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Computing the Unit Emergy Value of Computers – A First Attempt

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ABSTRACT

Dependence on computers has been sharply increasing during these past ten years mainly due to the availability of mobile computer types such as laptops, tablets, smartphones, and so on. Considering this trend of continuous high-tech progress, it is expected that more and more computers will be a permanent part of any human-made production system, mainly for those closely tied to Information Technology (IT) issues, i.e. systems located on the far right of a hierarchical chain. When identified, computers should be considered for an emergy evaluation, as they could play an important role in the systems "empower". A computer's Unit Emergy Value (UEV) is therefore fundamental for that purpose. In this sense, this work aims at a first attempt to estimate a computer's UEV. A sample of ten selected average computers is used, and the uncertainties related to parameters values are assessed under a Monte Carlo simulation. Results show that while the estimated computer's UEV accounting for services input is 1.6E+12 seJ/$g_{computer}$ and 3.1E+5 seJ/Flops (Floating-point operations per second), their counterparts without services are 8.9E+10 seJ/$g_{computer}$ and 1.7E+4 seJ/Flops. This huge difference related to services input highlights the fact that the "embodied information" in the computers production (for example, technology, knowhow, research, specialized personal involved, etc) is more significant (>90%) in the computer's "empower" than the input materials.

INTRODUCTION

The presence of computers and computer-based/operated gadgets in organizational and home environments has been experiencing exponential increase since the introduction of the first affordable and user-friendly Personal Computer in 1981. Included in the on-growing list are the modern tablets and smartphones, the amount of which, according to Gartner (2013), should increase by some figure around 6% worldwide in 2013 alone. In absolute figures, this means that 2.35 billion pieces of equipment are to be found in companies and homes, and an estimated 305 million of those are personal desktop and laptop units. Such figures considered, as well as the continuous technological advances in the field of Information Technology (e.g., internet and cloud computing), it is difficult - if not impossible - to even imagine production systems operating without the aid of information systems. Computers are used throughout the process, from spreadsheet and text elaboration to mathematical simulations, communication and mechatronic-related tasks.

Among other purposes, the emergy methodology (Odum, 1996) has been more and more utilized in the assessment of production systems - whichever they are - through comparison with alternatives. This is mandatory in a scenario of searching for higher sustainability under a global scale and from the donor's point of view. Realizing the increasing presence of computers in whichever systems undergoing assessment - especially those located further to the right in a hierarchical scale, based upon information technology -, the influence of computers flowing into the system boundaries and consequently on emergy results is higher and higher, calling for a precise account. In systems where computers exert little influence when compared to other system inflows (e.g. in Yang et al, 2013), the precision of the results is not effectively influenced by one's randomly selecting one or other Unit Emergy Value (UEV) for the computers. On the other hand, in systems in which they are highly representative, such as in Almeida and coworker's (2010) study (around 22% of total emergy), results can be highly influenced.

Computer accounting is usually either based on its weight in mass units (2.26E11 seJ/g; Almeida et al, 2013), or accounted as computer "units" (5.77E14 seJ/unit; Yang et al, 2013); such values, however, are estimates put forward by the analyst, based upon other previously published UEV's. Mass accounting may not be an adequate procedure as the computers from the 1990's, for example, apart from their lower processing capacity, are bulkier and heavier (higher mass) than the current models. In other words, such approach implicitly assumes that the emergy of those obsolete machines is higher than that of current models, which contradicts the current reality of technological advancements resulting from large economical investments on materials innovation and on personnel – the latter being carriers of high emergy information – involved in the research work necessary to technologically improve them. The same comment applies for accounting computers as "units", as the current computers demanded more emergy to be improved and produced than their predecessors did. At this point, the following question rises up: What is the most suitable UEV for a computer?

This work is a first attempt in the search for a proper UEV for computers, avoiding rough estimative that could have a strong effect on emergy synthesis involving computers as important system inflows. For this first attempt, aware as we are of the existence of a wide range of models and set-ups for computers in the market, a sample of ten laptops was considered for the calculation procedure. Emergy results are presented under two different functional units: (i) weight in mass; (ii) processing capacity measured in Floating-point Operations per Second (Flops).

METHODOLOGY

Data Source

Computers are made up of several electronic components made up of different materials. Precise data about computer material contents are rarely found in literature. Additionally, due to the inherent complexities – i.e., usually, a single industry is not in charge of the whole process involved in the computers chain production – and the industrial secrets involved in the computers production, it was not possible to obtain raw data *in situ*. Trying to overcome these barriers, in this study the MCC Technical Report published by Pedersen et al. (1996; see Appendix A) is used as source for raw data for materials used in an average computer structure.

Regarding the sample of laptops considered in this study, models were selected considering the following operational limitations: (i) the availability of computers; (ii) all samples must feature an Intel® processor and Windows® 8 as its operational system – the reasons for the above are described in the next section. The features of the laptops considered in this work are presented in Table 1.

Functional unit: floating-point operations per second (Flops)

Units able to show the robustness and/or processing capacity of computers could be considered as a better alternative than mass and/or "computer units" as functional units. Considering all measure units available in scientific and technological literature (for instance, benchmarks, MIPS, among others), the Floating-point Operations per Second (Flops) is suggested as the most appropriate as, under a common sense in the computers technological world, it is being used to classify the 500 faster computers worldwide (http://www.top500.org).

Flops is considered as a critical measure of computing power and speed. Even admitting that Flops directly relates to high performance computing (e.g., running complex mathematical models like those for weather reports), such unit is taken into consideration in this study due to its recognized importance as a supercomputers' performance measure.

During the data-collection phase for Table 1, it was verified through initial testings that the amount of Flops is not directly associated to the processor, but to the computational system as a whole, including circuit cards, electronic devices, available memory, operational system being used and, mainly, the system's operation load at the time the test is run. Thus, establishing the following test

Table 1. Description of laptops sample considered in the calculation procedure.

Item	Manufacturer	Model	Processor	Weight(g)	Billion Flops	Market value[a] (USD)
#1	ASUS	K43E	Core I5-2410	2,440	17.40	1,163
#2	ASUS	X45C	Core I3	2,440	7.02	673
#3	ASUS	X44C	Intel Pentium	2,440	14.38	444
#4	Compaq	CQ43	Core I5-2410	2,200	14.91	758
#5	Dell	Inspiron 14R-910	Core I5-480M	2,300	9.58	893
#6	HP	Envy Pro	Core I5-3317U	1,630	16.91	812
#7	HP	HP 1000-1460BR	Core I5-3230M	2,950	16.85	852
#8	HP	HP Pavilion dv4	Core I5-2410	2,220	14.75	893
#9	HP	Envy 4-1130	Core I3	1,750	13.48	1,346
#10	Lenovo	Ultrabook IdealPad Z400	Core I5	2,000	15.43	1,118

[a] Market prices obtained from a selection of e-commerce websites; money ratio of 2.23 BRL/USD

pattern to estimate the amount of flops of the sample computers became necessary: (i) the Linpack freeware made available by Intel (http://software.intel.com/en-us/articles/intel-math-kernel- library-linpack-download), was used for estimating the computers' Flops; (ii) the following parameters were set in the system entry file: Number of tests = 1, Problem sizes = 20,000 (from equation sqrt((total memory - 20%)/8)), Leading dimensions = 20,000, Times to run a test = 3, and Alignment values = 4; (iii) all tests were performed with the laptops plugged into their AC adaptors; (iv) the whole sampler pack feature Windows 8 as their operational system (OS); (v) the tests were run immediately after rebooting the OS.

Emergy accounting

Emergy accounting definitions, meanings, calculation procedures and case studies are presented by Odum (1996), Brown and Ulgiati (2004), among others, and by several publications in the emergy systems website (http://www.cep.ees.ufl.edu/emergy/index.shtml). The use of emergy accounting as a scientific measure for decision making is being spread worldwide by the scientific community, due to its methodology robustness and effectiveness under a systemic and donor-side approach. Besides supplying indicators regarding sustainability issues, emergy is being more and more considered as a managerial tool rather than one only for diagnosis.

Unlike large amounts of papers that have used the regular set of emergy indicators for sustainability assessment (for instance, EYR, EIR, ELR, and so on), this work aims to estimate the Unit Emergy Value (UEV) of computers. Due to a large amount of recent papers focusing on case studies whose boundaries lie far away from the natural and agricultural systems, computers have been more and more accounted as an input resource in emergy evaluations, thus emphasizing the importance of a proper computer UEV estimation.

An average computer's UEV is estimated in this work by considering the Flops and the computer's weight in mass as functional units, thus the final UEV is measured in solar emjoules per Flops (seJ/Flops) and per gram (seJ/g). Results are shown including and not including Services inputs; in this work, services represent the computer market price. The standardized emergy baseline of 15.83 10^{24} seJ/yr is considered throughout this paper. The work of Cohen et al. (2007) is the source of UEVs for the input materials in computer production (Appendix A).

Uncertainty in the computer's UEV estimation: Monte Carlo simulation

Recognizing the inherent uncertainties embodied within any biophysical approach – including emergy accounting, life cycle assessment, a.o. –, and aiming to make emergy accounting even more accepted and used by the scientific community, the use of uncertainty analyses has been increasing sharply in emergy evaluations; different approaches have been taken into consideration, such as the

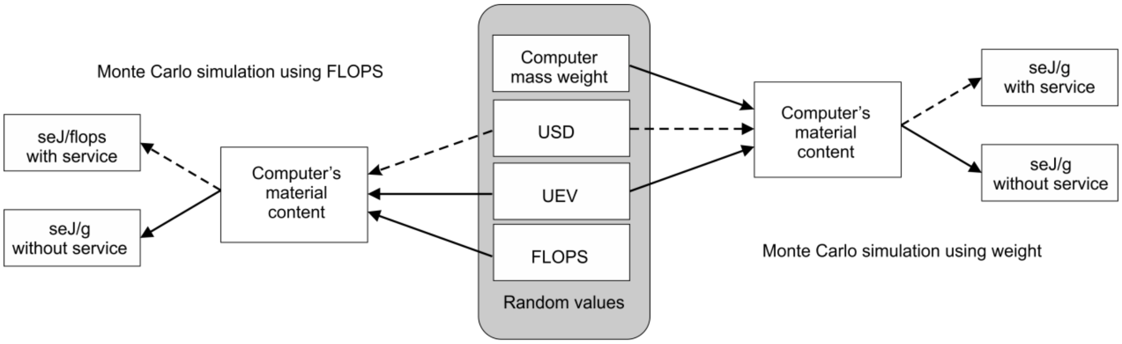

Figure 1. *Schematic algorithm used for the calculation procedure.*

stochastic (Ingwersen, 2010; Brown et al., 2011; Hudson and Tilley, 2013), analytical (Li et al., 2011), and fuzzy-based (Reza et al., 2013) ones. Among other potential framework definitions of uncertainty, the one used by the United States Environmental Protection Agency (USEPA) seems to be the most adequate for emergy studies. Such framework includes uncertainties from three different sources: parameter, scenario, and model (details in Ingwersen, 2010).

Parameter uncertainty is the only one considered in this work, even recognizing that all the other ones could be present. Hence, the stochastic method of Monte Carlo analysis was used, by generating random numbers from a range previously determined on a Probabilistic Distribution Function (PDF). So far, there has not been an accepted rule regarding the best PDF representing parameter values in emergy evaluations (Hudson and Tilley, 2013), therefore, the uniform PDF as suggested by Hayha et al. (2011) was considered in this work.

A value of 10,000 was considered in this present work as, rather than using commercial statistical softwares that usually demand high computational power and cost, the Monte Carlo Simulation was performed through a free-of-charge Microsoft Excel® add-in developed by Barreto and Howland (2006).

Figure 1 shows the schematic algorithm for the calculation procedures considered in this work. Four parameter values were simulated under a Monte Carlo analysis: (i) weight in mass of the selected computers (from 1,630 to 2,950 g; Table 1), reflecting directly on the materials amount going into the computer production; (ii) market value of computer (from 444 to 1,346 USD); (iii) UEV of materials input (a range of +/- 25% on the crustal elements UEV published by Cohen et al., 2007). A single source of materials UEV was considered in this present work as no other is presently available, so there is not a range between minimum and maximum values to be simulated in the Monte Carlo analysis. However, Cohen et al. (2007) recognize that their values present some uncertainties such as the lack of available data for Ore Grade Cutoff (OGC), the assumption that all mined materials are mineral rather than elemental ores, and that crustal elements UEV are linearly related to ore body enrichment from background concentrations. In this sense, considering a range of +/- 25% on the Cohen and coworker's UEV is justified. (iv) computer Flops (from 7.02 to 17.40 billion Flops).

RESULTS AND DISCUSSION

The energy diagram of computer production represented by Figure 2 shows that besides regular inputs of material, labor, and electricity, this system has information as another important input. Information here is assumed as representative of all technology involved in computer production, having demanded years of research efforts by scientists and technical staff - with high transformity - and high amounts of economic investment. As pointed before, raw data were not obtained *in situ*, thus, it was not possible to account for some energy/material inflows in the calculation procedure, i.e. all the emergy required for infra-structure, the direct electricity used in the production, and also the specialized labor input; all of them are represented by gray symbols in Figure 2. Aiming to surpass

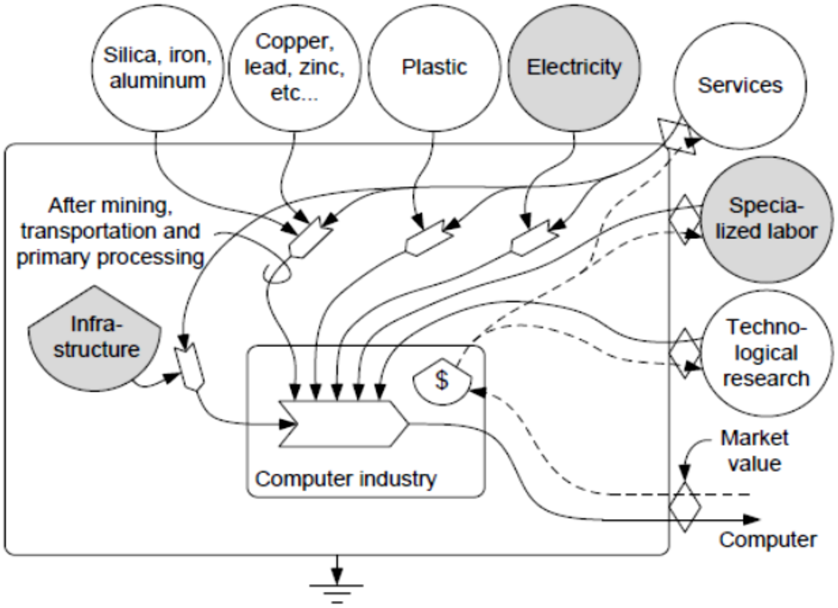

Figure 2. *Energy diagram of a computer production system. Grey symbols indicate flows indirectly accounted as services.*

such operational barrier, instead of including the physical amount (i.e., J and g) of these inputs and their respective market values (i.e., USD/J, USD/g) – which is the regular procedure of an emergy synthesis –, the market value of computers was assumed as representative of all these input flows, including materials, energy, specialized labor, “information”, as well as the industry profit. This accounting approach could lead to uncertainty in the results, however, it may be considered as the first further detailed study attempt so far, concerning a computer’s UEV.

Awareness of all the existing uncertainties in this work, mainly those related to input primary data and their UEVs, led to a sensibility analysis which was carried out with the aid of Monte Carlo analysis. The resulting graphs for the two simulations are shown by Figures 3 and 4. Only the seJ/Flops unit is graphed due to the fact that the seJ/g unit would result in a similar behavior. The most perceived aspect in the first graph is the representativeness of “services” input, ranging from 90% to 97% of total emergy. Such was already expected because, as represented in the energy diagram on Figure 2, the highest emergy amount of a computer industry comes from specialized labor and knowledge (information) rather than from physical materials and energy. This is especially true for systems demanding and/or producing high-tech goods, located far away from the natural systems in the extreme right-side of a hierarchical energy chain. Disregarding the “services” input, Figure 4 shows that Lead is the most representative material (from 26% to 42% of total emergy), followed by Bismuth (from 17% to 29%), Tin (from 14% to 25%), and Copper (from 5% to 10%).

After thoroughly checking and re-checking all primary data and their UEVs under the sensibility analysis, the final Monte Carlo simulation (Appendix B) was performed and resulted in the average values for a computer’s UEV shown on Table 2. The differences between “g” and “Flops” values are evident, as are the differences between the UEVs for the "with services" and "without services" scenario simulations under the same functional unit. The standard deviation obtained indicates that the precision fared by simulation #2 is the best one of the four ones analyzed, in which simulations #3 and #4 are at the same time closer and the worst ones. The higher standard deviation for Flops units is due to the large variation on Flops units verified among the samplers (Table 1), while the range of weight in grams of computers is smaller. This is an important aspect, for while the weight of computers sample is similar, their processing power is different. This implies in that

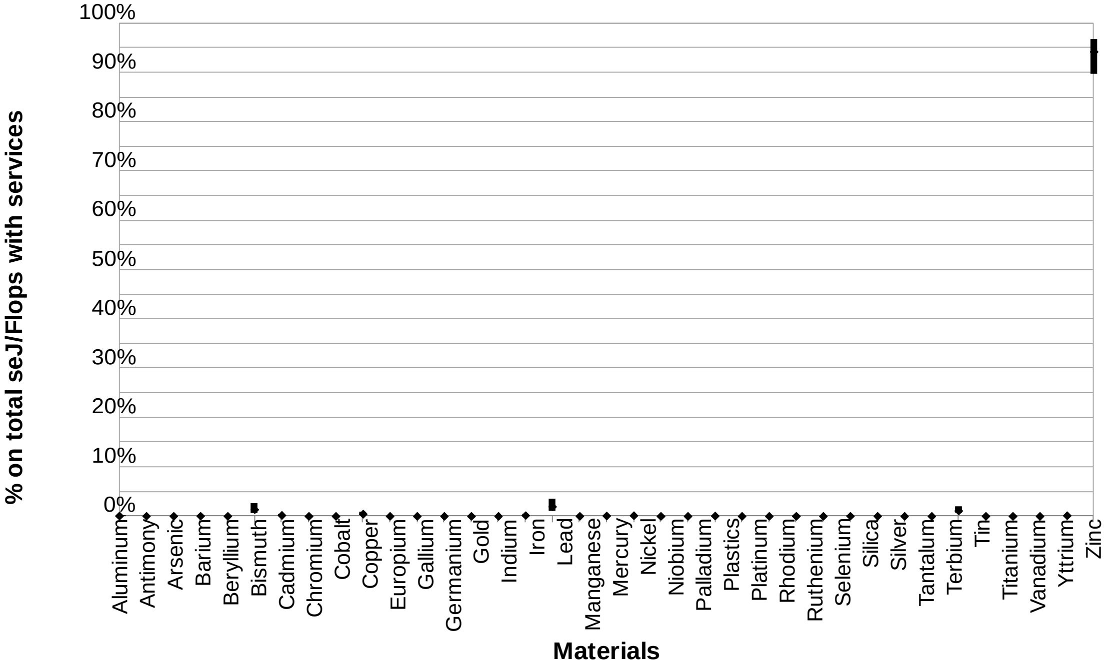

Figure 3. *Sensibility analysis of system resource inputs for seJ/Flops including services input. Assumptions: uniform probability distribution function with 100 interactions for Monte Carlo analysis.*

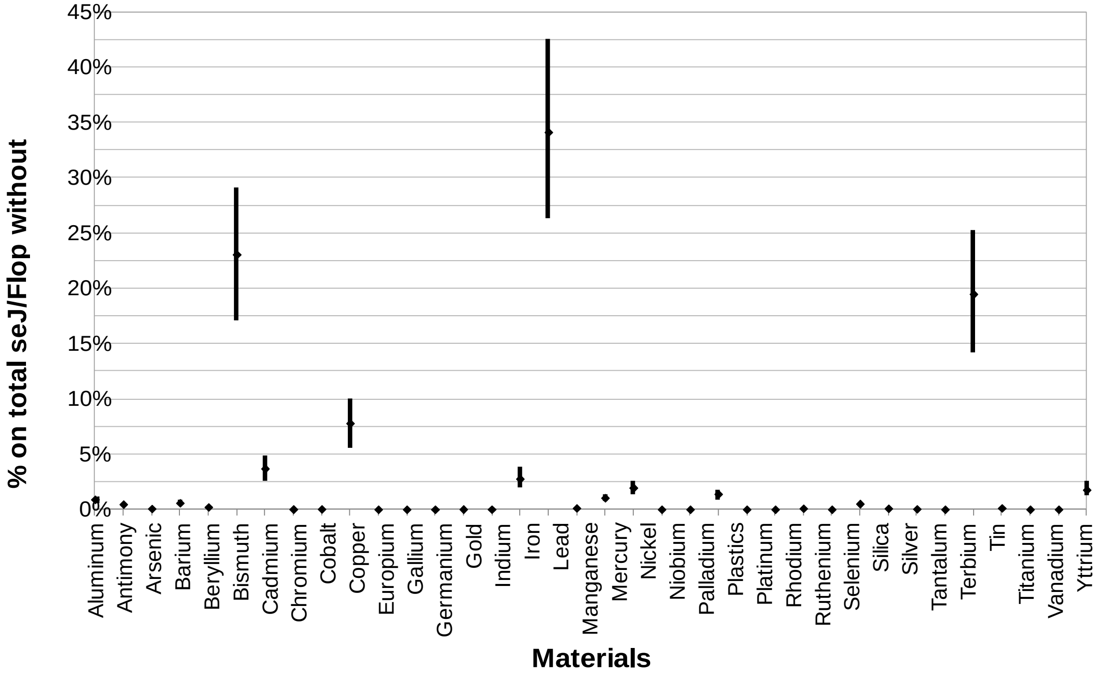

Figure 4. *Sensibility analysis of system resource inputs for seJ/Flops without services input. Assumptions: uniform probability distribution function with 100 interactions for Monte Carlo analysis.*

Table 2. Computer’s UEV obtained through Monte Carlo simulation.

Simulation	Average values (μ) [a]	Unit	Standard deviation (σ)	Observation
#1	1.6±0.2 E12	seJ/g	24 %	with services
#2	8.9±0.4 E10	seJ/g	7 %	without services
#3	3.1±0.6 E05	seJ/Flops	34 %	with services
#4	1.7±0.4 E04	seJ/Flops	33 %	without services

a Confidence interval of 95% calculated as $\mu \pm 1.96 * \sigma / (\text{sample size})^{1/2}$

computers emergy from materials content is quite similar, but the emergy from technology (information) is different. At this point, the first insight emerges: Should Flops be used to better represent a computer’s UEV rather than their weight in mass units?

The UEVs range size obtained is related to the confidence interval of 95% considered in this work. This means that, considering the same premises assumed for this work, any other computer UEV calculation has 95% of probability to be within the range obtained herein.

As already represented by Figure 3, services input – the reader must bear in mind that services, in this work, represent the computer’s market price – is worth over 90% of the total computer’s emergy, thus, accounting computers by its market price could be a valid first attempt when applying emergy synthesis. This could be considered a better estimative than other rough estimates and/or assumptions. This remark raises the second insight about the application of emergy synthesis on those systems with high dependence on computer inputs: Can the accounting of computers as monetary flows be considered as a good estimative?

Figure 5 shows the emergy of the individual units presented at Table 1. The graph provides some interesting information, if analyzed under different aspects:

(i) when using the calculated computer’s UEV "without services" (Table 2), there is a nonsignificant difference by either considering grams or Flops as the functional unit (from 1.2 to 2.9 E14 seJ) compared to a simulation in which computers' UEV "with services" is used (from 22.1 to 54.8 E14 seJ); this means that the functional unit is not so important when using computer’s UEV "without service", because the emergy of a computer’s power capacity is represented indirectly by the market price (services) instead of by the amount of materials used for computer construction;

(ii) as expected, using computers' UEV "with services" results in an at least tenfold higher emergy of computers than the "without services" UEV; of course, such figure is peculiar of Brazil because of its specific emergy per money ratio (3.4E12 seJ/yr). In more developed countries such difference will be lower, whereas it will be higher for the underdeveloped ones.

(iii) through a dynamic view, it can be verified that, when using the "in grams with service" UEV, increasing the computer’s market price causes a slight decrease in the computer’s emergy; on the other hand, a slight increase is also observed when using the "in Flops with service" UEV; this implies that market price relates more to the computers power capacity rather than to computers weight – an obvious aspect under a common sense – , also, it is in accordance with that higher power capacity relates more to research development (information) rather than materials consumption, and causes it to fall again on the previous second suggested insight.

Emergy evaluations featuring computer inflows in their analysis are rarely found in scientific literature. Aiming to show the influence of using the computer’s UEV estimated herein on published works, we were able to find only two related papers: (i) Almeida et al. (2013), who assessed the emergy of a university campus and the emergy embodied in the information received by undergraduate students of an engineering programme in Brazil; (ii) Yang et al. (2013), who used emergy synthesis to study a wind power system in China. While the former accounted computers in using an UEV of

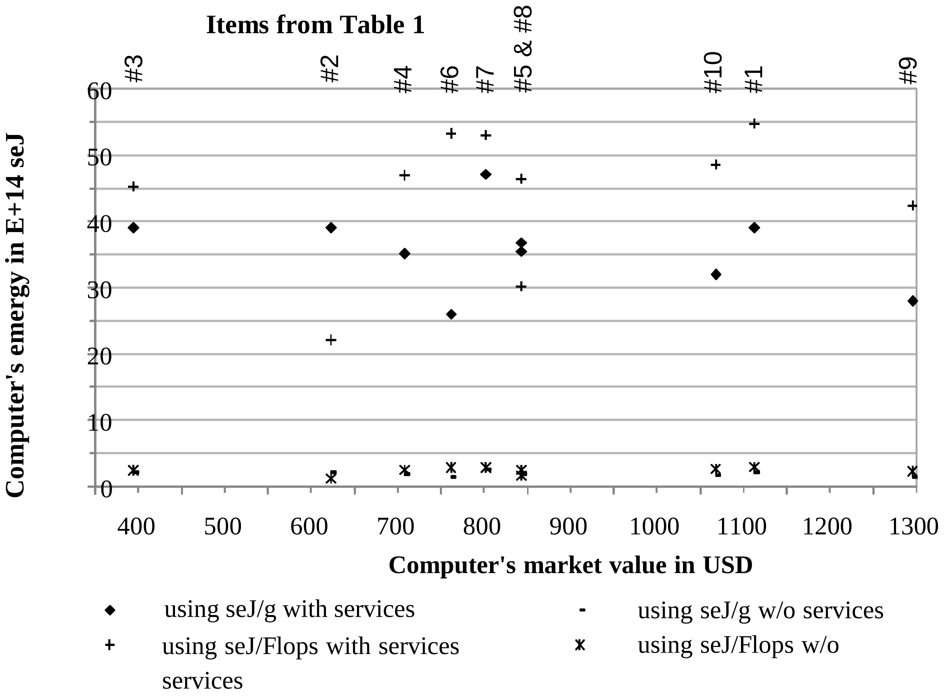

Figure 5. Emergy of a ten-computer sample calculated by using the four unit emergy values obtained in this work.

2.26E11 seJ/g (value borrowed from Cohen and coworker's paper in Agri. Eco. & Env., 2006, 114, 249-269), the latter used an UEV of 5.77E14 seJ/computer (value borrowed from a Chinese PhD dissertation). By considering the UEV estimated in this work according to simulation #1, the original influence of 22% for computers in Almeida and coworkers (2013) paper increases to 67%, while for the Yang and coworkers (2013) paper, the original influence of <0.01% moves up to 0.02% - insignificant, in this case.

It is recognized that systems with high dependence on computer inflows will exert higher influence on the total emergy related to such material input than systems with no/scarce use of computers will. This is particularly valid for systems related to Information Technology activities like, for instance, data centers and other computational clusters (like Google®). This paper represents the first milestone of a more complex study under development by the authors, in which traditional data centers are being assessed and compared against cloud computing, the latter being labeled as greener.

Although attempting to be extremely careful in obtaining primary data and their UEVs, as well as while performing the Monte Carlo simulation, authors recognize that results presented here can be considered as a first attempt to deeper assessments. The main identified weak points and potential uncertainties of this work can be listed as: (i) one single report (Pedersen et al., 1996) on computers' material content was considered for all computer used as case study; (ii) one single reference for UEVs was considered (Cohen et al., 2007), claiming for new published values; notwithstanding, these UEV represent the crustal elements in their natural form, disregarding the emergy of mining, transportation, and processing; (iii) a small sample of laptop computers was considered; (iv) the computer's market price is assumed as representative of all "information" embodied in the computer, disregarding the fact that in defining a product's market price, the company must take the consumer's willingness to pay into consideration; (v) there are potential uncertainties related to the PDF assumed in the Monte Carlo analysis; (vi) all material input was considered as non-renewable, i.e. their rate of use within the current window view is faster than their natural replacement time; thus, there is no double accounting in the applied emergy synthesis; (vii) the Flops unit is highly dependent on the computer's operational system and on the system's load at the moment it is being measured. This explains why a standardized procedure for measuring Flops is considered here. Different procedures could lead to different values; (viii) measuring Flops is not practical because it is a necessary to run the software in every computer.

CONCLUSIONS

According to the approaches, data source and assumptions considered in this work, the following conclusions can be reached:

(a) Considering the computer's mass as a functional unit, the suggested unit emergy value is 1.6E12 seJ/g (with services) and 8.9E10 seJ/g (without services);

(b) Considering the computer's power capacity as a functional unit, the suggested unit emergy value is 3.1E05 seJ/Flops (with services) and 1.7E04 seJ/Flops (without services);

(c) As expected, services input – represented in this work as the market price of computers – contributes from 90% to 97% of the total computer emergy, independently of the adopted functional unit. Thus, in the lack of a computer's UEV for an emergy synthesis study, to calculate it from its market value multiplied by the adequate emergy per money ratio (seJ/USD) could be a good alternative. However, this approach could be interesting only for systems with few computers input, and carefully used for systems that highly (significantly) depend on computers as inputs.

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REFERENCES

Almeida, C.M.V.B., Santos, A.P.Z., Bonilla, S.H., Gianetti, B.F., Huisingh, D., 2013. The roles, perspectives and limitations of environmental accounting in higher educational institutions: an emergy synthesis study of the engineering programme at the Paulista University in Brazil. Journal of Cleaner Production 52, 380-391.

Barreto, H., Howland, F., 2006. Introductory Econometrics: using Monte Carlo with Microsoft Excel. Cambridge University Press. Excel add-in available at: http://www3.wabash.edu/econometrics/index.htm. Accessed on 20th august 2013.

Brown, M.T., Protano, G., Ulgiati, S., 2011.Assessing geobiosphere work of generating global reserves of coal, crude oil, and natural gas. Ecological Modelling 222, 879-887

Brown, M.T., Ulgiati, S., 2004. Emergy analysis and environmental accounting. Encyclopedia of Energy 2, 329-354.

Buranakarn, V., 1998. Evaluation of recycling and reuse of building materials using the emergy analysis method. PhD. thesis, University of Florida, Gainesville, USA.

Cohen, M.J., Sweeney, S., Brown, M.T., 2007. Computing the unit emergy value of crustal elements. In: Brown et al. (editors), Proceedings from the fourth biennial emergy conference, Gainesville, Florida. Available at <http://www.cep.ees.ufl.edu/emergy/conferences/index.shtml>. Accessed on September 30th, 2013.

Gartner, 2013. Gartner Says Worldwide PC, Tablet and Mobile Phone Shipments to Grow 5.9 Percent in2013 as Anytime-Anywhere-Computing Drives Buyer Behavior. Available at: http://www.gartner.com/newsroom/id/2525515. Accessed on 10th September 2013.

Hayha, T., Franzese, P.P., Ulgiati, S., 2011. Economic and environmental performance of electricity production in Finland: a multicriteria assessment framework. Ecological Modelling 223, 81-90

Hudson, A., Tilley, D.R., 2013. Assessment of uncertainty in emergy evaluations using Monte Carlo simulations. Ecological Modelling, doi.org/10.1016/j.ecolmodel.2013.05.018.

Ingwersen, W.W., 2010. Uncertainty characterization for emergy values. Ecological Modelling 221, 445-452.

Intel. Linpack. Available at <http://software.intel.com/en-us/articles/intel-math-kernel-library-linpack-download>. Accessed on 10th November 2013

Li, L., Lu, H., Campbell, D.E., Ren, H., 2011. Methods for estimating the uncertainty in emergy table-form models. Ecological Modelling 222, 2615-2622.

Odum, H.T. 1996. Environmental Accounting: Emergy and Environmental Decision Making John Wiley and Sons. New York.

Pedersen et al., 1996. Electronics Industry Environmental Roadmap. Available at: http://www.ce.cmu.edu/GreenDesign/comprec/eier96roadmap.pdf>. Accessed on 3rd July 2013.

Reza, B., Sadiq, R., Hewage, K., 2013. A fuzzy-based approach for characterization of uncertainties in emergy synthesis: an example of paved road system. Journal of Cleaner Production 59, 99-110.

Yang, Q., Chen, G.Q., Liao, S., Zhao, Y.H., Peng, H.W., Chen, H.P., 2013. Environmental sustainability of wind power: an emergy analysis of a Chinese wind farm. Renewable and Sustainable Energy Reviews 25, 229-239.

APPENDIX A. The first 36 main materials found in a computer

Material	%[a] in mass	UEV[b] in seJ/g	Material	%[a] in mass	UEV[b] in seJ/g
Silica	24.8803	1.80E+09	Bismuth	0.0063	3.20E+14
Plastics	22.9907	9.86E+09	Chromium	0.0063	1.50E+11
Iron	20.4712	1.20E+10	Mercury	0.0022	4.20E+13
Aluminum	14.1723	5.40E+09	Germanium	0.0016	not available
Copper	6.9287	9.80E+10	Gold	0.0016	5.00E+11
Lead	6.2988	4.80E+11	Indium	0.0016	4.03E+11
Zinc	2.2046	7.20E+10	Ruthenium	0.0016	5.57E+12
Tin	1.0078	1.70E+12	Selenium	0.0016	not available
Nickel	0.8503	2.00E+11	Arsenic	0.0013	4.56E+12
Titanium	0.1570	6.40E+10	Gallium	0.0013	1.77E+10
Barium	0.0315	1.59E+12	Palladium	0.0003	1.20E+11
Manganese	0.0315	3.50E+11	Europium	0.0002	not available
Silver	0.0189	4.50E+11	Niobium	0.0002	4.20E+11
Beryllium	0.0157	1.10E+12	Vanadium	0.0002	7.22E+10
Cobalt	0.0157	1.30E+11	Yttrium	0.0002	1.43E+10
Tantalum	0.0157	1.70E+11	Platinum	<0.0000	3.70E+11
Antimony	0.0094	4.20E+12	Rhodium	<0.0000	1.20E+12
Cadmium	0.0094	3.40E+13	Terbium	<0.0000	not available

[a] Pedersen et al., 1996; [b] Cohen et al. (2007) except for plastic that comes from Buranakarn (1998).

APPENDIX B. Monte Carlo simulation results

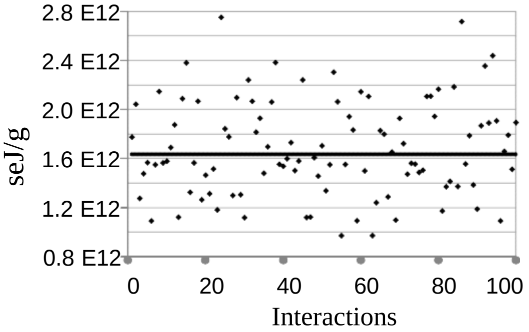

Figure B.1. *Computer's UEV in seJ/g with services. Average of 1.6E12 seJ/g; standard deviation of 0.20E12 seJ/g; 100 interactions; uniform probability distribution function.*

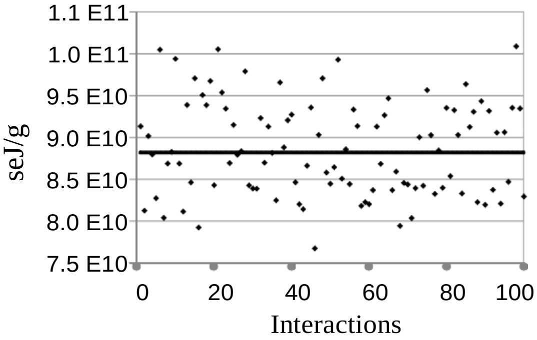

Figure B.2. *Computer's UEV in seJ/g without services. Average of 8.9E10 seJ/g; standard deviation of 0.4E10 seJ/g; 100 interactions; uniform probability distribution function.*

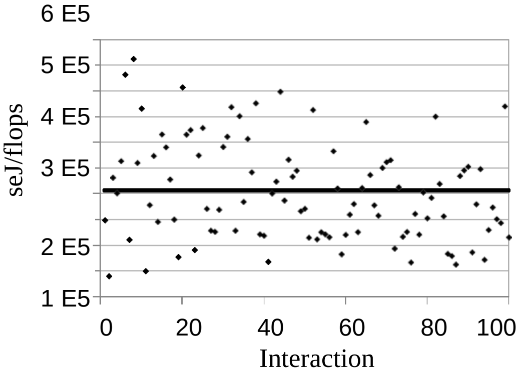

Figure B.3. *Computer's UEV in seJ/flops with services. Average of 3.1E5 seJ/flops; standard deviation of 0.6E5 seJ/flops; 100 interactions; uniform probability distribution function.*

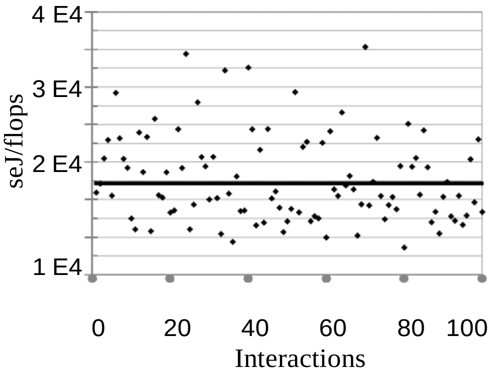

*Figure B.4.**Computer's UEV in seJ/flops without services. Average of 1.7E4 seJ/flops; standard deviation of 0.4E4 seJ/flops; 100 interactions; uniform probability distribution function.*