Dealing with Emergy Algebra in the Life Cycle Assessment Framework

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ABSTRACT

Life Cycle Inventory (LCI) represents one of the four steps of the Life Cycle Assessment (LCA) methodology, which is a standardized procedure (ISO 14040:2006) to estimate the environmental impacts generated by the production, use and delivery of goods and services and final waste disposal. The calculation of emergy using LCI databases is acknowledged to be of great advantage to improve the accuracy and transparency of the emergy results and their reliability for a broader policy makers and stakeholders’ community. The compatibility with the emergy algebra rules is not straightforward for complex process-based LCI models, which (differently than the emergy rationale) keep a logic of conservation and allocate resources among co-products. This aspect has so far limited a consistent calculation of emergy in an LCA framework. The aim of this position paper is to describe the challenges to overcome in order to implement emergy accounting in LCA and specifically to outline possible research paths related to the implementation of the emergy algebra into LCIs. The Ecoinvent database is taken as a reference system, since it represents one of the most advanced LCI databases in terms of data quality and models, with around 4,200 LCI unit processes (i.e. energy generation, materials and agri-food production, infrastructure and transportation). It is structured in a large and complex matrix system with thousands of connections and loops between products and processes. We argue that the implementation of the emergy method and calculation within Ecoinvent and other LCI databases could follow two different paths: 1) rigorously following the database structure, i.e. the network of processes used for the emergy calculation and implicitly assuming that the relation between the processes and products are those existent in the database, or 2) not entirely following the emergy rules (with formal and comprehensive justification), i.e. considering the database network as different from the processes network in the real world and consequently only partially implementing the emergy algebra, following several simplifying hypotheses. The benefits and drawbacks of the two approaches are investigated toward a formal definition of a consistent approach.

INTRODUCTION

Life-cycle thinking recognizes that all products’ life cycle stages (e.g. extracting and processing of raw materials, manufacturing, transportation and distribution, use/reuse, recycling and/or waste management) generate environmental impacts which need to be evaluated and then reduced (Guinée et al., 2011; Finnveden et al., 2009). This comprehensive perspective has been the basis for the development and standardization of the Life Cycle Assessment (LCA) methodology (ISO, 14040:2006). Nowadays, LCA is one of the most accepted and used tool for the environmental assessment of products and services (Curran, 2006; European Commission, 2010). During the last decade, LCA has become a core element in environmental policy or voluntary actions in the European Union, USA, Japan, Korea, Canada, Australia, and is increasingly used in booming economies like India and China (Guinée et al., 2011). Hundreds of scientific papers on LCA application and its methodological development demonstrate the worldwide interest for LCA, which come both from industry and the sustainability science community.
In recent years, complementarities between emergy evaluation (EME) and LCA were emphasized within the emergy community, encouraging researchers to provide contributions towards a novel integrated approach able to link the territory-oriented EME with the product-oriented LCA (Ness et al., 2007). The combination of EME with LCA has been suggested to be a tool for qualitative and quantitative evaluation of progress towards industrial symbiosis and sustainable production and consumption: while EME can provide information for maximizing resource use, LCA can provide information about emissions reduction and wastes re-use (Hau and Bakshi, 2004; Ulgiati et al., 2006; Ness et al., 2007). However, a complete integration of the two methods has been hampered so far by a number of methodological constraints, such as different system boundaries and allocation criteria (Rugani et al., 2011; Ingwersen, 2011; Rugani and Benetto, 2012). In particular, emergy owns a special set of algebraic rules that make difficult its comprehensive implementation using Life Cycle Inventory (LCI) databases such as Ecoinvent (Ecoinvent database, 2010). Such a new way to proceed to emergy accounting is acknowledged as having the potential to greatly improve the accuracy and completeness of the whole emergy calculation (Rugani et al. 2011; Ingwersen 2011; Brown et al. 2012). While LCA keeps a logic of conservation (by allocating the environmental interventions and the impact results at the level of component/process), EME originates from a notion of memorization, which does not allow a quantitative balance of flows. As a result, EME calculation rules are based on a completely different rationale than those used in LCA. However, a consistent quantification of emergy using LCI models should not disregard the specific algebraic rules that distinguish EME from other energy-based analyses (Brown and Herendeen, 1996).

The present article represents a position paper within the recently discussed topic (cfr. last 5th and 6th Emergy conferences) of advancing the combination between EME and LCA. Accordingly, this paper aims to tackle the current state of progress and outline possible research paths related to the implementation of emergy algebra in LCA. Before investigating the challenges of this implementation, it is helpful to remind the characteristics of the emergy algebra as described by the four following rules:

1) all source emergy to a process is assigned to the process output;
2) co-products from a multi-output process have the total emergy assigned to each pathway;
3) when a pathway splits, the emergy is divided among each ‘leg’ of the split based on its percentage of the total energy flow on the pathway;
4) emergy cannot be counted twice within a system: (a) emergy in feedbacks cannot be double counted, and (b) co-products, when reunited, cannot be added to equal a sum greater than the emergy source from which they were derived.

For the sake of clarity, co-products are “product items showing different physico-chemical characteristics, but which can only be produced jointly” (Sciubba and Ulgiati, 2005). They have the same emergy (and different transformity or Unit Emergy Value - UEV) since each of them cannot be produced without investing the whole emergy amount. On the other hand, splits are “originating flows showing the same physical-chemical characteristics” (Sciubba and Ulgiati, 2005). Therefore, emergy of split products will be different, proportionally assigned on the basis of their quantity, while their transformity is the same. In handling splits and co-products, a problem may arise when the sum of the emergy of all the co-products exceeds the emergy input. This issue is dealt with by the fourth of the algebraic rules listed above, which forbids double counting of surplus emergy embodied in co-products and feedbacks. The problem of flows allocation in EME is strictly related to the quality (i.e. nature) of outputs. When the quality of two outputs is the same (e.g. tap water that can be used both for drinking and for washing floors), EME copes with a case of split, while co-products represent flows of different quality (e.g. wheat-grains and wheat-straw from single wheat plant).

In this paper, the Ecoinvent database is considered as a possible supporting repository of consistent data for calculating emergy. Accordingly, UEVs of resources collected from the emergy literature should be associated to the corresponding resource flows listed in the database in order to calculate the final emergy of the product in a life cycle perspective, as suggested in (Rugani and Benetto 2012). Despite this operation might seem straightforward, the differences existing between
energy and LCA for allocation criteria and other issues (e.g. differences in dealing with the time and spatial scales of the process network, as highlighted in the rest of the paper) make that calculation quite complicated (Rugani and Benetto 2012).

The rest of the paper is organized as follows. A general description of the Ecoinvent system is firstly given. A short review of existing cases of life-cycle networks is performed to illustrate the range of possibilities for implementing the emergy calculation. Finally, the examples provided are investigated more in detail and insights are presented in the results and discussion section.

THE ECOINVENT DATABASE

Ecoinvent, which is the biggest and one of most used LCI databases worldwide, includes about 4,200 unit processes1 (products) in its latest version 2.2 (Ecoinvent, 2010). About 230 multi-output (MO) processes also exist but they are transformed into further (about) 500 unit processes before being recorded in LCA software structures such as SimaPro (PRé Consultants, 2012). This operation is performed in order to obtain a square matrix system, i.e. ≈4,200×4,200, thus allowing the matrix inversion. This is the basis for LCI calculations with Ecoinvent, which follows the matrix method for the solution of the inventory problem (Heijungs and Suh, 2002). Those derived unit processes include amounts of resources and emissions that are allocated to the functional unit according to the recommendations for allocation of the individual data providers, which can be based on mass, energy, exergy, or price values. In this respect, about 290 elementary flows of natural resources are included in the database as ‘environmental interventions’ for further resource assessments (pollutant emission flows are not of interest for emergy calculation purposes in this context (Rugani and Benetto 2012)).

In Ecoinvent, there is clearly only one average process/product which is representative of the several possible products of the same economic category/sector/type. In certain cases more than one product of the same (average) kind exist, such as the electricity mixes, which are differentiated by the plant location/country of origin, technological variants, and potentially raw materials. Moreover, in Ecoinvent neither time scale nor space location of resources extraction is taken into account, although developments of the database are progressing toward improving the support of regionalized inventories and impact assessment (Weidema et al., 2011). At present, if the user wishes to accomplish the LCA of a certain amount of a commodity used as the functional unit, the underlying assumption in Ecoinvent is that there are no constraints of any kind in the supply of that commodity, but an “average supplier” (average in space and time) will always be able to meet the demand of the commodity the user is asking for. Ecoinvent is thus a “model” of the reality and, as every model, it cannot exactly reproduce the reality. In this context this means that the network of interconnected processes visualized by an LCA software (such as SimaPro) linked to Ecoinvent, represents the outcome of the matrix calculation and not necessarily the real network established between the different plants. The system remains in steady state over a given time span (i.e. life span) and no commodities stocks are considered.

LIFE-CYCLE NETWORKS: REVIEW OF EXISTING CASES

In the following section a series of different cases (A1-A4) are illustrated that may arise when using Ecoinvent as a supporting framework for emergy calculations:

(A1) Ecoinvent is a process-based LCI model and database for which there are no foreground and background data, and the linkages between processes in the matrix represent material or energy flows.

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1 A unit process is the smallest portion of a product system for which data are collected when performing an LCA. A unit process may provide several products, i.e. co-products (e.g. grain and straw), that can be used as inputs for other processes.
2 In LCA, the foreground system is defined as those processes of the system that are specific to it (“specificity perspective”). The foreground system is also defined as those processes that can be managed by direct control or decisive influence from the point of view of the decision-context of a study (“management perspective”) (European Commission, 2010).
3 The background system is then represented by those processes where, due to the averaging effect across the suppliers, a homogenous market with average (or equivalent, generic data) can be assumed to appropriately represent the respective process. It comprises those processes that are operated as part of the system, but that are not under direct control or decisive influence of the producer of the good (or operator of the service, or user of the good) (European Commission, 2010).
Figure 1. Schematic representation of the network of processes in Ecoinvent for the case (A1). In black: selected process; in white: rest of the database processes and their linkages. The circles represent sources of resource.

Figure 2. Schematic exemplification of the LCI network for the case (A2): a water treatment plant is described with technological details (i.e. foreground information). The product is tap water. The plant produces wastes (from sludge treatment). The waste may have different disposal or treatment ways. The LCA must consider the waste state and further processing.

Each foreground LCI process (i.e. ‘gate to gate’) can be converted in a background process if used as an input by other foreground processes (i.e. ‘cradle to gate’). Therefore, all the processes are on the same level in Ecoinvent. Highlighted in black in the Figure 1 is a schematic representation of a selected process (data for gate to gate) for which the LCA (cradle to gate + gate to gate) should be calculated. As a remark on this case A1, it must be pointed out that the cradle to gate + gate to gate span is in agreement with the systems boundaries of the EME (i.e. the energy method considers the resources used directly and indirectly to produce something). Theoretically, the Ecoinvent database as such is sufficient for the energy calculation scope (the related drawbacks are discussed later). Consequently to the Ecoinvent properties described above, the UEV calculated on the Ecoinvent inventory matrix will be necessarily an average value representative of a mean product (probably the EU geographical area or, in general, the widest location comprising similar processes is the best choice because it is a more consistent mean among slightly different products of the same kind).

(A2) In the case of a detailed process description, e.g. a water treatment plant with its operational phases, an internal network describing the processes occurring within the plant is included. Site-
specific information regarding these processes can be used to build the foreground LCI dataset, which includes mass and energy flows and their connections (i.e. loops, splits, co-products). Then, the plant is linked to the background system (see Figure 2).

(A3) The last case that can involve Ecoinvent is represented by a network of unit processes created in the foreground system, e.g. a trophic network of processes within a territory. This is a very rare case of application, e.g. in industrial ecology and metabolism or in applications dedicated to a sectorial LCA at meso/macro scale (e.g. LCA of biofuels development at regional/national scale). Here, all the network’s structural elements are encountered: loops, splits, co-products, and their joint combinations.

(A4) Since process-based LCI databases cannot be holistic, hybrid LCI models (hereafter HLCI) have been recently developed to combine both the advantages of process-LCI (high resolution of the core processes in the foreground) and Input-Output LCA (IO-LCA) (ability to encompass the whole economic system in the background) (Crawford, 2008; Finnveden et al., 2009). In HLCI, most of the flows and loops that link processes in the foreground system are a simplification of the reality. The use of matrix models, which run through the solution of systems of linear equations, assumes that processes run at steady-state conditions. The background system is represented by global-average IO data. Flows are not physical, but of economic type. They show the interdependence between economic sectors. In this case, another type of flows and loops is faced, which stresses the fact that no industry can sustain its activity without permanent exchange with the others. As a result, loops observed in HLCI models are: i) a simplification of the reality at the process level, i.e. the foreground system defined as in (A1) or (A2), and ii) ‘real’ loops in the background (see Figure 3).

![Figure 3. A simplified representation of hybrid process-IO LCI (at different levels). Depending from the connections in the background (level 'n'), the evaluation of emergy along with the different levels would consequently change.](image)

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Footnotes:

1. Actually, it is rarely the same matter that flows from process $i$ to process $j$ and then back from process $j$ to process $i$, but they are two different flows in time and space. However, LCI is a static representation of processes interconnections: real flows of materials are aggregated into flows of materials of one kind.

2. Sometimes IO tables are represented in mass units (i.e. Physical Input-Output Tables, PIOT) but it does not change the issue: only the interdependence pattern is weighted differently. This depends on which representation describes better the nature of the technosphere at macro level: should it be better represented by material or economic flows remains an open question.

3. Some constraints and assumptions for HLCI models exist: i) there is no matrix algebra without linear equations; ii) there is interpolation because each value in the IO matrix is based on a sector-wide average and then used for a much smaller portion, therefore assuming the sector is homogenous; iii) the modeling of processes is linear because processes are assumed at steady-state over a significant period (a year), which enables to consider that a slight variation is of first order, i.e. linear (for further details see e.g. Lenzen and Treloar, 2003; Tukker et al., 2006; Crawford, 2008).
TWO DIFFERENT APPROACHES

When dealing with emergy calculation using life-cycle networks, two possible options arise: 1) an implementation of the emergy logic in a rigorous way (approach 1); 2) a theoretical investigation of the database structure that can justify a possible simplification of the emergy rules (approach 2). The two options are discussed below according to the aforementioned cases of life-cycle networks.

Approach 1: Complete Implementation of the Emergy Algebra

The approach 1 requires accounting for emergy by considering its algebra rules in their conventional formulation (see the Introduction section). It is essentially applicable when analysing life-cycle networks of the cases (A1) and (A2) and, to a certain extent, also (A3). The main challenge could be resumed in the application of the algebra rule n.4, which is constrained by two major tasks: 1) LCI allocation of resources must be avoided since it is in contrast with algebra rule n.2; i.e. all the MO processes must be included without allocation (Rugani et al., 2011); 2) specific rules for co-products, splits and feedback allocation at each node of the network; this means that rule n.4 must be applied at each internal node of the network depending on the surrounding nodes and links.

Such a procedure is feasible when carried out manually for very simple systems, as shown in (Li et al., 2010) for a 11x11 matrix. In the paper by Li et al. (2010), the authors first classified configurations of networks energy flows into seven types based on commonly occurring combinations of feedback, splits, and co-products. Afterwards, they applied a method of structuring the network equations for each type (called “preconditioning”) using the rules of Emergy algebra, prior to calculating transformities. After preconditioning the authors applied the matrix model to a case study, whose results were compared with those obtained for the same case study tackled with the track summing method (Tennenbaum 1988) and the minimum eigenvalue model (Collins and Odum, 2000). Besides the fact that the preconditioning of the system’s matrix could turn out into a very challenging task, in practical case studies, where large networks of thousands of processes are studied, the application of the solution method itself is unfeasible. For this reason, so far an automatic implementation of emergy algebra was impossible for very large (realistic) systems (Rugani et al., 2011; Li et al., 2010; Rugani and Benetto 2012), such as the technosphere matrix contained in the Ecoinvent database.

However, these implementation problems have been overcome and are described here with the approach 1. An example of case study (a simplified ‘flat glass’ production, modelled in a 7x7 matrix) has been already provided by some of the authors of this paper to demonstrate the consistency of a new operational framework for approach 1 (Benetto et al., 2011; Marvuglia et al., 2011), and its application to larger (involving >1,000x1,000 matrices) Ecoinvent-based LCI networks tested and proved to be feasible (Marvuglia et al., submitted). The problem was formalized in a matrix-based structure, which comes directly from the LCA framework (Marvuglia et al., 2011; Heijungs and Suh, 2002)7 and a variant of the track summing algorithm (Tennenbaum, 1988) was developed. The whole network representing the studied system (where each process represents a node of the system and the nodes are interconnected through the energy and mass flows they exchange) is explored as a graph, where the different nodes are visited following the Depth-First search strategy (Russel and Norvig, 2009), which was implemented in C++. In Depth-first search (DFS) the search starts at the root8 and explores as far

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7 An exact solution of the system can be obtained only if the matrix A is non-singular (which imposes it to be square) (Marvuglia et al., 2011; Heijungs and Suh, 2002). Since the rows of this matrix represent the commodities’ flows and its columns represent the processes producing those commodities, only unit processes with one valuable output of product (e.g. 1 kWh of electricity, 1 kg of steel) can be used, otherwise the matrix would not be square. In this regard, specific allocation factors are defined for the multi-output processes before they are entered in the matrix that will be inverted. The same allocation factors are used to allocate the corresponding environmental interventions (Heijungs and Suh, 2002). Refer to Rugani et al. (this volume) for further details.

8 The algorithm is launched as many times as there are Emergy sources and each time the node representing the Emergy source taken into account represents the root.
as possible along each branch before backtracking, i.e. before going back to the last explored node from which it was possible to visit a new branch of the tree.

This framework entails two major tasks as pointed out before. The first task is to reshape the allocation criteria used in Ecoinvent in order to deal with the emergy rule n.2. In this case, the full amount of environmental interventions (i.e. resources) must be assigned to all the co-products of the database originating from the multi-output processes. As a result, we can obtain a modified square matrix A, to be (re)imported in SimaPro (i.e. LCA software) and used as new background database for the LCI being developed by the user. Once the user has set up the product-LCI at the foreground, the related matrices A and B can be exported from SimaPro. The second task foresees the calculation of the UEV of the functional unit defined by the user. Firstly, matrices A and B must be manipulated in order to obtain their scaled (to the functional unit) versions. Then, UEVs of resource collected from the emergy literature (Rugani et al., 2011) can be applied in B to convert the scaled amount of their corresponding resources in sources of emergy. The novel algorithm based on graph search applied in (Marvuglia et al., submitted) can be finally applied to the scaled A and B matrices (Marvuglia et al., 2011). The algorithm tracks emergy values for each emergy independent source, spinning off new paths as they are encountered and maintaining the set of previously visited elements to prevent cycles, and sums up the results independently (Marvuglia et al., 2011). This ensures the exact calculation of the final product UEV following the emergy algebra rule n.4. For the simplified case of ‘glass flat production’, the emergy value obtained practically coincided with that derived using EmSim9 (Marvuglia et al., 2011). For cases involving very large matrices, some variant of the algorithm were designed to improve the running time. The final version of this algorithm allows the achievement of a reproducible, consistent, and transparent calculation of emergy values for thousands of products in the Ecoinvent database (Marvuglia et al., 2011).

Despite these innovative findings, an implicit drawback of approach 1 is that the calculation of the UEVs is limited to the scale of a product. Indeed, Ecoinvent is a very large, comprehensive and representative system, but it is static. This means that it can support an accurate calculation of emergy considering the complete supply chain and, at the same time, it can suffer from truncation of the system boundaries. It normally includes average production processes, which only refer to the functional unit or process output, and neglects the effect of marginal changes in the market out of the LCI system boundaries. So far, the structure of Ecoinvent does not support the description of the territorial dynamics of commodities’ trade. In contrast, the territorial scale is probably the most relevant case for applying the principles of EME and of the energy systems theory.

**Approach 2: Partial Implementation of the Emergy Algebra**

This approach attempts to partially violate the rules of emergy algebra. Accordingly, the emergy rules should be partially applied in order to cover the requirements of all kinds of life-cycle network models, in particular with regard to the case A4. If the Ecoinvent database network is compared to the real world (i.e. giving a local connotation to each process), it is inherently clear that a strong simplification exists on the links between different processes, product splits, co-products, etc. In the real world, products are manufactured and distributed in different parts and with different patterns around the globe, and even in different time periods. Moreover, two or more flows that converge in a node of the system’s network and would actually be co-products (which re-unite and give rise to a loop) if originally delivered by the same plant at the same moment, are most probably not co-products since in the reality they have been produced in two different sites or in the same site, but in different periods. A manipulation of the emergy rules should occur only partially on the allocation issue in the co-production processes (rule n.2) and more consistently on the accounting system for feedback loops and co-products that re-unite (rule n.4). Of course, the real process network is generally unknown or hard to

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9 The software EmSim (Valyi and Ortega, 2004), a free-share emergy simulator that can work with life-cycle systems using a graph instead of a matrix, was only used to validate our results. Indeed, EmSim does not allow for a direct link to automatic calculation routines, since it requires the system’s diagram to be drawn by the operator.
be modelled in particular with regard to the background processes. Therefore, it is impossible to consider the real network, but rather it is feasible to propose several hypotheses having a general validity.

A preliminary consideration must be formulated regarding rule n.2, since it is inherently clear that the energy calculation should not disregard its unique nature of holistic accounting for the complete available energy necessary to produce simultaneous products. Let process A and process B be two MO processes that produce the same co-products, i.e. \( p1(A) = p1(B) \) and \( p2(A) = p2(B) \) from a chemical and physical point of view, but in different industrial sites, e.g. A is in Europe and B is in the US (Figure 4). Let energy source in A and B be equal to 950 and 1000 seJ, respectively. Let process C be our investigated production system, which needs, at its LCI foreground level, the two inputs \( p1 \) and \( p2 \). Despite Ecoinvent would generally model the demand of \( p1 \) and \( p2 \) in C as coming from the same MO process, it might happen in the reality (e.g. for economic reasons) that process C selects \( p1 \) from process A and \( p2 \) from process B, leaving \( p2(A) \) and \( p1(B) \) out of the system boundaries (Figure 4). However, even if one manually adopts this ‘real’ condition, by using the original Ecoinvent procedure the resources’ balance is always kept to 100%, because of the ‘Ecoinvent’ nature of splitting resources upstream in the MO processes. In contrast, if one applies the energy rule n.2, the full burden (100%) of resources’ allocation should be assigned both to \( p1(A) \) and \( p2(A) \) and to \( p1(B) \) and \( p2(B) \). Since A and B are the same technological processes, in the usual model of energy calculation the input \( p1(A) \) should not be counted for the rule n.4b (because 950<1000), and energy of C is equal to max \( p1(A), p2(B) \) = max (950, 1000) = 1000 seJ. However, in the reality the energy of C is equal to \( [p1(A) + p2(B)] = 950 + 1000 = 1950 \) seJ: the inputs should be all summed up since the two sources of energy are simply independent, coming from different locations and likely different times. If this assumption is valid, the entire Ecoinvent database of MO processes should be modified according to the energy algebra rule n.2 (as discussed in the previous section) and the rule n.4b should eventually not be considered. As a result, all the co-products included in the LCI of an investigated product should be summed up, leading to a final value of energy that is much higher than expected.

As pointed out before, Ecoinvent uses average (in space and time) data of commodity flows, like if for each commodity there was always an average producer able to supply it at any time. This is in contrast with the reality, where products (that reunite downstream in the network) apparently originating from co-production processes (e.g. electricity and heat) have been actually produced in different locations or in the same plant but not at the same time. It is only because of the static representation of Ecoinvent that one can look at them as co-products that reunite and give rise to a loop, since Ecoinvent is not able to seize this difference in space and time. Even though this may hold true for most of the processes contained in the database, there might well be very few cases in which this is false. Let us consider the case of two metal ores which are always extracted together and only in one (or very few) mines of the planet. In this case, however, is the node of the system where these metals reunite, the probability that they come from the same mine and have been extracted at the same time (i.e. assumed the same ‘yearly’ time as consistent proxy in this case) is very high. Accordingly, the assumption that we can avoid considering them as co-products that reunite is no more valid and this case has to be dealt with applying the traditional emergy algebra rules.

The problem of co-products that re-unite in a complex network can be avoided from a conceptual point of view through a system expansion of the background processes: as long as someone else, somewhere else, is using one of the other co-produced flows in some other way (which is a realistic, rather than modelling perspective), we can assume valid the Ecoinvent allocation procedure as a first approximation, thus avoiding the double counting of the total emergy assigned to each co-product (rule n.4b). At least, allocation factors might be changed at a level of individual specific multi-output processes when we know exactly the real path of the two co-products (e.g. same mining sites for two metals all over the world). In this case, a hybrid algorithm should be implemented and used to account for the energy algebra rule n.4b both in the background and in the foreground systems for those peculiar cases. This is particularly true for the cases A2-A3 described above.
Figure 4. Simplified example of emergy calculation in ‘real economy’ conditions. The co-products from A and B have the same physical and chemical characteristics: p1(A)=p1(B); p2(A)=p2(B).

Figure 5. Simplified diagram of product from recycled material (source: Amponsah et al., 2011).

Another case that would imply a careful consideration of the spatial and timing differences when dealing with the emergy algebra is the ‘recycling treatment’. It has been already investigated how, because of its basis in a memorization logic, the quantification of loops in EME has been handled differently than in LCA. As pointed out before, when a product is reused within a system, its emergy is conserved, except in the static case where the emergy that made up that product came from the same source as the emergy driving the system. In this case, that emergy from the same source is “dropped” to avoid double counting. While in a simplified static example it is clear that this emergy that is not independent in origin is dropped to avoid double counting, when a more realistic dynamic case is considered (where time is a variable), the emergy recycling back is not the same emergy as the emergy coming in from virgin material, because the recycled material is the sum of energies captured during a different space and time position than the incoming virgin material. The emergy of a recycled product can be illustrated with the diagram in Figure 5 and the equation (1).

\[ \text{EME}_p = A + B + C \]  

where \( \text{EME}_p \) = emergy of the product, \( A = \text{emergy of the virgin material input} \) (1 – the fraction of recycled material, \( B = \text{the emergy involved in collection and transformation of the recycled fraction} \) (q) of material, and \( C = \text{the emergy of the previous product} \) (at time, t-1). Brown and Buranakarn (2003) illustrate that, as a consequence of this algebra, a product made from recycled material will have a greater specific emergy than a product made from virgin material. However, this fact seems to disagree with the rule n.4a of loops when the observation period of the system is less than the loop specific time (i.e. turnover time). Amponsah et al. (2011) further illustrate this concept and examine the consequences of recycling emergy in the case of a material being recycled multiple times. They find that emergy continues to accumulate in a product as the number of recycling steps increases until ultimately reaching an asymptote. In contrast, the handling of recycling in LCA is based on a
conservation logic, where the environmental characterization of a flow is lost (not conserved) after a single use in the technosphere. According to this logic, in the diagram above the sum of any environmental impact, EI, would be estimated only as

\[ \text{EI}_p = A + B \]  \hspace{1cm} (2)

where A would be the upstream environmental impact of the virgin material and B would be the environmental impact of the collection and transformation processes. It must be noted, however, that the case of Amp onsah et al. is special because related to the recycling in metallurgy, where recycling is performed \( n \) times with cadenced sequences use+recycling. But when a system is considered in a continuous stationary functioning (flow), there is no more notion of \( n \) recyclings, since matter flows continuously. In this case, the conservation laws take the space and time characteristics into account.

A tradeoff solution to the traditional emergy approach have been proposed by Ulgiati et al. (2004), whereby the emergy of a recycled product is calculated without including the emergy in the recycled material. This proposal for calculation of recycled material in emergy follows the logic of conservation and is equivalent to the LCA-like handling of recycled flows. Accordingly, it might be an alternative justifiable assumption to avoid the problem of not accounting for splits that make feedback in the network (rule n.4a).

In general, a loop in Ecoinvent indicates that a given product is used upstream in the network, so it is partially consumed for its own production. This is the case for the largest part of the products in the technosphere in the aggregated model of an LCI database such as Ecoinvent. But the database network structure does not represent the real world as discussed above. In the reality, identical products can be generated by different plants separated in space and time, even in different networks. A given product can be re-used in other networks to generate a similar product. Their upstream re-use can also occur in a different network, and in this case there is no real loop to be considered. The simplest example is the re-use of wheat seeds produced by the farm 1 in the farm 2 for producing the same kind of wheat. In Ecoinvent, this situation is represented by a loop (i.e. only one farm, where production is split between the re-usable seeds and the consumed seeds) while in the reality the system is much more expanded and without loops (i.e. two farms in series). This case is quite complicated to be implemented in LCA because of the lack of knowledge of the real network structure. Not considering aggregated loops as they are defined in Ecoinvent means multiplying processes, i.e. considering individual plants for all products involved in a given study. To our knowledge, such a system expansion is not feasible because of the complexity and insufficient understanding of the real network size and composition to be numerically handled with an IT tool.

The approaches 1 and 2 can be both adopted for the cases A1-A3. The difference between these cases lies in the fact that the foreground processes and links can be defined in A2 and A3 as they occur in the reality (by a descriptive flow sheet). Nevertheless, the background processes and associated network conserve their virtual character. By following the approach 2, the user must be aware that the use of emergy algebra is limited only to the real cases. It means that the emergy algebra can be adapted to the life cycle models without forgetting their principles of memorization, but adapting the rules to make the calculation of emergy easier in complex and not static networks such as in the cases (A3) and (A4).

**CONCLUSIONS**

In this work we identified and discussed two approaches for the implementation of an emergy calculation within common LCA-based systems. The use of emergy algebra in complex life-cycle based networks of goods and services production, representing both average (in space and time) technological conditions (i.e. conventional life cycle inventory models) and economic conditions (i.e. hybrid input-output models) was carefully investigated. The possibility of adapting the rules of emergy algebra to these networks has been outlined, leading to the consideration that their rigorous implementation could be feasible but limited by the scarce knowledge and the ‘static’ character of those systems. However, the theoretical investigation of these database structures was performed here
which enabled us to justify a partial application of the emergy rules without eventually preventing the consistent assessment of emergy at the scale of an economy (approach 2).

On the other hand, some of the authors have recently experienced (Benetto et al., 2011; Marvuglia et al., 2011) the possibility to account for emergy through LCI databases using the emergy algebra in a rigorous manner (approach 1). As a result, an automatic quantification of UEVs for thousands of technological goods and services (all kinds of material, energy generation processes, infrastructures, transportation services, etc.) is now possible using a specific LCI database called Ecoinvent (Marvuglia et al., submitted). This is a very large dataset that also allows for a regionalized quantification of the UEVs for some categories of commodity such electricity generation or agricultural production. This means that, once the Ecoinvent database will be upgraded in the near future with further hundreds of regionalized production models, an extensive dataset of UEVs could be automatically obtained. Those UEVs, quantified according to the emergy algebra, might be used as source of emergy data in a standardized way. Moreover, these emergy results will be consistent and could be used with systems defined at similar levels of aggregation. As a note of caution we recommend those values not to be used at national or territorial emergy analysis level because of the different scales used to derive them.

ACKNOWLEDGMENTS

The authors thank Dr. Marco Raugei for the precious advices on the example of metal industry evaluation. Benedetto Rugani and Damien Arbault also thank the administration of the National Research Fund of Luxembourg (FNR), which supported this work (cofunded under the Marie Curie Actions of the European Commission: FP7-COFUND).

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