resources (such as sunlight, wind, and rain) as well as for the indirect environmental support embodied in human labor, services and commodities.

Interestingly enough, Emergy can also account (with a certain approximation) for the value of information embedded in the chain of processes which have led to the delivery of the studied resource (Abel 2013).

Emergy is based on a very specific set of algebra rules (Tiruta-Barna and Benetto 2013), which have historically hampered its application to models of large real systems like the complex supply chains behind the production of any commodity in our days. However, recent advancements on the automatic implementation of the Emergy algebra rules make EMA now possible also for large systems (Marvuglia et al. 2013; Keena et al. 2018; Nimmanterdwong et al. 2018). This can potentially render the calculation of Emergy-based indicators possible also for CE settings.

The aim of this paper is therefore to give a new perspective on the opportunity to use some Emergy-based indicators, which we deem suitable to describe circular systems, within the framework of the broader CE concept application, focusing on the differences (advantages and drawbacks) with the circularity indicators defined in the “Circularity Indicators Project” launched by the Ellen MacArthur Foundation.

1. Emergy-based indicators for the Circular Economy

As pointed out by (Geng et al. 2013), “given CE’s broad systemic aspects, monitoring can be enhanced through Emergy-based indicators, a set of environmental accounting indices and ratios capable of capturing both resource generation (upstream) and product (downstream) dimensions”.

However, conventional EMA has been traditionally based on simplified models to describe resources formation, as well as incomplete data inventories (Hau and Bakshi 2004). For this reason, the idea has been advanced that EMA could benefit from the use of existing Life Cycle Inventory (LCI) databases used in the Life Cycle Assessment (LCA) context, which contain hundreds of environmental flows solicited by thousands of industrial processes. EMA shares a strong user-dependence in the choice of framework and data for the inventory-building phase with other LCA methods. The use of inventory modelling principles behind LCA may therefore improve EMA, with EMA potentially representing an ‘added value’ to LCA, providing a donor-side and truly holistic perspective that is missing in LCA (Ingwersen 2011; Rugani and Benetto 2012; Rugani et al. 2013; Arbault et al. 2014; Raugei et al. 2014).

Emergy-based indicators conceptually lend themselves very well to the evaluation and monitoring of circular processes as: 1) Emergy does not allow for the double counting of feedback flows; 2) Emergy accounting keeps track of interactions among system components across scales; 3) Emergy allows, among other things, quantifying information flows, labour investment, human and natural capital (e.g. ecosystem services), thus yielding a complete picture of the “global effort” needed to run the system at its given level of complexity. In this regard, Emergy has the unique feature of enabling the evaluation of systems which do not only belong to the pure “technosphere”, but in which nature is embedded in the technological system (techno-ecological systems or techno-ecosystems) (Bakshi et al. 2015; Saladini et al. 2018). The term “techno-ecosystem” was firstly coined by Z. Naveh in 1982 (Naveh 1982) and placed in the context of its interaction with the ecosphere (termed as “total human ecosystem”) in 2000 (Naveh 2000). Obviously, each technological process nests within surrounding ecosystems at a specific ecological (thus spatial) scale that is suitable to describe this interaction completely (Bakshi et al. 2015; Liu and Bakshi 2018). For example, if one deals with a manufacturing process, then the smallest ecological scale suitable to describe the interaction between the plant and the surrounding ecosystem could be the plant site or the corporate campus (Bakshi et al. 2015). The left part of Figure 1 highlights the flows that can be observed between the technological system and the ecological system at a given scale, when a techno-ecological synergy is studied. The right part of Figure 1 shows an example of a techno-ecological system in which the *regulating services* provided by two ecosystems (wetland and forest) are used to treat effluents from a manufacturing plant (as if they were additional “pieces of equipment” installed in the plant) within a techno-ecosystem. In this perspective, ecosystems are used instead of technological equipment (e.g. in this case a wastewater treatment plant and air treatment facilities, such as filters, cyclones, etc.).

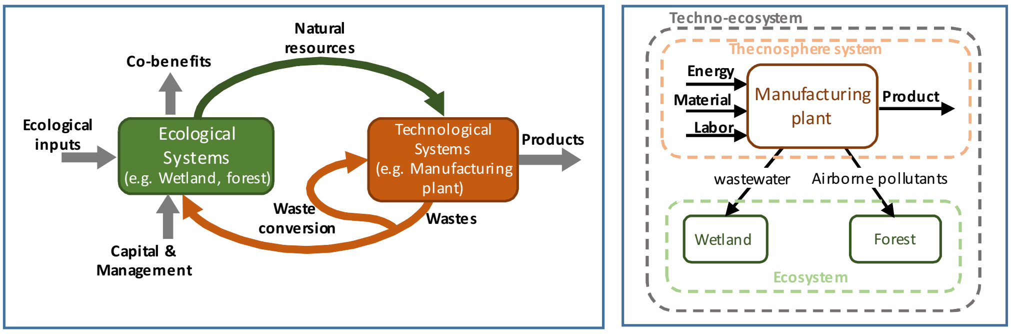

Fig. 1. Representation of a techno-ecological synergy on a selected scale (left); example of a techno-ecological system (right). Inspired by (Bakshi et al. 2015; Saladini et al. 2018)

Rys. 1. Przedstawienie synergii techniczno-ekologicznej na wybranej skali (po lewej); przykład systemu techniczno-ekologicznego (po prawej). Zainspirowany przez (Bakshi i in. 2015) oraz (Saladini i in. 2018)

When modelling such interrelated systems, it would be difficult to conduct an environmental sustainability assessment of the ecological component without resorting to an Emergy-based approach, since the traditional accounting methodologies (LCA, material flow analysis – MFA) are still not fully adapted to account for services and resources provided by natural (ecological) systems (Rugani and Benetto 2012), despite the recent advancements that have been carried out in the development of a computational framework to assess techno-ecological synergies in LCA, including ecosystem services in the life cycle inventories (Liu et al. 2018a, 2018b).

Implementing the CE concept implies a shifting from a take-make-dispose linear business model, where the generation of waste is functional to the conservation of the system, to a completely different, more complex, network-oriented production and consumption model. CE models are typically characterized by material and energy recovery within a peculiar new framework in which more value is given to collaboration and wellbeing, instead of increased consumption (Ghisellini et al. 2016). To this end, economies should try to emulate natural systems, in so doing minimizing waste, maximizing collaboration, using less resources, preventing upstream instead of fixing downstream (Santagata et al. 2017). In general, conventional monodimensional indicators for sustainability assessment seem to be unable to disclose and evaluate the complex features of CE, in particular with respect to some critical aspects such as: 1) lack of social/environmental indicators; 2) lack of indicators on urban/industrial synergies; 3) lack of indicators for responsible and sustainable business; 4) lack of prevention-oriented indicators (e.g. material/energy reduction, networking rate, etc.). Table 1 shows a comparison between the characteristics and peculiarities of conventional indicators and Emergy-based indicators applied for CE analysis goals. Conventional indicators are business- and profit-oriented. They assess the benefit to the user. Emergy-based indicators assess a process performance within the biosphere constraints. They focus on the network stability and balance. Emergy is the only measure that relates every resource used in products' life cycles back to the natural processes necessary to replace those resources, and hence it is potentially the best measure of the long-term environmental sustainability of production (Ingwersen 2011).

A preliminary review of the scientific literature dealing with Emergy-based assessment of circular systems allowed us to identify a number of Emergy-based indicators as suitable in the context of CE. These indicators are listed and explained in the remaining of the paper.

1.1. Emergy difference between noncircular and circular patterns (ΔU_{circ})

This index is derived from Ulgiati et al. (2007), where an example is shown of a set of three processes (A, B and C) which are clustered in such a way to exchange some of their still usable waste resources, in addition to delivering their main products. This clustering can be considered a step to implement a CE model. According to Ulgiati et al. (2007), the ΔU_{circ} indicator can be defined as described in Table 2.

TABLE 1. Comparison of common mono-dimensional indicators for linear economies and Emergy indicators related to circular economy (Santagata et al. 2018)

TABELA 1. Porównanie wspólnych jednowymiarowych wskaźników dla tradycyjnej liniowej gospodarki i Emergy odnoszących się do gospodarki o obiegu zamkniętym

Linear economy	Conventional indicators	Circular economy	Emergy-based indicators
Business-based	Linear	Network-based	Systemic
Stand-alone (systems not networking together)	Mono-dimensional (one aspect only)	Integrative (Environment -Energy-Economy nexus)	Comprehensive (includes global aspects of a system's performance)
Mono-criteria (value depending on maximized outcome)	User-oriented (value in what can be extracted)	Multi-Criteria (value depending on choices for wellbeing)	Donor-oriented (value in what is invested by nature)
Design and planning for ever increasing resource use (unlimited growth)	Non-recognized limits to production processes	Preventative eco-design and planning for decreased resources use and easy recovery (resources are limited)	Processes and economies must consider biosphere constraints (planetary boundaries)
Conservative ("more of the same" approach)	Exploitation-oriented (resource extraction for processing and market)	Regenerative (improvement instead of exploitation and depletion)	Enhances appropriate use of natural capital and ecosystem services by attributing environmental value to resources and system's components
Acquisitive (getting more, spending less)	Competitive (better performance than other market operators, increase business, displace competitors)	Redistributive (more jobs supported by better use of resources)	Optimization across scales (maximum empower through all levels of a system's hierarchy)

The summations of $F_{i,j}$ in Eq. (1) goes from 1 to n external inflows, while it stops at n–1 external inflows in Eq. (2) to take into account the fact that in a circular system some resources are recycled, thus reducing the need to use external resources. For the sake of simplicity, it is assumed that in the circular system the resources provided by the n-th external inflow can be replaced by the resources recycled from the system.

Let us now take the example of the system shown in Figure 2, where the effects of circularity are clear:

1) Creation of links and exchange flows among components.

2) Decreased waste release.

3) Additional Emergy investments needed for circularity.

4) Advantage depending on the extent of Emergy savings and of the decreased Emergy demand for waste management compared to investments.

Circular systems are made with processes that exchange resources. When a process receives an input from another process, it does not need to import new resources. However, implementing an exchange of resources requires suitable infrastructure that bear an Emergy cost. The challenge

TABLE 2. Environmental support to the local system of production processes A, B, and C, with and without boosting circularity

TABELA 2. Wsparcie środowiskowe dla lokalnego systemu procesów produkcyjnych A, B i C, z lub bez promowania gospodarki o obiegu zamkniętym

System	Emergy supplied (sej)
$(A+B+C)_{\text{linear}}$	$\sum_i R_i + \sum_i \sum_{j=1}^{n} F_{i,j} + \sum_i f(W_i) + \sum_i N_i$ (1)
$(A+B+C)_{\text{circular}}$	$\sum_i R_i + \sum_i \sum_{j=1}^{n-1} F_{i,j} + \sum_i g(W_i^u) + \sum_i f(W_i^r) + \sum_i N_i$ (2)
ΔU_{circ}	$\sum_i F_{i,n} - \sum_i g(W_i^u) + \sum_i f(W_i) - \sum_i f(W_i^r)$ (3)

R_i – renewable Emergy input (both locally produced and imported) to the *i*-th process.
$F_{i,j}$ – imported non-renewable Emergy of the *j*-th input to the *i*-th process.
$g(W_i^u)$ – Emergy invested to transfer still usable waste materials W_i^u from the *i*-th process to any other process.
$f(W_i)$ – Emergy invested for disposal of total waste from the *i*-th process or for repair of the related damage.
N_i – locally produced non-renewable Emergy input to the *i*-th process.
$f(W_i^r)$ – Emergy invested for disposal of residual waste W_i^r (unused) from the *i*-th process or for repair of the related damage.
i – A, B, C.
n – number of external sources of environmental inflows.
j = 1,..,*n*–1.

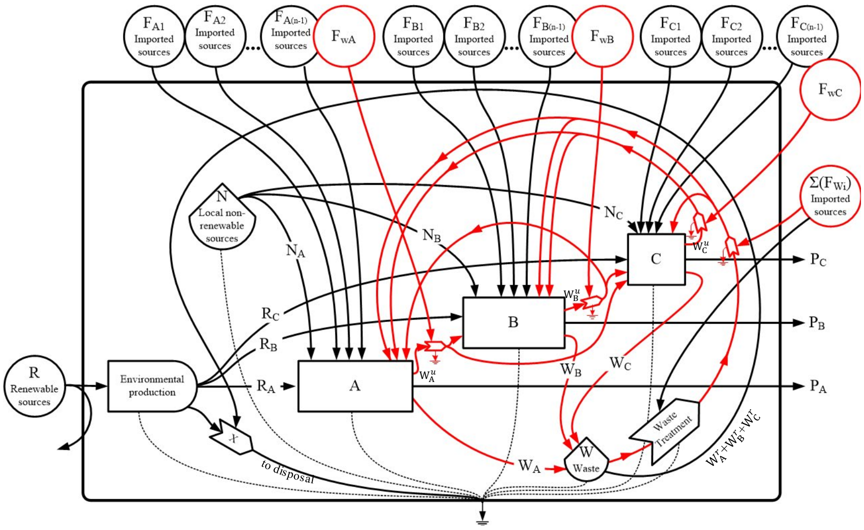

Fig. 2. System diagram of an integrated production system, in which the waste released by one process is at least partially used as raw resource by another process. Circularity paths are highlighted in red. P_i – mass of product(s) from the *i*-th process

Rys. 2. Schemat zintegrowanego systemu produkcyjnego, wykorzystujący odpady z jednego procesu stanowiące częściowy wsad do innego procesu. Ścieżki obiegu zamkniętego są zaznaczone na czerwono. P_i – masa produktu (ów) z *i*-tego procesu is to make sure that the additional costs are lower than the value of the saved resources, resulting in a more sustainable system.

1.2. Recycle benefit ratio (*RBR*)

The recycle benefit ratio (*RBR*) (Brown and Buranakarn 2003) is the ratio of the Emergy required in providing a material from a raw resource (E_{raw}) over the Emergy required to recycle a product after consumption in order to substitute the raw resource. This latter is the sum of the Emergy associated to the collection of the recyclable materials (E_{col}) and the Emergy associated to the recycling process itself (E_{rec}):

$$RBR = \frac{E_{raw}}{E_{col} + E_{rec}} \tag{4}$$

1.3. Recycle yield ratio (*RYR*)

The Recycle Yield Ratio (*RYR*) (Brown and Buranakarn 2003; Amponsah et al. 2011) is the ratio of the Emergy in a recycled material (E_{rm}) over the Emergy linked to the recycling of the material (E_{rec}).

$$RYR = \frac{E_{rm}}{E_{rec}} \tag{5}$$

This index accounts for the net benefit received by society for recycling. In other words, *RYR* is a measure of the Emergy that the society receives in return for the Emergy that it has invested for recycling. In this respect, *RYR* is very similar to the Emergy Yield Ratio (*EYR*) used to express the net benefits gained by society from energy sources (Brown and Ulgiati 1997).

1.4. Landfill to recycle ratio (*LRR*)

The landfill to recycle ratio (*LRR*) is the ratio of the Emergy required to landfill a material (E_{lf}) over the Emergy required to recycle the material (see Brown and Buranakarn 2003; Ghisellini et al. 2018). *LRR* is expressed by Eq. (6), where the higher the ratio, the higher the benefit for society of recycling the material rather than dumping it in a landfill:

$$LRR = \frac{E_{lf}}{E_{rec}} \tag{6}$$

2. Comparison with the material circularity indicator

In order to define the potential benefit of coupling Emergy-based indicators to other types of indicators used to assess the advantage of putting a CE model in place, we consider comparing them to the traditional material circularity indicator (*MCI*) defined in Ellen MacArthur Foundation & Granta useful (2015; p. 25).

The definition of the *MCI* starts from the calculation of the linear flow index (*LFI*), which measures the proportion of material following a linear path (i.e. ending up as unrecoverable waste) over the total mass flow. Total mass flow is understood as the sum of the amount of material flowing in a linear fashion and the amount of material flowing in a restorative fashion. As explained in Ellen MacArthur Foundation & Granta (2015), the *LFI* is given by the expression:

$$LFI = \frac{V + W}{2M + \frac{W_F - W_C}{2}} \tag{7}$$

where:

V – the mass of virgin feedstock used in a product,
W – the amount of unrecoverable waste associated with the product,
M – the mass of the finished product,
W_F – the mass of unrecoverable waste generated when producing recycled feedstock for the product,
W_c – the mass of unrecoverable waste generated in the recycling of parts of the product.

The *MCI* of a product *P* is defined by Eq. (8):

$$MCI_P = \max(0, MCI_P^*) \tag{8}$$

where

$MCI_P{}^*$ – is defined by Eq. (9):

$$MCI_P^* = 1 - LFI \cdot F(X) \tag{9}$$

being $F(X)$ a function F of the utility X of the product defined as:

$$F(X) = \frac{0.9}{X} \tag{10}$$

Eq.(10) has been defined in such a way that MCI_P^* takes, by convention, the value 0.1 for a fully linear product (i.e., $LFI = 1$) whose utility equals the industry average (i.e., $X = 1$).

However, the *MCI* defined by Eq.(8) cannot be used to compare two products which follow a very linear path (low circularity), because in this case they might have both a $MCI = 0$. This is a first remarkable difference with the indicators based on Emergy, presented above. They can in fact be used to compare directly two products.

It is important to highlight that the *MCI* defined above is based purely on a material balance, while the Emergy-based indicators assess sustainability broadly, being based on a (bio)exergy balance, which of course depends also on the quantity of the recovered material.

In order to also take into account the material losses that occur throughout the supply chain of the product, Ellen MacArthur Foundation & Granta (2015; Appendix B) developed a more complex indicator (MCI_P') developed, which is based on the mass of product discarded in each step ψ of the supply chain. This latter depends, in turn, on the recycling and reuse rates in the step ψ. The calculation of MCI_P' can be quite complex, not only because of the possibility that many pieces of data might be unavailable, as one goes backwards along the supply chain, but also because all the material losses have to be tracked for all the production steps. This tedious process is error-prone and ultimately makes it difficult to calculate the *MCI* for large supply chains.

Although EMA has been long applied only to small networks (notably trophic networks), it has then been extended to the metabolism of entire regions and countries' economies, even though based on a very simplified description of the systems at stake. Nonetheless, it is currently possible to apply EMA also on large systems (supply chains), availing from the implementation of automatic calculation procedures and the coupling with LCA type data structures (using the life cycle inventories – LCI – commonly used in LCA, with a much higher level of detail in the description of the studied systems) in the software tool SCALEM® (Marvuglia et al. 2013). Therefore, the calculation of the Emergy-based indicators presented above is now possible for the large supply chain in a much easier way than the MCI_P'.

Finally, as already mentioned above, it is worth highlighting another possible advantage of using Emergy-based circularity indicators, namely the possibility to compute them also for biological systems. This is particularly the case of those natural systems used in support of technological systems, in a combination that has been termed "techno-ecological synergy", as described in Bakshi et al. (2015). By its nature, Emergy is capable of accounting for the biogeosphere work necessary to make resources and natural systems (like ecosystems) working at their present level of organization available. For such reason, Emergy-based indicators, differently than the *MCI*, potentially lend themselves very well to evaluate the circularity of systems that include not just technological cycles, but also biological cycles.

3. The summary of pros and cons of Emergy-based indicators

While the *MCI* focuses on the operational life of a product (including its recycling cycles), EMA is able to account for natural inputs (e.g. sunlight, tidal energy, rainfall, and soil organic matter) which are used not only at the time of production of the studied product or service (e.g. biomass used in a biogas plant, or the sunlight necessary to produce the biomass), but also at the time of the formation of resources extracted and used in the product lifecycle (e.g. sunlight and deep earth heat for the formation of fossil fuel deposits; sunlight, soil organic matter and rainfall for old-growth forest wood, etc.). Furthermore, EMA can also assess the value of 'information' in the chain of processes that lead to the final good or service. Finally, EMA allows for a direct comparison of products that follow a linear path (i.e. with very little or no restorative paths), differently from the *MCI*. In contrast, the *MCI* allows for an absolute evaluation of the degree of system circularity with respect to the maximum circularity value 1 (which is attained when both the mass of virgin feedstock used in a product – V – and the amount of unrecoverable waste associated with the product – W – are equal to zero). The evaluation realized with the Emergy-based indicators instead provides a comparison of the Emergy investment needed to run the system in a restorative way versus the Emergy investment necessary to keep the system in a linear fashion. It is not a crisp value indicating how far the system is from its maximum (optimum) degree of circularity. This leads to the consideration that the two indicators should be considered as complementary, highlighting one more time that they take two different perspectives: MCI is focused on the material flows, therefore is still a human-centered metric, while the Emergy-based indicators are nature-centric metrics.

Apart from the positive elements highlighted above, EMA also carries some intrinsic pitfalls. First, the rationale followed to include resource formation processes and information generation and propagation is often difficult to explain and defend and is subject to different interpretations (Raugei et al. 2014). Consequently, while the results of the assessments made using indicators based on material balances are easier to communicate, it is certainly more difficult to communicate the results of an EMA. Second, uncertainty communication along with the calculation of UEVs is not yet common practice in EMA, although more than one order of magnitude of uncertainty is a plausible error range for UEVs (Ingwersen 2010). While the incorporation of uncertainty is common in LCA and is necessary to make comparative analyses that are disclosed to the public, this is currently not the case for EMA and only very few studies have so far addressed uncertainty in Emergy accounting (Ingwersen 2011; Li et al. 2011; Reza et al. 2013; Hudson and Tilley 2014; Yi and Braham 2015).

In this respect, it is important to notice that Emergy, unlike energy or exergy, is not an intrinsic property of the resources. It is rather a memory of the biogeosphere work done to make those resources available, and, per se, cannot be made available to the end user. Moreover, exergy describes the amount of available energy in substances, which is different from the amount of energy involved directly and indirectly in their creation in nature (Ingwersen 2011). This distinction is very important especially when dealing with non-renewable resources such as fossil fuels, for which the sequence of natural processes responsible for their formation and concentration is so long that the Emergy of a given amount of fuel can be orders of magnitude higher than the exergy actually contained in it (Brown et al. 2011). The same holds, even to a further extent, for minerals and metal ores (Cohen et al. 2007).

As a last note, we highlight that despite their conceptual simplicity, the calculation of Emergy-based indicators is not easy in large (industrial) systems, because Emergy accounting for technosphere systems remains difficult to perform, due to the complexity of the application of the Emergy algebra rules to large systems. Although research has advanced in this respect (Marvuglia et al. 2013; Le Corre and Truffet 2015; Nimmanterdwong et al. 2018), a systematic application of Emergy accounting for industrial systems (even linear ones, as opposed to circular) is not yet common practice.

Conclusions

This paper introduced the concept of Emergy Accounting and provided a literature overview of the use of Emergy for the calculation of indices that can serve to assess the environmental sustainability of production systems, in particular when the focus is on increasing their level of circularity. Our analysis especially lingers on the comparison of the approach hinging upon the Emergy-based circularity indicators and the approach consisting of material balances, which is the basis for the calculation of the *MCI* defined in the “Circularity Indicators Project” launched by the Ellen MacArthur Foundation (MacArthur Foundation & Granta Design 2015).

The advantages of using an Emergy-based approach lie mainly in the potential to account not only for the resources used at the time of the production of the studied product or service, but also for the effort made by nature at the time of the formation of the resources (e.g. the formation of the fossil fuel deposits). For example, for the system showed in Fig. 2, the *MCI* would take into account only the balance between the amount of materials used (including the part which is recycled) in the system depicted inside the box, and the amount of materials which go to disposal (exiting from the lower part of the box). The ΔU_{circ} indicator would instead take into account the emergy that is used up by the system depicted inside the box, but comes from the inflows ($F_{i,j}$ and R) outside of the borders traced by the box. This therefore reflects a nature-oriented perspective, which is much more prominent than in any other approach. However, it goes at the expenses of the complex, and sometimes controversial, interpretation and communication of the results obtained with Emergy accounting.

As this paper discusses, the nature of the algebraic structure underpinning Emergy accounting is such that in principle Emergy-based indicators conceptually lend themselves well to the evaluation and monitoring of circular processes. However, their calculation is not easy in large (industrial) systems, due to the complexity of application of the Emergy algebra rules to models of large real systems. Precisely with the aim of allowing this calculation for large (human-dominated) systems, a few authors have recognized the potential of taking advantage of the coupling between EMA and LCA accounting structures (see Wang et al. 2015 and references therein), and have therefore worked in the last years to the application of computational algorithms (Marvuglia et al. 2011; Le Corre and Truffet 2015; Nimmanterdwong et al. 2018) and the development of software tools (Marvuglia et al. 2013) to perform EMA on systems described using an LCA -like structure (and therefore availing of data coming from quite detailed LCIs).

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Wskaźniki Emergy do pomiaru obiegu zamkniętego: obietnice i problemy

Streszczenie

W ciągłym dążeniu do zrównoważenia systemów społeczno-przemysłowych definicja użytecznych, wiarygodnych i informacyjnych, a jednocześnie prostych i przejrzystych wskaźników jest ważnym krokiem w ocenie obiegu zamkniętego ocenianych systemów. W kontekście gospodarki o obiegu zamkniętym, literatura naukowa zidentyfikowała już brak nadrzędnych wskaźników (społecznych, miejskich, zorientowanych na zapobieganie itd.), wskazując, że wskaźniki jednowymiarowe nie są w stanie uchwycić złożoności systemu, *close-loop*, funkcji sprzężenia zwrotnego gospodarki o obiegu zamkniętym. Pod tym względem rachunkowość *Emergy* jest jednym z podejść, które zostały zidentyfikowane jako posiadające potencjał do uwzględnienia zarówno zasoby, jak i produkty, co pozwala na ocenę systemu w perspektywie gospodarki o obiegu zamkniętym.

Ze względu na definicję *Emergy* i jej strukturę obliczeniową, wskaźniki oparte na *Emergy* bardzo dobrze nadają się do oceny i monitorowania procesów o zamkniętych pętlach. Dodatkowo *Emergy* ma unikalną cechę umożliwiającą ocenę systemów, które niekoniecznie są tylko systemami technosfery, ale także systemami technologicznymi, które biorą pod uwagę naturę (systemy techniczno-ekologiczne).

W niniejszym artykule przedstawiono propozycję zestawu wskaźników Emergy, które zostały zidentyfikowane jako odpowiednie do oceny systemów zamkniętych, i nakreślono inną perspektywę w porównaniu ze wskaźnikami zdefiniowanymi w zakresie obiegu zamkniętego przez Ellen MacArthur Foundation w Circulariity Indicators Project.

Słowa kluczowe: wskaźniki Emergy, gospodarka obiegu zamkniętego, promowanie gospodarki o obiegu zamkniętym