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Theory and Applications of the Emergy Methodology

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50

Criteria for Quality Assessment of Unit Emergy Values

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ABSTRACT

Different procedures for calculating the Unit Emergy Values (UEVs) and a large number of estimates of UEVs for energy, goods, services and information flows are now available in emergy-related books, papers, reports and PhD dissertations worldwide. A critical selection of these values and calculation procedures is a primary task for any solid emergy evaluation. The demand for a handbook of UEVs has continued to grow as more and more scientists around the world conduct emergy studies. Easily accessible, well-defined and meaningful UEVs and thorough supporting documentation could improve the entire process of conducting an emergy evaluation and ensure that a study uses the highest quality data. Analysts could complete their work more quickly and efficiently and have a higher level of confidence in their results. The use of inappropriate UEVs can lead to faulty indices and erroneous conclusions. The present work aims at identifying the main aspects that need to be taken into account for the calculation of UEVs as well as for the construction and use of a database of values and related diagrams and procedures.

INTRODUCTION

The number of practitioners of the Emergy Synthesis method (Odum, 1996) is growing worldwide (Brown and Ulgiati, 2004a; Dong et al., 2008; Brown et al., 2009) due to increased recognition of the potential offered by this methodology for the evaluation of natural capital, ecosystem services, and human made products and processes. Such a trend also translates into a large number of papers applying the emergy methodology to the evaluation of natural, agricultural and industrial processes, published in international journals. Referring only to the Elsevier "Science Direct" website (http://www.sciencedirect.com), the number of articles dealing with the emergy methodology was 44 in 2005, 140 in 2006, 92 in 2007, 101 in 2008, 140 in 2009, 115 in 2010, and finally 220 in the year 2011. Besides that, in the most recent years several emergy based papers were presented in international workshops and conferences related to resource use and related environmental and economic issues, such as the International Biennial Workshop "Advances in Energy Studies" (http://www.societalmetabolism.org/aes2010.html), the annual ECOS Conferences (International Conference on Efficiency, Cost, Optimization, Simulation and Environment Impact of Energy Systems – http://www.ecos2010.ch) and, more specifically, the Biennial Emergy Research Conferences (http://www.emergysystems.org).

As with many other important approaches dealing with energy and/or matter flows (i.e., Embodied Energy Analysis, Slesser, 1974, Herendeen, 1998; Material Flow Accounting, Schmidt-Bleek, 1993, Hinterberger and Stiller, 1998; Exergy Analysis, Szargut et al., 1988), a proper application of the emergy method needs a large and reliable database of conversion factors so-called Emergy Intensities or Unit Emergy Values (UEVs), used to convert the input flows (energy, matter, money, labor and information) into flows of emergy driving a process. Lack of a suitable and constantly updated database undermines the evaluation process and weakens any calculated performance indicators. Efforts towards generating such a database have been led by worldwide researchers (Brown and Arding, 1991; Ortega, 1998; Abel, 2011; among others). The Center for Environmental Policy, University of Florida (http://www.emergysystems.org), has posted a series of Emergy Folios online since the year 2000, intended to become a Handbook of Emergy Evaluation procedures and related Emergy Intensities (UEVs). However, some of the published databases still suffer from major inconsistencies or lack of agreed upon criteria about the way UEVs were calculated, which makes it difficult to refer to them as a suitable basis for future studies.

High quality UEVs (transformities, specific emergies, emergy/GDP ratios, emergy/area, etc) are crucial for the reliability of emergy analyses and results. Such emergy values - as explained more clearly in the following pages - express the unit environmental cost of the direct and indirect support provided by the biosphere to the production of a given product or service. They depend on (a) the direct biosphere contribution, and (b) the human intervention for extraction of resources and manufacturing. It is therefore of paramount importance to make sure that the two components (a) and (b) of an UEV are correctly calculated. The first component (a) requires that the biosphere work is calculated over long time scales and large spatial scales, which entails a non-negligible uncertainty on all calculation steps and assumptions. The total flow of emergy resources driving the biosphere is referred to as the "global baseline" and has undergone several recalculation efforts (Odum, 1996; Odum, 2000, Campbell, 2000; Campbell et al, 2005; Brown and Ulgiati, 2010). The second component (b) depends on the previous one as a starting point but also includes the specific aspects of the investigated process. As a consequence, the component (b) is time-, technology-, location- and society-specific, which leads to values that may change over time which requires a continuous updating effort.

Thus, two basic aspects about emergy methodology should be clarified in order to reduce future mistakes and strengthen the approach: (a) standardize the global baseline calculation procedure; (b) standardize the procedure for the calculation and use of the UEVs. The aim of this paper is to establish an acceptable criterion for the quality assessment of UEVs and their applicability to other studies in different processes and situations.

EMERGY INTENSITY VALUES AND THEIR MEANING

All environmental accounting methods developed up-to-date (LCA, Material Flow Accounting, Ecological Footprint, Embodied Energy, among others) face non-negligible data gaps, mainly related to the unavailability of suitable inventory data at local and global scales, as well as reliable intensity factors that can link the inventory to measures of the size or impact of input flows to, or output flows from, the process. The problem with such intensity factors, be they energy, matter, or emission intensities, is that they are unavoidably case-, location-, time-, or technology- specific and cannot by definition be considered stable over time. Moreover, they are most often affected by non-negligible uncertainties that are likely to affect the final results of an evaluation. The emergy synthesis approach faces similar problems with its Unit Emergy Values (also named emergy intensities by some authors: transformity, seJ/J; specific emergy, seJ/g; emergy-to-GDP ratio, seJ/currency; emergy-to-labor ratio, seJ/time; emergy/area, seJ/m^2; etc). These values are used to convert input flows into emergy values. The reliability of the results of an investigation heavily depends on the factors used for such a conversion. Furthermore, because emergy is a systems approach, the emergy unit values are constrained and affected by the specific state of the system and its links to the surrounding environment, so that it is impossible to compute a value that fits all the situations and can be used in a deterministic way as an optimum conversion factor independent on the specific case. Therefore, each value is strictly linked to the process for which it was calculated, so that a database of Unit Emergy Values (UEVs) is unavoidably a database of ranges and related systems (diagrams).

A biological or technological transformation is a process that converts one or more kinds of available energy into a different type of available energy, while dissipating much energy to unusable waste heat. All such transformations can be arranged in a series, and the position of an energy flow in the series is marked by its Emergy Intensity. The Emergy Intensity (also named Unit Emergy Value, or UEV) is the emergy driving a transformation divided by the available energy (or the mass, the economic value, the information content, or any other identifying numeraire) of the transformed product. The term “intensity” highlights the “convergence” of environmental support (emergy) to the unit of product or service, and is synonymous of “Unit Emergy Value”. In the emergy nomenclature these terms are equivalent, while other terms are used when focus is placed on specific typologies of flow.

In accordance to Brown and Ulgiati (2004b) there are at least six very important types of emergy intensities, as follows:

(a) **Transformity:** defined as the emergy input per unit of available energy (exergy) output expressed in solar equivalent joules per joule of output flow ($seJ*J^{-1}$). The transformities in the geobiosphere range from a value equal to one for solar radiation to trillion of solar emjoules for categories of shared information (Odum, 1988), and express three different features: (a) the demand for environmental support to a product; (b) the biosphere-scale efficiency of the production process; (c) an energy-scaling factor for items within the hierarchy of the planet. According to the second law of thermodynamics, all energy transformations are accompanied by energy degradation, which represents a measure of the work done in generating a smaller flow of higher-quality product. Solar radiation energy is the largest but most dispersed available energy input to the Earth: as a consequence, the solar transformity of sunlight was set equal to 1.0 $seJ*J^{-1}$ by definition (Odum, 1996).

(b) **Specific Emergy:** defined as the emergy per unit mass of output, and usually expressed as solar emergy per gram ($seJ*g^{-1}$). Solids may be evaluated best with data on emergy per unit mass of a given chemical species times its concentration. Since available energy is required to concentrate materials, the unit emergy value of any substance increases with concentration. Elements and compounds not abundant in nature therefore have higher emergy per mass ratios when found in concentrated form, since more environmental work was required to concentrate them, both spatially and chemically. More details, definitions and a database with several crustal elements can be found in Cohen et al. (2007).

(c) **Emergy per Unit Money:** defined as the emergy supporting the generation of one unit of economic product (expressed as currency of a given country or as international reference currency such as euro or dollar; $seJ*currency^{-1}$). It is used to convert money flows into emergy units. Since money is paid to people for their services (indirect labor to make a resource available to the system) and not to the environment, the contribution to a process represented by monetary payments translates into the emergy that can be purchased by that money. The amount of resources that money buys depends on the amount of emergy supporting the economy and the amount of money circulating. An average emergy per money ratio in solar emjoules per unit money can be calculated by dividing the total emergy use of a state or nation by its Gross Economic Product. It varies by country and generally decreases over time as a consequence of inflation accompanying a country’s economic development. The emergy per money ratio is useful for evaluating service inputs given in money units where an average wage rate is available.

(d) **Emergy per Unit Labor:** defined as the amount of emergy supporting one unit of labor directly supplied to a process. Laborers apply their work to the process, and in doing so they indirectly invest in their activity the support emergy that made their labor possible (food, technical training, education, transport, etc). Such an emergy intensity of labor is generally expressed as emergy per unit time ($seJ*year^{-1}$ or $seJ*h^{-1}$), but emergy per money earned ($seJ*currency^{-1}$) is also used. The indirect labor required to make and supply the input flows (goods, commodities, energy, etc) to a process is generally measured as dollar cost of services, so that its UEV is calculated as solar emjoules per currency.

(e) **Emergy Density (**ED): It measures the amount of emergy invested on one unit of land for a specific production process or development (in units of $seJ*m^{-2}$ of land). ED may suggest land to be a limiting factor for the process or, in other words, may suggest the need for a given amount of support land around the system, for it to be sustainable (Brown and Ulgiati, 2004b). Higher ED’s characterize city centers, information centers such as governmental buildings, universities and research institutions, power plants, industrial clusters, while lower ED’s are calculated for rural areas and natural environments (Odum et al., 1995; Huang et al., 2001). Renewable and nonrenewable emergy densities are also calculated separately by dividing the total renewable emergy by area and the total nonrenewable emergy by area, respectively.

(f) **Empower**: The Emergy per unit time is a measure of power, indicating the flow rate of a given resource (seJ*year^{-1}): the flow of global resources invested on, or captured by, a process per unit time affects the development rate of the process itself, from the large scale of biosphere to the smaller scale of economies, farms, individuals and bacteria.

The universe is hierarchically organized (Brown et al., 2004), with lower levels supporting higher levels, each of them characterized by increasing UEVs. An emergy intensity is therefore a measure of a system's hierarchical organization and is applicable to all kinds of matter, energy or information flows (Odum, 1996; Figure 1).

CORRECTIONS BASED ON AVAILABLE ENERGY (EXERGY)

The emergy definition implies that the actual flows to a process are accounted for as "available energy" flows (or exergy) (Odum, 1996, Table 1.1 at page 13). Most often, such definition was not implemented properly and generated UEVs that are not consistent with the basic principles of the method as well as with those values that were, instead, calculated on the basis of available energy flows (for example those for minerals calculated by Gilliland et al., 1978 and by Gilliland and Eastman, 1981). Inaccurate UEVs of basic flows also affect all the other flows that are calculated after them. Although the inaccuracy is not very large in most of the cases (also considering the uncertainty in estimates of global flows), the theoretical inconsistency of the practice with the basic definitions was pointed out by some Authors (Ulgiati, 2000; Bastianoni et al., 2007; Sciubba, 2009; among others). Bastianoni et al. (2007) suggested an exergy correction factor in order to account for the differences arising when flows are expressed by means of an energy or exergy numeraire.

Petela (1964) demonstrated a relation between the energy E_s and the exergy Ex_s of solar radiation:

$$Ex_s = 0.9327 * E_s \qquad \text{Eqn. (1)}$$

This means that accounting for the solar radiation in energy terms instead of exergy overestimates such a flow by about 6%. Sciubba (2009) noted that "because of the Emergy hierarchical arrangement of energy flows, this 6.6% difference propagates downstream, affecting the absolute values of all emergy content of material and immaterial goods in a measure that depends on the structure of the production process". Moreover, after pointing out that exergy values of Earth's flows were independently calculated by Kabelac (2005), Szargut et al. (1988), Chen (2005) and Hermann (2006), Sciubba (2009) estimated that using energy instead of exergy as a numeraire to quantify the tidal potential and the deep heat as in emergy Folio 2 (Odum, 2000) overestimates the actual incoming work potential by about 28%.

As a consequence, using a numeraire that can be applied to all kinds of inflow is important and should not be further disregarded. An input of organic matter may carry very different work potential depending on the percentage of water content and its actual chemical composition: while mass, even if dry matter, does not properly account for such differences, chemical exergy does. Furthermore, an input of water to a process carries more or less work potential depending on its temperature; and finally, expressing mass as grams and energy as joules does not allow any comparison between the calculated UEVs of mass and energy flows. For such a reason, mass and energy numeraires should be replaced, for the purpose of calculating UEVs, by the exergy numeraire and all UEVs recalculated accordingly. This is not only because of the need for more accurate values, but is mainly aimed at re-establish the consistency with the basic principles as well as among the different UEVs in our databases. In general, values of energy and available energy (exergy) differ when it deals with heat flows, where temperature plays a non-negligible role, while show very small or negligible differences when dealing with flows of mechanical, chemical and electric energy.

BIOSPHERE EMERGY BASELINES

Odum's attention was increasingly focused on the development of a theory of energy quality and its quantitative definition (Odum, 1977a). In the latter half of the 1970s, Odum introduced a fossil fuel work equivalents (FFWE), the quality of energy based on a fossil fuel standard with rough equivalents of 1 kcal of fossil fuel equal to 2000 kcal of sunlight. The ratios used to convert all energy forms to FFWE were called "Energy quality ratios". Later termed coal equivalent (CE) calories, eventually the system of evaluating quality was placed on a solar basis and termed solar equivalents (SE) in Odum (1977b). In an appendix to his book Environmental Accounting (Odum, 1996), Odum provided a table listing a chronology of nomenclature and emergy conversions. The table provides insight into the development of the emergy concept. An updated version of such development story was presented by Brown and Ulgiati (2004a).

The history of the emergy method is intertwined with the history of consecutive recalculations of the total emergy driving the biosphere (so-called "emergy baseline") as a consequence of the coupled action of solar, geothermal and gravitational flows of available energy. The vales of UEVs kept changing over time, as a consequence of both new biosphere baselines and more refined assessment methods. For example, the UEV of surface wind was 623 seJ/J in Odum et al. (1987), 1496 seJ/J in Odum (1996) and finally became 2450 seJ/J in Odum et al. (2000). While the possibility of corrections and updates is implicit in any scientific assessment, it is apparent that these changes mainly depend on the baseline choice and therefore may appear a weak point of the approach.

It is not possible here to provide a detailed discussion about the assumptions underlying the different baseline calculations and results, and therefore we will only limit to a few of such published values. The difference among these values mainly stems from assumptions about the extent to which the three main energy sources driving the biosphere are coupled over the different geological and biological time scales. More updated values of global flows from recent satellite measures and the choice of the numeraire to be used (energy or available energy) for basic flows also affect the calculated values. Odum (1996) derived a geobiosphere baseline of 9.44 E24 seJ/yr, that included sunlight, tidal momentum and geothermal energy, converting each of them into equivalent solar emergy. Later on, Campbell (2000) calculated a new baseline (9.26E24 sej/yr), based on the assumption that geothermal energy does not provide any significant contribution to the oceanic geopotential over time scales of 10,000 years or less (and therefore should not be included in its calculation). Odum (2000) refined his calculation procedure by acknowledging that the three forms of energy (solar, heothermal and gravitational) were linked and required a series of simultaneous equations in order to compute their UEVs, thus leading to a baseline of 15.83 E24 sej/y. The most recent recalculation of the global baseline (Brown and Ulgiati, 2010) uses the simultaneous equation method of Odum (2000), with three modifications: first it uses available energy (exergy) of sources as originally intended by Odum (1996). Second, it uses a slight modification of the contribution of radiogenic sources to total geothermal energy based on a better understanding of the relative position of this source in the crust rather than in the earth's core, which affects exergy. Third, it relies on recent more accurate measurements of ocean surface elevations via satellite as new estimates of oceanic geopotential. This led to a slightly modified baseline of 15.2E24 seJ/yr, thus practically confirming Odum's previous baseline (however with different UEVs of tidal momentum and deep heat). The debate about baselines is still open and calls for urgent definition, in order to remove the existing uncertainties about UEV values.

CRITERIA FOR EVALUATING THE QUALITY AND RELIABILITY OF EMERGY INTENSITY VALUES

Unlike monetary accounting systems, all the environmental accounting methods suffer from a limited application to real cases. So that they become able to complement monetary evaluations, it is important to standardize their application to production processes and whole economies, to use them with reliable data and standard calculation procedures, and finally to test and model how environmental indicators change over time following changes processes and economies. The above requisites also apply to the emergy method, which is the main focus of the present paper. There is no doubt that accuracy and reliability of emergy accounting is critical to help make decisions to promote a more sustainable way of resource appropriation and use. For this reason, the basic products of an emergy calculation procedure – Unit Emergy Values – should be continuously monitored, double checked and updated, and every effort should be made to improve their completeness and reliability.

Criteria for UEV Quality Assessment

The acceptability of a given UEV should be checked against strict and agreed upon criteria, that take into account the uncertainty of environmental resource parameters, the quality of the study referred to, the assumptions underlying a given calculation procedure, and several other aspects that make a result reliable and applicable. An important theoretical step ahead was made, in this regard, by Ingwersen (2010), who first attempted to describe sources of uncertainty in Unit Emergy Values (UEVs) and presented a framework for estimating this uncertainty with analytical and stochastic models. Based on LCA practice and past studies on data quality (Funtowicz and Ravets, 1990; Litman, 2008; Spaapen, 2007; Pannell, 2009), we aim in this paper at designing acceptable criteria for the quality assessment of UEVs and their applicability to other studies in different processes and situations. Table 1 shows a set of preliminary criteria suggested for the selection of acceptable and reliable values of UEVs, towards a critically evaluated database in support of future studies. Criteria can be grouped into four main categories (Methodological, Data Quality, Documentation provided, Publication level).

Some of the criteria identified in Table 1 try to meet several concerns that apply to all kind of databases, not only to UEVs. A reliable database must consist of values that are temporal consistent with the system modeled (criterion "H"), capable to include description of uncertainty (criterion "P"), based on consistent accounting procedures (criteria "A, B"), representative of the most used or best available technologies (criterion "D"), and based on studies easily accessible to the international readers (criterion "G").

Other criteria may require further explanations: data obtained as averages or ranges from a larger set of cases may be considered more representative than data only referring to a unique case investigated (criterion "C"); data and calculation procedures confirmed by several independent investigators worldwide may be more reliable than data only based on the authority of one single investigator or team (criterion "E"); data published in peer-reviewed international journals are subject to more external scrutiny than data published in Working Papers of the investigator's Institution without peer review (criterion "F"). The existence of time series (criterion "I") is also of paramount importance, in that it provides information the effects of ongoing changes of technology, resource availability, and economic performance on the UEV: by having a clear picture of a value's stability over time, it is much easier to determine if the result of a study is robust against potential changes occurring in one step of or one input to the process. In other words, there may be fast evolving technologies from which fast changing UEVs are generated: such values cannot be transferred to other studies and the investigator needs to recalculate it for the new specific case, until it shows to be stabilizing.

Some criteria are specific to the emergy method (criteria B, L, M, N and O), and are not shared with other methods. For example, the final results of an emergy calculation procedure lead to a total value of the emergy used, that includes renewable, nonrenewable, local and imported emergy flows as well as the emergy allocated to non-material flows such as labor, services and information (know-how), not usually included in other approaches. Moreover, some flows are only partially renewable, in that their renewable origin is complemented by nonrenewable input flows in order to make them available to the process. Drinkable water is an illuminating example of this statement: rainwater is

Table 1/ Criteria and issues addressing the quality and acceptability of Unit Emergy Values (UEVs).

#	Category	Criterion	Issue
A	Method	Identification of a suitable numeraire	What numeraire is used (Energy, Exergy, Mass, Currency) in the calculation procedure as well as in the final result?
B	Method	Consistent use of the global baseline	Are all UEVs used as well as the new UEVs calculated in this study based on the same global baseline?
C	Data	Study Representativeness	Number of case studies investigated to reach the final result.
D	Data	Technological Representativeness	Does the value rely on the best available or the most used technologies in the year the study was performed?
E	Publishing	Consensus	How many different authors have published similar data about a given process/product?
F	Publishing	Scientific reliability	What kind of publication medium is referred to? Was the paper peer-reviewed?
G	Publishing	Accessibility	Is the result published in a paper using English language? Is the referred paper available in print or online?
H	Data	Up-to-datedness	How old is the value or UEV used, compared with methodological updates or new data occurred?
I	Data	Time series	Are there time series available for the value under consideration?
L	Method	Downstream impacts	Recovery of natural and human assets requires emergy. Are the effects of GHG emissions, toxic effluents, solid waste, erosion, biodiversity loss, and/or water quality deterioration accounted for in terms of additional emergy costs?
M	Method	Inclusion of labor and services	Is the emergy of labor and services included in the accounting? Is such an inclusion clearly shown as an independent component of the final value?
N	Method	Distinction between renewable and non-renewable	Does the evaluation show which fraction of each input flow is renewable versus nonrenewable?
O	Method	Distinction between local and imported flows	Does the evaluation show which fraction of each input flow is local versus imported?
P	Method	Uncertainty	Is the value accompanied by a description of its uncertainty that takes into account all sources of error/uncertainty/variability?
Q	Documentation	Calculation procedures	Are the calculation procedures clearly indicated and explained? Is a systems diagram provided?
R	Method	Spatial and time Scales	At which (spatial or time) scale was the UEV assessed? (The same UEV may not be applicable across scales.)

renewable and its natural convergence patterns in watershed is also driven by renewable driving forces. However, collecting, treating, storing and distributing water to a city requires concrete, steel, energy, and chemicals, which are all nonrenewable input resources. The final product, drinkable water, must be considered at least partially non-renewable according to the nonrenewable fraction of used resources. As a consequence of the fact that a given resource can be renewable or not, local or not, depending on the case (e.g. withdrawal rate) and the assumptions, the final performance indicators of another process where this resource is used are significantly affected by the assumptions made (criteria N and O). Direct labor and services are also an important component of the final result, since labor carries a non-negligible fraction of the emergy supporting the whole societal economy. Most emergy studies include labor and services in the calculation of the UEV of a given product. Such an inclusion must be clearly highlighted, so that it may be possible to calculate the UEV with and without labor and services. The rationale of such a requirement (criterion M) is that technological processes are increasingly similar worldwide due to globalization while economies are different in the different areas of the planet. Furthermore, some resources are extracted and some commodities are produced only in very specific areas of the planet and then exported everywhere (e.g. lanthanide minerals in China). As a consequence, the contribution to the UEVs that is related to resource availability and technological aspects can be assumed more or less the same everywhere, although within a confidence range, while instead the fraction related to labor and services heavily relies on the level of the economy and the different trade steps of a commodity through international markets. Such a different dependence upon spatial and time scales imposes the need to disaggregate physical data and economic data, in order to treat them properly. Finally, criterion B refers to the urgent need for an agreed biosphere baseline for the calculation of global emergy flows and consequent local flows and related UEVs (Odum, 2000), as already pointed out earlier in this paper.

Ranking UEVs According to their Quality and Reliability

An UEV evaluation system can be built based on the different extent of fulfillment of the criteria defined in Table 1. The extent of fulfillment may translate into "quality scores" similar to those suggested in Table 2 in order to show the robustness of the UEV, and finally identify a more accurate range of Unit Emergy Values by means of a sensitivity analysis procedure. Finally, an overall score can be calculated according to Table 3.

A preliminary effort should be made to reach the consistency of the numeraire used in the inventory of the basic emergy flows. Until UEV's are expressed in terms of mass (sometimes disregarding water content and chemical composition), and energy (the quality of which most often depends on temperature, pressure and chemical composition of the energy source or carrier), it will be impossible to reach a reliable database with comparable values. Instead, the use of available energy (exergy) to quantify mass and energy flows allows all flows be expressed by the same numeraire (Joule of available energy). As a consequence all UEVs would be calculated according to Odum's basic definitions, and UEV values would be consistent and comparable (as seJ/J).

Secondly, an effort is absolutely needed in order to adjust the global baseline to the use of the available energy numeraire. Such an adjustment would reinforce the approach, by meeting the correct criticisms that were put forward by some energy and emergy practitioners, as previously noted. We chose to assign a high score to all kinds of exergy-adjusted baseline (such as, but not exclusively, Brown and Ulgiati, 2010) and a intermediate score to the Odum (2000) baseline compared to previous ones, because Odum (2000) takes into account the coupling and strong interaction of the main Earth driving forces (sun, deep heat and gravitation), while other baselines keep driving forces as separate and not interacting sources of biosphere support.

Last, but not least, each emergy practitioner should personally evaluate every UEV from literature before including it in a new calculation procedure. As a consequence of increased awareness, focus and quantification of UEV quality, further efforts will be encouraged towards higher quality UEVs. Once a quality characterization of UEV's databases is achieved, according to Table 2, the reliability and acceptability of UEV's can be stated (based on % score, P, Table 3), so that the investigator may decide about using it or calculating a new value for the specific case. The introduction of newly calculated values for the same product or service would allow a range of values, the calculation of an average value within such a range, and finally an estimate of the uncertainty characterizing the value itself. The inclusion of high quality UEV in new studies will likely generate much more reliable results.

If a database of UEVs is finally created as a result of such efforts, each UEV may be scored based on these data quality criteria and then labeled by means of the global percentage score P (Table 3) in order to suggest its quality to the potential users. Each emergy evaluation would largely benefit from a "quality certification" of the UEVs used in the calculation procedure as well as of the final results. Papers submitted for publication should always include such a UEV quality certification

Table 2. Quality Assessment of Unit Emergy Values.

Score / Criterion	0: Unreliable	1: Questionable	2: Acceptable	3: Trustable
Identification of a suitable numeraire	Use of currency to account for input flows other than labor and services (L&S)	Mass: needs to specify chemical composition and if dry or wet.	Energy: all flows accounted for as heat; disregards some user-side quality aspects	Available energy/exergy
Consistent use of the global baseline	No mention of any baseline	Reference to baselines before Odum (2000)	Reference to the 15.83E+24 seJ/yr baseline (Odum, 2000)	Reference to an exergy-adjusted baseline (e.g. Brown and Ulgiati, 2010)
Representative-ness (§)	Educated guess about order of magnitude without reference to case studies	1-2 cases	3-5 cases worldwide	> 5 cases worldwide
Technological representative-ness	Very old or very local technology	Unspecified technology from another country or system	Best available technology for the specific system	Most used technology for the specific system
Consensus	No officially published value	1-2 authors only	3-5 authors worldwide	> 5 authors worldwide
Scientific reliability	Class report; working paper, with no review	Master or PhD thesis, with internal review	Handbook; Edited book; Book of proceedings, with internal review	Journal or book with peer external review
Accessibility (language and online)	Only published in the author's country language	Published in English, only in print.	Published in English and available online	Published in English, available online with full calculation details
Up-to-datedness	Very old data (before 1990)	Intermediate age data (1991-2000)	Relatively recent data (2001-2006)	Up-to-date (last five years)
Time series	No past time series investigated	Short past time series available (10-20 years)	Long past time series available (20-50 years)	Scenarios of future trends available
Downstream impacts	No mention of downstream impacts	Cost of waste management included	Emergy of lost natural and human made capital included	Emergy investment for damage recovery included
Inclusion of labor and services	No mention about L & S (uncertainty if it is included)	L&S not included as a choice of the analyst	L&S included, but aggregated in one value	UEV calculated with and without L&S, disaggregated
Distinction between renewable and nonrenewable flows	Renewable fraction of input flows is not identified	Renewable fraction of input flows is identified	Renewable fraction of L&S associated to input flows is also identified, if applicable	Renewable fraction of calculated UEV is clearly identified, with and without L&S contribution
Distinction between local and imported flows	Local fraction of input flows is not identified	not applicable	Local fraction of input flows is identified	Local fraction of input flows is clearly identified, with reference to boundary
Uncertainty	No mention of uncertainty analysis	Qualitative description of uncertainty	Quantitative description of uncertainty including either data or UEV uncertainty	Quantitative description of both UEV and data uncertainty
Calculation procedures	Not indicated	Calculation procedures for input data. Results and emergy indicators are clearly indicated.	Systems diagram provided (in addition to calculation procedures)	Statistical treatment also implemented (sensitivity, percentages)
Spatial and time scales	Not indicated	Scales not discussed but implicit in diagram and methodological section.	Space and time window of interest clearly assessed.	Comparison of results across space and time scales.

(§) This criterium should be based on the percent representativeness of the specified process in its field (e.g. <1% of all production, >10% of production, >50% of production). At present, the published papers on the topic are so few that such percentage cannot be assessed. In the future the criterium will be updated.

Table 3. Confidence score (P) evaluation of Quality Assessment Criteria in Table 2.

Maximum possible score S_{max}= sum of maximum individual scores, $s_{i\ max}$.	S_{max}= 3*16= 48
Score assigned S= Sum of individual scores, s_i, in each category	S= Σ s_i
% score P= (Score assigned, S / Maximum possible score, S_{max})*100	$P_{\%}$= (S/S_{max})*100

performed by the author, as a much larger check than just the traditional sensitivity analysis, therefore making results much more robust and widely acceptable.

Finally, once a database of high quality and robust UEVs is available, it would be possible (and very useful) to use it in some of the commercially available Life Cycle Assessment softwares, in order to allow the emergy practitioner to benefit from the large number of case studies performed by other colleagues worldwide (Raugei et al, 2006).

CONCLUSION

We design in this paper a tentative approach to the assessment and improvement of the quality of UEVs, i.e. the quality of the "emergy quality factors". The basic definitions and concepts of the emergy approach are compared with the usual practice of emergy practitioners and some of the weakest aspects are identified and stressed, in order to suggest criteria for improvement. The quality of UEVs is of paramount importance for the future reliability of emergy synthesis studies as well as for the acceptance of their results by the scientific community and policy makers.

The criteria listed in Table 1 as well as the scores assigned in Tables 2 may well not be the only ones nor the most important or relevant, but they are an unavoidable step ahead towards a reliability check of the UEVs used in emergy accounting. In order to avoid misunderstandings, it is important to point out that criteria and scores apply to both individual values (calculated by a single investigator or based on a specific technology) as well as to average values or ranges derived from a selected number of case studies (different investigators exploring a given set of technologies). In the first case, the UEVs rank low in the representativeness and consensus criteria. Instead, when more values converge from a diversity of cases towards an average estimate within a database (endowed with an uncertainty interval), the score is very likely to be higher as a consequence of increased consensus and representativeness. The construction of a database of high quality UEVs and a set of criteria for their acceptance, use and improvement would certainly reinforce the efforts of the worldwide emergy community.

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