



Urban solid waste plant treatment in Brazil: Is there a net emergy yield on the recovered materials?

Feni Agostinho, Cecília M.V.B. Almeida, Silvia H. Bonilla, José B. Sacomano, Biagio F. Giannetti*

Universidade Paulista (UNIP), Programa de Pós-graduação em Engenharia de Produção, Laboratório de Produção e Meio Ambiente, Brazil

ARTICLE INFO

Article history:

Received 28 September 2012

Received in revised form 20 January 2013

Accepted 4 February 2013

Keywords:

Composting
Emergy accounting
Urban solid waste
Recycling

ABSTRACT

Disposal alternatives of urban solid waste (USW) are being considered one of the main topics on the political agenda worldwide due to high concerns related to economic, social and environmental issues. In São Paulo Municipality, Brazil, the Sorting and Composting Waste Treatment Plant (SCWTP) is suggested as an appropriated way to manage the 14,000 Mg of USW generated daily by 11 million inhabitants in 2010. The argument is that recovering materials from USW is aligned to sustainable development concept, however there is a lack of a deeper sustainability assessment, raising doubts about the benefits received by society on recovering materials. In this sense, emergy accounting (spelled with “m”) suggests to be a good alternative when assessing these benefits under a global scale. The aim of this work is to assess the São Paulo’s SCWTP using Emergy Accounting. Results shown that currently there is an emergy balance by sorting paper (ratio of recovered by invested emergy of 0.97), and an emergy benefit for iron&steel (2.65), plastic (2.91) and compost (2.57). However, there is an emergy cost by sorting glass (0.23) and aluminum (0.20). A plausible scenario by increasing the recovering efficiency of glass from current 11.6% to 52.9%, and aluminum from 4.7% to 24.7% (both in wet weight), results in an emergy benefit for all materials. The Net Emergy Benefit indicates the SCWTP as a better alternative when the total net emergy return to society is the focus, because while it makes available about $3.13E+14$ sej/Mg of treated USW, the landfills have an average emergy deficit of $-3.39E+13$ sej, indicating that landfill uses more emergy than makes available. Results indicates that SCWTP must receive political incentives due to its good emergy performance and others social beneficial aspects, however, aiming to improve the overall performance, each individual citizen must collaborate with waste reduction and the separation of non-organic material from the organic ones at origin.

© 2013 Elsevier B.V. All rights reserved.

1. Introduction

The Biosphere has a limit to supply resources and to absorb waste, but increasingly amount of resources are demanded at the same time in which higher amount of waste are generated due to current development pattern adopted by worldwide society (Meadows et al., 2004; Hall and Day, 2009). According to *Global Footprint Network (2010)*, this limit (also called as the Earth biocapacity) have been exceeded in 50%, in which nowadays society is using the natural capital storages produced at past. Natural capital storage is being reduced by both direct demand of resources (for instance wood, petroleum and minerals) and indirect demand for natural treatment of human residues. Regarding specifically urban solid waste (USW), nowadays the time needed for its natural

treatment is too long due to reduction of natural capital storages simultaneously with high rates of waste production, mainly in urban centers with high population density. USW can result in serious damages to society and environment when handled incorrectly, as example those ones related to proliferation of disease vectors, generation of bad odors, atmospheric emissions, soil contamination, and surface water and groundwater contamination. Thus, reducing the load on the environment by handling efficiently the USW becomes an important factor regarding sustainable development.

The United Nations Environmental Program (UNEP, 2010) endeavor to align with the prioritization of activities presented in the following waste hierarchy: waste prevention; re-use; recycling; waste-to-energy; and landfill as the latest option. Notwithstanding, almost 64% of USW collected in Brazil is disposed in sanitary landfills, 16% in controlled landfills, 18% in open sky dumps, 2% is recycled and a negligible fraction is incinerated (IBGE, 2008). Even recognizing that sanitary landfills are designed to protect the environment against potential burdens, the three following main disadvantages on landfills can be listed: (i) high amount of methane

* Corresponding author at: Universidade Paulista (UNIP), Programa de Pós-Graduação em Engenharia de Produção, Laboratório de Produção e Meio Ambiente, Rua Dr. Bacelar, 1212, CEP 04026-002, São Paulo, Brazil. Tel.: +55 11 55864127.

E-mail addresses: biafgian@unip.br, feniagostinho@gmail.com (B.F. Giannetti).

emission (Themelis and Ulloa, 2007), even that a fraction of this gas could be collected and burned for electricity generation; (ii) risk of leachate leakage causing damage on water resources (Reyes-López et al., 2008); (iii) the lack of available place for landfills close to urban centers (Leão et al., 2004). Open sky dumps are recognized as an unacceptable practice due to exponential increase of risk factors already existing on landfills. Waste-to-energy is an option slightly supported by the current Brazilian's energetic politics, because about 74% of all consumed electricity by the country is generated through hydropower (Brazilian Energy Balance, 2011), which was adopted in Brazil as the main electricity energy source due to landscape conditions, water availability, and also to know-how established during the last 60 years. Thus, it becomes evident that alternative ways for waste management are mandatory, however, as pointed out by Dijkema et al. (2000), a paradigm change is needed, in which refuse cannot be considered as waste, but something that must be recovered or re-used as a potential resource – waste should be considered as a temporary attribute of a resource. Lino and Ismail (2011) emphasizes the energetic potential gain by feed-backing a fraction of USW into the market as a resource, or even using it directly as energy source. On the other hand, Tiezzi (1998) argues that considering waste a useful resource for a determined process, the energy dissipation is reduced at minimum levels when compared to burning processes for electrical generation or waste disposal at landfills.

Recycling is being suggested as a better alternative for waste management, in which different technological processes are currently available for USW sorting and recycling. According to Yuan et al. (2011), attention should be given to more than economic motivation when assessing performance and choosing a waste treatment project from the perspective of the sustainable development. In this sense, using energy approach could be a good solution, however, the energy efficiency of reusing a resource depends on several aspects as sorting, the production of goods oriented for recycling, the adoption of new transformation processes, among others. In short, the recycling strategy adopted for reducing the amount of USW carried on to landfills cannot demand higher amount of energy than that used for landfill operations, i.e. the energy efficiency under a systemic view for recycling USW should be higher than landfilling it. In this sense, Emergy Accounting (Odum, 1996) is suggested as powerful tool for evaluating under a global scale perspective the energy efficiency of waste management alternatives, supplying quantitative indicators from a donor-side view. Emergy (spelled with “m”) is the available energy of one kind of previously used up directly and indirectly to make a service or product. It is being used by several authors for assessing theoretical aspects on conservation and recycling (Tilley, 2011; Amponsah et al., 2011, 2012) and case studies (Giannetti et al., 2012; Rugani et al., 2011; Yuan et al., 2011; Zhang et al., 2010; Marchettini et al., 2007; Brown and Buranakarn, 2003; Luchi and Ulgiati, 2000; Tiezzi, 1998).

The Brazilian government established in 2010 a national regulation (Política Nacional de Resíduos Sólidos, 2010) aiming an efficient solid waste management by recovering those materials from USW which contains market value. This political effort is considered fundamental because the amount of USW generated in Brazil reaches 190,000 Mg/day, in which São Paulo Municipality solely is responsible for about 7.5% of that total (Abrelpe, 2010). In an attempt to minimize all potential problems associated with landfills, the Municipality of São Paulo has implemented a Sorting and Composting Waste Treatment Plant (SCWTP) to recover abiotic materials and produce compost with the organic materials present into the USW. Although the SCWTP is being considered a good alternative, the mere fact of adopting different destination for USW than landfilling is not enough to ensure that it is a better waste management option among several others available.

Indicators of efficiency are mandatory. Studying scenarios for USW handling in São Paulo Municipality, Mendes et al. (2003) pointed out that when biodegradable wastes are diverted for composting or biogasification and only the non-organic fraction is landfilled, a significant reduction in environmental impacts are observed from a life cycle inventory perspective. Similar results were found by Cherubini et al. (2009, 2009) assessing management alternatives for USW in Rome (Italy) under a multi-criteria multi-scale assessment, in which recycling showed a better performance than landfill and incineration. Even recognizing that São Paulo's SCWTP has a potential to release lower amount of harmful gases to the atmosphere than landfilling USW, whose characteristic validate the implementation of the SCWTP “*per se*”, a doubt still remains: is there an emergy benefit to society by recovering materials into São Paulo's SCWTP?

Recognizing Emergy Accounting as an effective tool to show the system's energy efficiency in a global scale view, the objective of this paper is to use it to assess the net emergy return to society of materials recovered by São Paulo's SCWTP.

2. Methodology

2.1. Description of the Sorting and Composting Waste Treatment Plant (SCWTP)

São Paulo Municipality is located at São Paulo State, Brazil, being considered one of the most developed and richest cities of Brazil with a Gross Domestic Product of 20,000 USD per capita. This economic performance is accompanied by a high population density of 7400 inhabitants per square kilometer, or 11,000,000 inhabitants in total, and several social-environmental problems characteristics of rich cities in developing countries. The negative social aspects could be summarized by the low performance for Gini index of 0.45 (IBGE, 2010), expressing a huge imbalance in the income distribution, i.e. the biggest fraction of economic resources is concentrated in the hands of few people. Regarding environmental issues, one of several problems is related to the appropriated management of the increasing amount of USW, reaching about 14,000 Mg/day (Abrelpe, 2010).

In Brazil, the use of USW to make compost has started at seventies, in which São Paulo Municipality implemented two composting plants called as “Vila Leopoldina” and “São Matheus”. In the nineties, both plants also started to recover abiotic materials for recycling, being labeled as Sorting and Composting Waste Treatment Plant (SCWTP). One of these plants, “Vila Leopoldina”, is located close to an important agricultural market distribution center, thus the idea was that producers bringing their agricultural products to the distribution center could take back the organic compost, optimizing the use of trucks and replacing part of the industrial fertilizers by organic compost produced at the SCWTP.

The SCWTP was initially developed to treat about 1600 Mg per day of USW generated by 2,000,000 inhabitants, corresponding to 18% of Municipality's total inhabitants. Usually, the household urban waste is packed in plastic bags and left in front of residences from where they are taken by a collecting team (manual collection and special trucks for compaction, storage and transport, each one encompassing a truck driver and three or four collectors) working day and night and covering about 270 linear kilometers per day. After collection, the waste can be handled through conventional ways in sanitary landfills, be incinerated or even sent to SCWTP. Fig. 1 shows that while the majority amount of USW (84.5% in wet weight) is taking to sanitary landfills, only 13.5% is sent to SCWTP, and the remaining 2% is incinerated. This figure changes when considering the 6.6% of rejected material by SCWTP, resulting in a net amount of 91.1% of total Municipality's USW going to

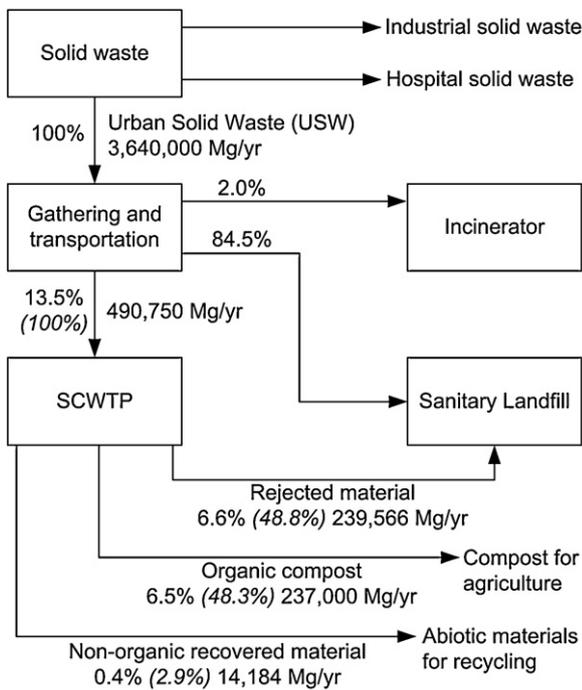


Fig. 1. Flowchart of urban solid waste destination in São Paulo Municipality. Percentages in wet weight of waste.

the sanitary landfill instead 84.5%. Additionally, only 6.9% instead 13.5% of total USW are being effectively recovered (including biotic and abiotic materials).

An overview of all processes involved into the SCWTP can be seen at Fig. 2. After collection, the waste is transported to the plant and discharged into a receiving hopper. Crawlers transport the waste to the primary separation, in which workers separate manually all potential recyclable abiotic materials constituted by paper, glass, plastic and aluminum, which are sold. In the same primary separation process, all abiotic non-recyclable materials (for instance tires, textiles, wood and bricks) are separated and taken to the sanitary landfill. After the primary separation, the ferromagnetic materials (mainly iron and steel) are automatically separated by electro magnet equipment, and the remaining organic material goes to the biodigester. During the aerobic biodigestion, the size of organic materials is reduced and revolved by blades, and the temperature is roughly controlled by an atmospheric air counterflow. The resultant material is sieved, and the thicker fraction is sent to the sanitary landfill. The finer fraction is arranged in piles at open sky to finalize the biological treatment. This last process consumes approximately 30 days, in which the piles are revolved each 10 days and water is added aiming to reduce the temperature of the compost. At the end, the abiotic recyclable product previously labeled as waste becomes a new product on the supply chain, while the organic compost is sold to be used in agriculture.

All raw data used in this work were supplied by the Urban Waste Management Department, responsible for managing the solid urban wastes of São Paulo Municipality. Additional information was obtained “in situ” when needed.

2.2. Emergy accounting

Emergy Accounting evaluates the environmental performance of the system on a global scale, accounting for all considered “free” environmental resources such as sunlight, wind, rain, soil, and the indirect environmental support embodied in human labor and services. The accounting is extended back in time to include the

environmental work needed for resource formation, thus emergy is a measure of the past and present environmental support to any process occurring in the biosphere (Brown and Ulgiati, 2004b). These characteristics make emergy accounting a powerful tool when assessing energy efficiency under a large window view and time, which are not usually included in traditional Embodied Energy Analysis¹, recognized and used worldwide as an important tool to assess energy efficiency of production processes.

According to second law of thermodynamics, each transformation process degrades the available potential energy, but the “quality” of the remaining energy in the product is increased, given a qualitative value for each energy unit. The idea that a calorie of sunlight is not equivalent to a calorie of fossil fuel strikes many as preposterous, since a calorie is a calorie. However, different forms of energy have different abilities to do work, for instance, the work done by a joule of sunlight is not the same as the work done by a joule of fossil fuel, or a joule of food. Sunlight drives photosynthesis but cannot drive an automobile without significant efforts to concentrate it and becoming a useful fuel for internal combustion engines (Brown and Ulgiati, 2004b). Energy quality is a crucial point related to emergy accounting, being expressed by the emergy intensity values.²

Emergy accounting is organized as a top down approach. For its application, initially the system under study must be represented by an energy system diagram using the symbols proposed by Odum (1996). Subsequently, all raw values of the energy and mass going into the system are multiplied by their respective emergy intensity values, resulting in flows represented with the same unit: solar emjoules (seJ). Finally, these flows are aggregated to calculate the emergy indices to draw conclusions about the system’s energetic-environmental performance. Deeper understanding about emergy accounting rules, meanings and calculation procedure can be found mainly at Odum (1996) and Brown and Ulgiati (2004a,b).

Usually, the indices considered in emergy studies are transformity, specific emergy, renewability, emergy yield ratio, emergy investment ratio, environmental loading ratio and sustainability index (see Brown and Ulgiati (1997, 2004a) and Odum (1996) for details of these indices), but in this work it was considered only the emergy indices related specifically to recycling provided by Brown and Buranakarn (2003) and Odum (1996). The first authors developed several indices of recycle effectiveness, defining them using the aggregated patterns of material use in Fig. 3. Raw resources (R_2) are refined requiring an emergy input of fuels, goods and services, and human labor (A_2) – for instance, the conversion of iron ores in marketable steel plates. Then, this refined product is transformed in goods directly usable for society (for instance for food package), it is used and disposed, collected and recycled, feeding back to the transformation process to substitute some portion of the raw resources. All these processes require an amount of input emergy, for instance fuel for heat transfer, for combustion, electricity to move machines, materials for infrastructure and several

¹ Energy Analysis is defined by International Federation of Institutes for Advanced Study (IFIAS) as the process of determining the energy required directly and indirectly to allow a system to produce a specified good or service. In this approach, only the marketable energy is accounted for.

² Emergy Intensity Value (also called as Unit Emergy Value – UEV) represents all emergy used to make a unit of product. The definition of Emergy Intensity is very similar to Energy Intensity (used in Energy Analysis), but Emergy Intensity accounts for more than only market energy. One of the most important UEV is denominated as Transformity, representing the amount of emergy that was originally required to provide one joule of a good or service (units in solar emjoules per joule, seJ/J). As example, if 1,000 solar emjoules are required to generate a joule of ethanol fuel from biomass, then the Transformity of that fuel will be 1,000 solar emjoules per joule, or seJ/J. Other UEVs are: Specific Emergy (seJ/g); Emergy per Monetary Unity (seJ/\$), usually expressed as seJ/USD; and Emergy per Unit Labor (seJ/h; defined as the amount of emergy supporting one hour of human labor).

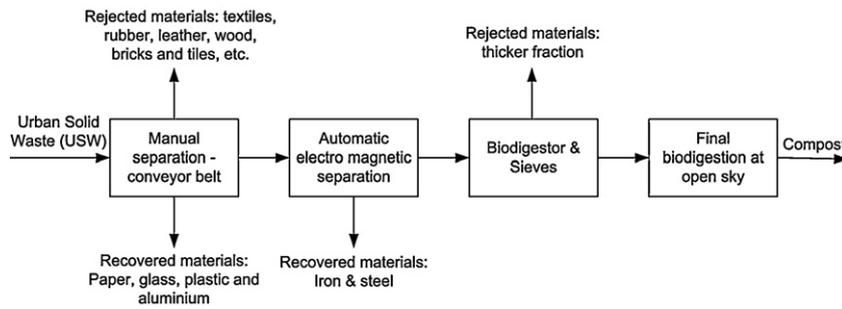


Fig. 2. Overview of processes used by the Sorting and Composting Waste Treatment Plant (SCWTP).

other materials used directly by the process, services and human labor. All these energy flows are symbolized on Fig. 3 by B_2 , C_2 and F_2 arrows.

A key issue studying recycling under an emergy accounting perspective is to know and understand what is the emergy intensity of the recycled material, because until now emergy theory lacks clear rules regarding recycle. According to Fig. 3, the emergy of recycled product (E_2) returning to the transformation process is the sum of the emergy in the raw materials and all the emergy inputs required to maintain the material system cycle ($R_2 + A_2 + B_2 + C_2 + F_2$). However, if the original emergy of materials (R_2 and A_2 flows) are accounted for, then recycling surely will never show an emergy benefit, because for each feedback cycle, the total emergy would increase. Ulgiati et al. (2004) argues that if wastes are treated and re-enter to a production process as a substitute material, only the emergy invested in the collection and recycling process should be assigned to recycled resources, i.e. in Fig. 3 only the C_2 and F_2 flows should be considered. The justification is that after using a product, its utility or “emformation” is lost (see Fig. 3). This implies that in a sufficiently efficient recycling process, secondary materials (derived from wastes) potentially will have lower emergy intensity than the corresponding original ones, thus recognizing the advantage of recycling in open or closed cycles. However, as emphasized by Amponsah et al. (2011, 2012), recognizing that emergy is the memory of the energy dissipated, can the memory be forgotten? These authors affirm that Ulgiati and coworker’s suggestion of resetting the emergy content in recycling process to eliminate the emergy cumulative problem is a good alternative when no information about the number of recycling cycles is available. Amponsah et al. (2011) suggest a correction factor to be used in emergy synthesis of system regarding recycling, but knowing the number

of recycling cycles is hard and sometimes impossible in practical terms, thus, the alternative suggested by Ulgiati et al. (2004) was considered in this present work. Other important study proposing alternatives to emergy rules regarding recycling was published by Tilley (2011), in which the concept of “emformation” is jointly considered into the dynamic emergy account aiming a robust method for modeling the emergy dynamics of systems containing material recycling. Nevertheless, there is still not a standardized and easy-to-be used procedure available.

Taking into account all methodological discussion presented, three emergy indices were considered in this work: (i) Two regarding recycling as suggested by Brown and Buranakarn (2003) to provide information about the appropriateness of a particular material recycle system, however, one of them was modified from the original algebra; (ii) the net emergy (Odum, 1996) showing whether there is a benefit or a cost for society due to alternative waste treatment adopted. The emergy indices considered in this work are described as follows:

- (a) Modified Recycle Yield Ratio ($m-RYR = (R_2 + A_2) / (C_2 + F_2)$) – The ratio of emergy in the refined material ($R_2 + A_2$) to the emergy invested in recycling ($C_2 + F_2$). This index evaluates the benefit that society receives by recycling materials than using the raw resource from nature, i.e. what society gets back in emergy terms compared to the emergy invested in the recycling process. The original RYR index (Brown and Buranakarn, 2003) includes the “ B_2 ” emergy flow in the numerator, however, we understand this flow as mandatory and similar for both pathways of material source (recycled or original from nature) in the transformation process (see Fig. 3). Thus, we believe that a fairer comparison is given by the emergy of original refined

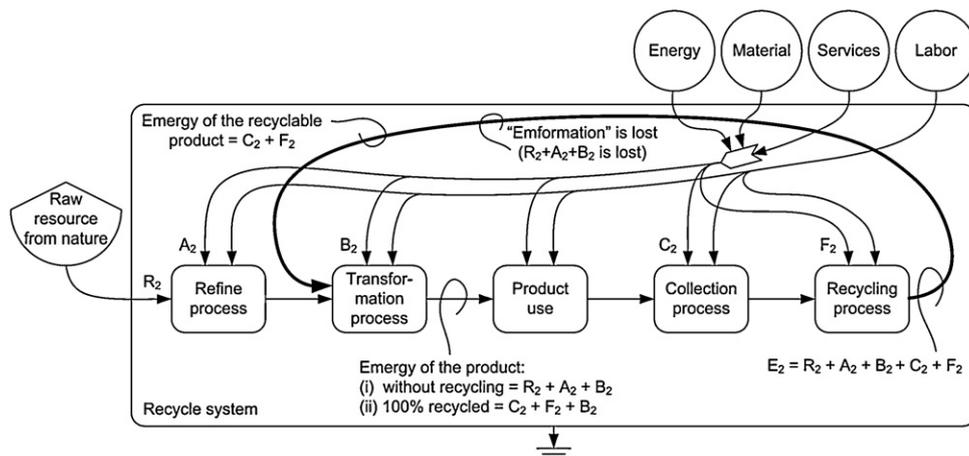


Fig. 3. Aggregated emergy diagram showing the recycle trajectory. Letters R, A, B, C and F refers to the emergy of the inputs demanded by each process and are used to calculate the emergy indices for recycling. Diagram adapted from Brown and Buranakarn (2003). “Emformation” is defined by Brown (2005) as the emergy demanded to create form. When a material is dispersed (or recycled) the stored emergy decreases, and it carries only the emergy of the material, losing the emergy in its form.

material ($R_2 + A_2$) against the energy demanded for collection and recycling ($C_2 + F_2$).

- (b) Landfill to Recycle Ratio ($LRR = (C + F) / (C_2 + F_2)$) – The ratio of energy required for landfilling a material ($C + F$) to the energy required for recycling ($C_2 + F_2$). LRR shows whether recycling waste demands lesser energy than waste landfilling. C and F energy flows were previously calculated by Almeida et al. (2012), in which an energy synthesis of “São João” sanitary landfill (635,000 Mg of waste per year) located at São Paulo Municipality, Brazil, was performed. The author accounted for the waste collection, transportation and disposal, including all materials, energy, human labor and services demanded for this task, resulting in a total energy ($C + F$) of $2.02E+19$ seJ/yr, or $3.18E+13$ seJ/Mg of raw waste.
- (c) Net energy benefit ($NEB = (\text{energy benefits}) - (\text{energy costs})$) – This index supply information about the extensive advantage of one treatment system or process compared to another one, defined as the difference between the energy benefits (considered as useful output for society) and the energy cost (investment in waste treatment plant construction and operation). Values for NEB higher than zero indicates a net saving of energy. It is used in this work to compare the SCWTP with the “São João” sanitary landfill previously assessed by Almeida et al. (2012).

2.2.1. Energy ternary diagrams

Aiming to help the readers to visualize the results obtained in an easy-to-understand way, the energy ternary diagram proposed by Giannetti et al. (2006) is used to graphically represent the results, and also to simulate the ideal situation in which all collected waste is recovered. This diagram is being considered within energy assessments focusing on different aspects, since case studies assessing the energy performance of large watersheds (Agostinho et al., 2010), industrial and agricultural production

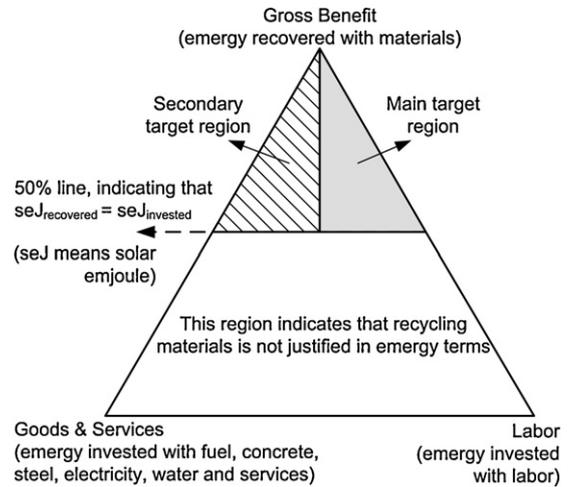


Fig. 4. Energy ternary diagram and its three main regions regarding materials recycling.

systems (Almeida et al., 2007; Agostinho et al., 2008), until evaluating the interactions of human-dominated systems with the environment (Giannetti et al., 2011). In a general way, the ternary diagram comprises three variables associated with the percentages of total used energy, in which the constant sum constraint allows to represent three variables in two dimensions within a triangle. For the purposes of this present work, the energy ternary diagram (Fig. 4) was built according to: (i) the upper apex represents the recovered energy associated with the recyclable materials, i.e. it indicates the energy gross benefit of recycling; (ii) the lower right apex represents the energy of labor used in the materials recovering processes; (iii) the lower left apex represents the sum of invested energy in fuel, concrete, steel, electricity, water and

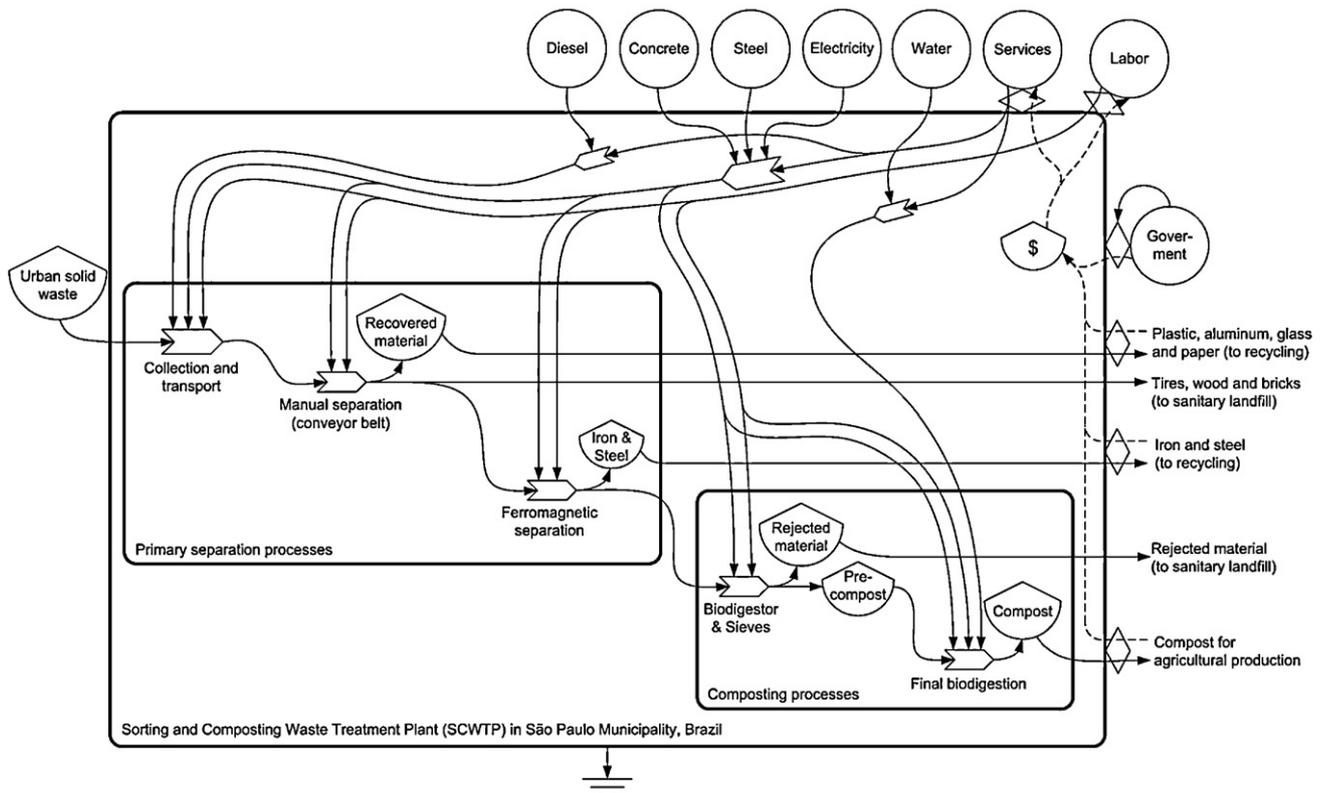


Fig. 5. Energy system diagram of Sorting and Composting Waste Treatment Plant (SCWTP).

Table 1
Recovered material amount from the Urban Solid Waste (USW) received by the Sorting and Composting Waste Treatment Plant (SCWTP). Values in wet weight unit.

Waste characterization	Amount of waste received		Recovered material Mg/yr	Recovering efficiency % In wet weight
	Mg/yr	% In wet weight		
Paper	54,375	11.1	2580	4.7
Glass	8784	1.8	1020	11.6
Iron & steel	7410	1.5	5440	73.4
Plastic	78,029	15.9	4990	6.4
Aluminum	3288	0.7	154	4.7
Organic material	282,378	57.5	237,000	83.9
Others ^a	56,485	11.5	Rejected material	Rejected material
Total	490,750	100.0	251,184	51.2

^a Textiles, rubber, leather, ash, waste water, wood (any kind), bricks and tiles residues from construction.

services demanded for material recycling processes; (iv) the bottom region (trapezium) within triangle represents the region in which recycling is not justified in emergy terms, i.e. a higher amount of emergy is being invested than that recovered with recycling; (v) the upper left region (crosshatched little triangle) represents the secondary target region, i.e. a net positive emergy is obtained by recycling, however, most of the emergy invested comes from goods and services, often recognized as non-renewable resources, and at the same time making the system less resilient to the market behavior; (vi) finally, the upper right region (little triangle with gray color) represents the main target region, i.e. the emergy invested is recovered, and most of the emergy invested comes from human labor, which is considered positive under the social aspect. The main target region is explained by the fact that creating jobs is an important aspect of the SCWTP being evaluated, because its goal is, equally, to be an alternative for the USW

management and give opportunities for those socially marginalized people.

3. Results and discussion

The energy system diagram of SCWTP is given by Fig. 5, representing the external demand and also internal flows of materials, energy and labor. As example of external demand, it can be cited the diesel used to move trucks, steel for trucks construction, plant infrastructure and equipments, electricity to move engines, and labor used by waste collection and plant treatment. While diesel and water are used specifically for collecting and final biodigestion processes respectively, all other inflows are used by all other processes into the SCWTP. Even that economic indicators are not calculated in this work, the exchange of money is represented by the dashed lines on the right side of Fig. 5, symbolizing the recyclable materials

Table 2
Emergy synthesis for construction and operation phases of Sorting and Composting Waste Treatment Plant (SCWTP). Values in wet weight of urban solid waste (USW) received at SCWTP's gate.

Note ^a	Item	Unit	Flows in unit/Mg of USW	Unit emergy value in sej/unit (from literature ^b)	Emergy flows in sej/Mg of USW ^c
Materials for infra-structure and machines (assuming a 30 years lifetime)					
1	Concrete	kg	3.39E-02	2.59E+12	8.77E+10
2	Steel	kg	2.92E-01	1.13E+13	3.30E+12
Materials, diesel and electricity for operating phase					
3	Electricity (primary separation)	J	1.25E+07	2.52E+05	3.16E+12
4	Electricity (composting)	J	2.92E+07	2.52E+05	7.37E+12
5	Water	J	1.90E+06	6.89E+04	1.31E+11
6	Diesel	J	3.27E+07	1.81E+05	5.92E+12
Labor and services for operating phase					
7	Labor (primary separation)	h	1.33E+00	7.21E+12	9.61E+12
8	Labor (primary separation and composting)	h	1.76E+00	7.21E+12	1.27E+13
9	Services	USD	9.00E-01	1.17E+13	1.05E+13
10	Cost for paper transformation ^d	USD	2.40E-01	1.17E+13	2.81E+12
11	Cost for glass transformation	USD	3.16E-02	1.17E+13	3.69E+11
12	Cost for iron&steel transformation	USD	1.24E+00	1.17E+13	1.45E+13
13	Cost for plastic transformation	USD	1.46E-01	1.17E+13	1.70E+12
14	Cost for aluminum transformation	USD	3.63E-02	1.17E+13	4.24E+11
15	Cost for compost transformation	USD	0.00E+00	1.17E+13	0.00E+00
Total emergy demanded for:					
	Paper sorting and transformation (items #1, 2, 3, 6, 7, 9 and 10)				3.54E+13
	Glass sorting and transformation (items #1, 2, 3, 6, 7, 9 and 11)				3.30E+13
	Iron&steel sorting and transformation (items #1, 2, 3, 6, 7, 9 and 12)				4.71E+13
	Plastic sorting and transformation (items #1, 2, 3, 6, 7, 9 and 13)				3.43E+13
	Aluminum sorting and transformation (items #1, 2, 3, 6, 7, 9 and 14)				3.30E+13
	Composting production (items #1, 2, 4, 5, 6, 8, 9 and 15)				4.00E+13

Reference unit of 1890 Mg of USW (wet weight) daily received.

^a Detailed calculation procedure, assumptions and reference for emergy intensity values are presented in Appendix A.

^b Emergy intensity values considering an emergy baseline of 15.83E+24 sej/yr from Odum et al. (2000).

^c (sej/Mg of USW) = (Unit/Mg of USW) * (sej/Unit).

^d Cost for transformation includes basically the emergy demanded by cleaning and crushing the sorted material (post-SCWTP processes) to make it useful again into the industrial processes.

and the compost sold to the market, and the payment of workers and services. It also can be observed a direct governmental subsidy for construction and maintenance of waste treatment plant, indicating a political effort in reducing the amount of urban waste sent to landfills. The two internal subsystems called as “primary separation” and “composting” processes represent the sorting of abiotic (non-organic) materials and composting of biotic (organic) materials, respectively.

Table 1 shows that 51.2% (in wet weight) of total annual amount of waste received by the SCWTP is separated for recycling, while the remaining 48.8% is sent to the sanitary landfill. The worst efficiency was obtained for paper and aluminum materials, with only 4.7% recovered, followed by plastic (6.4%) and glass (11.6%). Iron&steel recovering and organic material composting reached high efficient values, with 73.4% and 83.9% respectively. Usually, householders put the all waste in a plastic bag, which is disposed in front of their houses to be collected and carried to the SCWTP. This procedure causes a contamination of the potential abiotic recyclable materials, which are exposed to the high humidity of the organic materials, making them economically non-attractive for recycling. Even recognizing as low the general efficiency level of 51.2% obtained by SCWTP on the total waste amount received at gate, approximately 250,000 Mg of USW is feedback yearly to market as raw resource, avoiding its disposal in landfill and also the requirement for new raw material from natural stocks.

After understanding the system and elaborating its energy diagram, the emergy synthesis was performed including all flow of goods and services demanded for the SCWTP construction and operation phases (Table 2). Due to a clear division for electricity and labor pathways flowing into the system, they were divided into primary separation and composting processes (see Fig. 5)—this approach allows a more precise assessment of the net emergy return for each recovered material. Items #1 and #2 represent the emergy used for plant construction, while items #3 to #15 represent the annual emergy demanded for operation phase. Labor and services demand the highest amount of emergy, followed by diesel, electricity and steel. It is worthy to note that co-product emergy rule used in this study does not allow allocation procedure, since it is assumed that all processes are connected and cannot run independently. Further information about emergy algebra is available at Odum (1996), Brown and Herendeen (1996), and Bastianoni et al. (2011).

Items #10 to #15 of Table 2 represent an additional emergy demanded for materials transformation, i.e. the emergy used to make the recovered material into a raw available material for different industrial/agricultural processes that could use them. For example, plastic bottles separated in the SCWTP must be cleaned, crushed and melted before their further use. The processes of cleaning and crushing were considered. This additional emergy should be accounted for allowing a fair comparison when discussing the emergy efficiency of the recovered material and the original raw

material, i.e. both materials should be at the same stage of utility. The importance in accounting for the emergy of a post-SCWTP processes is highlighted mainly by the high emergy demand for iron&steel (item #12 of Table 2), because it represents about 30.8% of total emergy demanded for iron&steel sorting and transformation. Other values for additional emergy demand for materials transformation on the total emergy used were 7.9% for paper, 4.9% for plastic, 1.3% for aluminum and 1.1% for glass. Compost is a final product of the SCWTP and has no additional emergy cost.

Table 3 shows the amount of recovered materials by the SCWTP in mass and emergy units. One important aspect is expressed by the numerical differences between mass and emergy units. For instance, it can be observed that the recovered amount of compost in mass units is about 43.4 times higher than iron&steel, but the emergy recovered with iron&steel is about 1.2 times higher than compost. This is explained due to higher specific emergy of iron&steel, i.e. producing a kilogram of iron&steel demands higher emergy investment that for producing the same amount of compost. This typical example shows that mass units are not able to represent the effort made by the biosphere in producing a resource, thus a real value of a resource (in a donor-side view) should never be assumed as its amount in mass units. The highest amount of recovered material is the compost with 482 kg/Mg of waste, whose equivalent in emergy units is $1.03E+14$ seJ/Mg of waste, corresponding to 27.4% of total emergy recovered by SCWTP. The other materials obtained 33.2% (iron&steel), 26.6% (plastic), 9.1% (paper), 2.0% (glass) and 1.7% (aluminum) of total emergy recovered. These values show which material is responsible for the highest emergy recovered (compost), but they do not represent the emergy cost for recovering. To validate a system, it is mandatory that the recovered emergy from materials by the SCWTP must have a net positive emergy return to society, and it also must have a better emergy efficiency compared to others USW management alternatives, for instance landfilling.

3.1. Modified recycle yield ratio (m-RYR)

The emergy spent in the collection and separation of each material (Table 2) can be now compared with the emergy recovered with materials (Table 3), in which a 50% represents an equilibrium, i.e. all emergy invested is obtained back as raw resource. The ternary diagram of Fig. 6 shows that emergy of plastic, iron&steel, and compost are higher than the emergy invested to recover them, resulting in a positive net emergy return to society, i.e. recycling those materials are justified considering an emergy accounting perspective. The best performance was obtained for plastic (75%), followed by iron&steel (73%) and compost (72%). Paper's performance could be considered in balance (almost 50%), i.e. all emergy invested in its recovering is obtained back as raw material.

Fig. 6 shows, through the m-RYR index, that about 2.91 times more emergy is returned to society per emergy unit invested

Table 3

Emergy of materials recovered by the Sorting and Composting Waste Treatment Plant (SCWTP). Values in wet weight of urban solid waste (USW).

Note ^a	Recovered material	Unit	Flows in unit/Mg of USW	Unit emergy value in seJ/UNIT (from literature ^b)	Emergy flows in seJ/Mg of USW ^c
16	Paper	kg	5.25E+00	6.52E+12	3.42E+13
17	Glass	kg	2.08E+00	3.63E+12	7.53E+12
18	Iron & steel	kg	1.11E+01	1.13E+13	1.25E+14
19	Plastic	kg	1.02E+01	9.83E+12	9.98E+13
20	Aluminum	kg	3.13E-01	2.10E+13	6.58E+12
21	Compost	kg	4.82E+02	2.13E+11	1.03E+14
	Total emergy recovered with materials:				3.76E+14

^a Detailed calculation procedure, assumptions and reference for emergy intensity values are presented in Appendix A.

^b Emergy intensity values considering an emergy baseline of $15.83E+24$ seJ/yr from Odum et al. (2000).

^c (seJ/Mg of USW) = (Unit/Mg of USW) * (seJ/Unit).

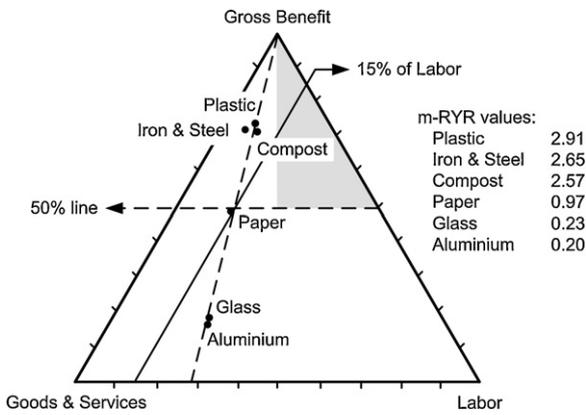


Fig. 6. Ternary diagram comparing the total energy demanded for collection and separation of recyclable materials against the original energy of recovered materials. The acronym m-RYR means modified recycle yield ratio index.

when plastic is recycled. On the other hand, recycling glass and aluminum cannot be justified under an emergy accounting perspective, because they demand more energy for their recovery, i.e. there is a negative net emergy feedback to society. The m-RYR shows that for each emergy unit invested on glass and aluminum recovering, only 0.23 and 0.20 emergy units become available. It must be emphasized that obtained results do not say that landfilling or other waste management alternative is better than the SCWTP, but only that recovering some materials by the SCWTP is more appropriated than recovering others. To obtain this kind of answer, a multicriteria approach including other evaluation tools and indices should be used comparing different waste destination (see for instance Cherubini et al., 2008, 2009). For the current efficiency on material recovering at SCWTP, results on Fig. 6 indicate that while for plastic, iron&steel, and compost there is a net emergy return to society, for glass and aluminum the balance is negative; the product “paper” can be considered in balance. This result runs against the hypothesis of that recycling is always the best option for any kind of material at any recycling process. Similar results were obtained by Tiezzi (1998) assessing the waste treatment for “Comune di Modena”, Italy, in which recycling plastic and batteries showed an emergy cost for society, while glass, paper, bricks, metals and compost showed an emergy benefit. However, the same author argues that disposing waste in landfills or burning it is considered as resource wastage, because waste comprises large amounts of emergy stored during time, whose amount is larger than the emergy demanded by collecting, sorting and recycling them. Thus recycling should be prioritized, but the process efficiency for recycling materials in the SCWTP must be improved.

It is worth to note in Fig. 6 that the human labor contribution to the recovery of all materials follows a tendency of about $15 \pm 9\%$, which suggests being a standard behavior in the SCWTP, regardless the intrinsic emergy embodied in each recovered material. The dashed line drawn from the upper apex crossing through all points shows that, keeping the same ratio between goods & services and labor demand, the secondary target region can be reached by increasing the amount of recovered material, i.e. increasing the recovering efficiency. Two main possibilities can be explored aiming to increase the performance of emergy net return: (i) to reduce the emergy demand in the collection and operation phases (e.g. reducing expenses with electricity, diesel, workers, machines, services, etc), and (ii) to improve the material recovering efficiency.

Regarding the first possibility, among all different sources of invested emergy represented by the nominated Goods & Services (lower left apex of Ternary Diagram), “services” and “fuel” items are responsible from 60% to 82% of the total emergy amount. Services represent the maintenance costs of the SCWTP, reaching a

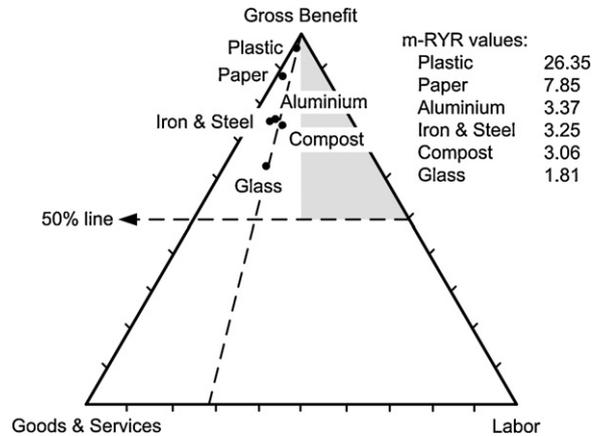


Fig. 7. Ternary diagram comparing the total energy demanded for collection and separation of recyclable materials against the emergy recovered considering a scenario for an efficiency of 100% for all materials recovering. The acronym m-RYR means Modified Recycle Yield Ratio index.

value of 442,000 USD/yr (Note#9 in Appendix A). It is recognized that it is hard to reduce maintenance costs, however, an effort in this sense could be prioritized by using machines, equipments and all the infra-structure in a conservative way. To reach this goal, appropriated instructions (practical courses, workshops, etc) to workers could be a good and cheap alternative. Other expressive item within the total emergy invested is the diesel used by trucks during the waste collection and transportation to the SCWTP, which reaches 452,000 L/yr (Note#6 in Appendix A). Aiming to reduce this demand, better logistic could be planned for waste collection or the replacement of diesel by biofuels (biodiesel, ethanol, etc), whose potentially have better emergy efficiency, i.e. lower transformity values. In this sense, the production of biogas from waste organic fraction biodegestion and its use could be considered a good alternative.

3.1.1. A scenario approach

Regarding the second possibility to increase the emergy net return, a scenario of 100% efficiency for all recovered materials using data from Table 1 is shown in Fig. 7. In this scenario, the ternary diagram indicates that all materials have a positive net emergy contribution to society, i.e. the emergy of the recovered materials is higher than the emergy used to collect and sorting them. This result indicates that SCWTP's structure, processes, energy, material and labor demand are currently enough to reach a good emergy performance, on the other hand, no information is supplied about an alternative and potentially better way to manage the system (for instance, logistics for waste collection, equipments with higher technology, labor efficiency, and so on), whose variables could improve (or not) even more the final results. More than show the potential of recovering materials, Fig. 7 also indicates that currently there is a loitered amount of storage emergy in the SCWTP, i.e. all the available infra-structure and process operations are overestimated considering the low current efficiency for recovering materials.

According to Tiezzi (1998), the higher environmental cost to produce a good or service, i.e. the higher its original transformity, higher also will be the potential benefit to recycle it. In this sense, recycling aluminum would have higher recycling benefit to society than plastic and paper, because while aluminum has a original specific emergy of $2.10E+13$ seJ/kg (Table 3), plastic and paper have $9.83E+12$ seJ/kg and $6.52E+12$ seJ/kg respectively. However, Tiezzi's (1998) statement was not reflected by Fig. 7, because even the original aluminum material possess higher transformity compared to all other materials, it obtained lower m-RYR than plastic

Table 4

Comparison of emergy benefit and cost for three different Urban Solid Waste (USW) treatment alternatives in São Paulo municipality. Values in seJ/Mg of weight USW.

Index	System		
	SCWTP (this work)	Sanitary landfill (Almeida et al., 2012)	Sanitary landfill with CH ₄ recovering and electricity generation (Almeida et al., 2012)
Gross emergy benefit	3.76E+14	Zero ^a	2.16E+14 ^b
Total emergy cost	6.30E+13	3.18E+13 ^c	2.52E+14 ^d
Net emergy benefit ^e	3.13E+14	−3.18E+13	−3.60E+13

^a There are several economic, social and environmental benefits related to a sanitary landfill compared to traditional open sky dumps, but only the direct emergy or material recovered were considered here.

^b Electricity generated by CH₄ recovered = (3.40E+8 kWh/yr) (1000 W/kW) (3600 s/h) (1/635,000 Mg of waste/yr) (1.12E+5 seJ/J from Brown and Ulgiati, 2004a).

^c Total emergy of 2.02E+19 seJ/yr; annual average of 635,000 Mg of weight USW.

^d Total emergy of 1.60E+20 seJ/yr; annual average of 635,000 Mg of weight USW.

^e Net emergy benefit (NEB) = gross emergy benefit – total emergy cost.

and paper. Probably, this happened because the system studied (the SCWTP) is a plant handling USW containing different materials instead a specific one, i.e. its overall recovering efficiency is reduced because it is not specialized in recovering a specific material. In other words, a different result could be obtained if the SCWTP's focus would recover only a specific material (glass as example), in which all emergy demanded for recycling (C_2 and F_2 emergy flows in Fig. 3) would be maximized to reach higher m-RYR index.

Other interesting aspect that deserves some attention is the fact that for both figures (Figs. 6 and 7) none of them were able to reach the main target, i.e. the upper right region within triangle. This indicates that systems demand higher amount of emergy from economic resources (goods & services) than from human labor, and that this last one should be more explored to improve the social aspect of the SCWTP.

Working on maximum efficiency as showed by Fig. 7 could be considered difficult due to practical problems faced nowadays related to the contamination of non-organic materials by the organic ones, i.e. they are disposed together in the same plastic bag in front of houses to be collected and transported until the SCWTP. However, an increase in recovering glass from current 1020 Mg/yr (Table 1) to a scenario of 4650 Mg/yr, aluminum from current 154 Mg/yr (Table 1) to a scenario of 815 Mg/yr, and paper from current 2580 Mg/yr (Table 1) to a scenario of 2680 Mg/yr will result in an m-RYR of 1.00 for all materials, indicating that emergy used to recover them will be available again in the form of raw material. In this scenario, the process of collecting and sorting of all materials for recycling assessed here will result in a net positive emergy return to society and should be encouraged as a public policy.

3.2. Landfill to recycle ratio (LRR)

The emergy demand for the waste treatment plant assessed in this work is equal to 6.30E+13 seJ/Mg of waste ($C_2 + F_2$ flows in Fig. 3 obtained by adding items #1 to #6 and #8 to #15 of Table 2), while the emergy demand for the sanitary landfill considered as comparison is 3.18E+13 seJ/Mg of waste ($C' + F'$) from Almeida et al. (2012). The LRR resultant of 0.5 indicates that landfilling the USW demands about 50% less emergy than handling it by the SCWTP, indicating that the sanitary landfill should be promoted instead of the SCWTP when taking into account only the total emergy investment. However, it should be highlighted that LRR does not account for the emergy of products output, social issues and also other direct environmental burdens, instead it only compares the emergy demand for infra-structure and operation phases of alternatives waste disposal and treatment. In this sense, we believe that a more appropriate index to show which waste management alternative should be promoted is the net emergy benefit, discussed in the next item.

3.3. Net emergy benefit (NEB)

Table 4 shows the SCWTP supplying the highest gross emergy benefit to society (3.76E+14 seJ/Mg of waste), followed by the sanitary landfill with electricity generation (2.16E+14 seJ/Mg of waste). The sanitary landfill without electricity generation obtained “zero” benefits. It should be emphasized that benefits in this work express the emergy of products, in which only direct material and emergy recovered from waste treatment were accounted for (for instance the CH₄ recovered for electricity or heat generation, recyclable materials, and so for). Sanitary landfill with electricity generation has higher emergy cost (2.52E+14 seJ/Mg of waste) compared to other two systems, because it demands high amount of emergy for its construction and operation phases. The SCWTP has an intermediary emergy cost of 6.30E+13 seJ/Mg of waste, however it is able to supply a positive net emergy benefit (NEB) of 3.13E+14 seJ/Mg of waste to society, while both sanitary landfills have a negative value for NEB, i.e. they have an “emergy cost” rather than a benefit—this is usually called an entropy trap. Similar results were obtained by Björklund et al. (2001) assessing the emergy demand for wastewater sludge biodigestion for electricity production in Sweden, in which purchasing electricity directly from the Sweden's distribution grid would be more resource-efficient. All these numbers highlight that high gross emergy benefit should not be considered as the target to be reached, or even the emergy investment, rather than the net emergy benefit suggest being a more appropriated index when evaluating the net emergy return to society.

Converting the sanitary landfill into another one with electricity generation by investing about 7.9 times more emergy (from 3.18E+13 seJ/Mg of waste to 2.52E+14 seJ/Mg of waste; Table 4) will not result in a net emergy benefit to society, thus, under an emergy perspective, it should not be promoted. However, it must be emphasized that some economic, social and also environmental aspects (for instance, gas emissions to atmosphere, soil and water contamination by leachate, jobs availability, among others) were not considered to support this conclusion. Regarding the SCWTP, assuming a scenario of 100% efficiency for material recovering, the gross emergy benefit would be 2.78E+15 seJ/Mg of waste, resulting in a net emergy benefit of 2.72E+15 seJ/Mg of waste, a value about 8.7 times higher than currently.

4. General comments

Instead limited to action of individual factors, the success of a recycling program requires an interaction among public and private sectors. Public participation is related to governmental subsidy for waste treatment plant construction (infra-structure and machines) and also related to citizens' individual responsibility regarding pre-separation of abiotic material from the biotic ones at the origin. Public participation is increasing in the last decades, due to all socio-environmental problems related to waste management, especially

in large urban centers as São Paulo Municipality. Few decades ago, these problems were not considered as priorities, but currently they are one of the most important in the political agenda. Private sectors are important in supplying technical knowledge and training for workers, some financial support when needed, and mainly to make possible the market of recovered materials by investing in industrial processes that demand them. Private participation is also growing due to public pressure on a cleaner production, in which each time more the companies are concerned with its image by the consumers.

The biggest problem concerning the success of a recycling program is overcoming the issue related to waste contamination at origin. Nowadays, the non-organic (abiotic) fraction of raw waste collected and transported until the waste treatment plant arrives mixed (contaminated) with the organic (biotic) fraction at high moisture, becoming not useful for recycling or useful only after high amount of emergy used to cleaning it. Hopefully, a State law (Lei Estadual 12300, 2006) establishes that public sector represented by São Paulo State's Government must incentive each Municipality by the implementation of a program for separation of solid urban waste at origin, aiming to improve the efficiency in recovering materials and feedback them to industrial processes again. This practice for sure will improve the efficiency of waste sorting at treatment plant, mainly for those materials derivate from paper and plastic whose are usually the most contaminated by the organic fraction.

Coming back to research question of this work ("Is there an emergy benefit to society by recovering materials into São Paulo's SCWTP?") it could be said YES for some materials and NO to another ones considering the current efficiency in recovering. Results showed a good emergy performance for iron&steel, plastic and compost, however, there is not an emergy benefit for society by sorting glass and aluminum. Paper obtained a balance between the emergy invested and the emergy recovered. These results could be changed by improving moderately the recovering efficiency of glass and aluminum, or even better, considering a scenario of 100% efficiency for all materials – in both cases the answer to research question would be YES for all materials. Regarding specifically the aluminum, the low efficiency in recovering it (4.7% in wet weight; Table 1) can be explained by the fact that there is an informal market for this material, i.e. people are encouraged to collect it and sold it in a parallel market to have an additional profit. Thus, when the aluminum is sorted within the SCWTP, it is collected and sold directly by SCWTP's employees instead following the regular steps done by all other materials as plastic, paper, iron&steel, etc. This procedure is allowed by the SCWTP managers, because the project itself is an effort to establish a good technical-economic alternative for managing the USW at the same time collaborating with those people living under minimum lifestyle conditions. High economic profit is not the primary aim of the SCWTP, which instead needs sustain itself economically, simultaneously overcoming the USW problem and providing jobs for marginalized people.

Other important issue raised in this work is related to which kind of USW treatment is better under an emergy accounting view: Does the SCWTP have better emergy performance than landfill? Results showed that SCWTP has higher net emergy benefit to society compared to both landfills considered as comparison. Additionally, the lack of available space for landfill construction will perhaps, as well as the potential environmental (leachate acting on water bodies and soil) and social impacts, mainly those ones concerning human health (disease vectors); even recognizing that sanitary landfill is projected and strongly controlled to avoid these potential problems. Emergy Accounting suggest to be a good tool assessing under a global scale (systemic view) the best alternative for USW management, however all local environmental load as gaseous emissions, water and soil contamination, among others,

were not considered by emergy synthesis because it is a donor side approach. We recognize that all emergy invested to avoid those potential environmental load (for instance a biofilter installation to collect gas contaminants at waste management plant (Mendes et al., 2003), wastewater treatment, soil contamination control, and so on) should be accounted for to have a more precise result, however the SCWTP and the landfills considered in this work have an environmental damage plan control working in which only some gases (mainly CH₄ and CO₂) are released to atmosphere. Thus, it seems that including the emergy cost of goods and services to control these emissions will not modify significantly the results.

Currently, the USW treatment plants are being considered as a business opportunity on Clean Development Mechanism (IPCC, 2007), but probably this approach will not solve the waste issue problem, rather than it is only one way to few people have financial benefit on a larger societal problem. The main point in which we would like to call attention is that society needs a paradigm change, in which waste should not be considered as longer as a problem, but part of a more mature complex system dominated by humans; in natural systems, waste is a word that does not exist. According to Tiezzi (1998), whether the waste is not considered again as a resource, the entire work of the biosphere in producing that resource will be lost. In a planet where the limits to growth are each day put into doubt (Meadows et al., 2004), waste should be considered as a source of resource, in which different industries working in clusters should incorporate the by-products of one system into a valuable raw resource for other process. Specifically in this work, we emphasize that USW should be returned to human dominated production systems, including agricultural and industrial sectors.

5. Conclusion

According to methodology and assumptions considered in this work, the following conclusions can be raised:

- (i) The current efficiency of SCWTP for sorting and composting USW results in a net positive emergy return to society when dealing with paper (m-RYR of 0.97, representing a balance between recovered versus invested emergy), iron&steel (m-RYR of 2.65, recovering 2.65 more emergy than investing), plastic (m-RYR of 2.91) and compost (m-RYR of 2.57). On the other hand, sorting glass (m-RYR of 0.23) and aluminum (m-RYR of 0.20) is not justified under an emergy accounting perspective.
- (ii) Assuming a potential scenario of increasing the SCWTP's recovering efficiency in 100%, all materials reach a net positive emergy return to society by recovering more emergy than investing. However, increasing solely the glass recovering efficiency (from current 11.6% to 52.9% in wet weight; from 1.020 Mg/yr to 4.650 Mg/yr) and aluminum (from current 4.7% to 24.7% in wet weight; from 154 Mg/yr to 815 Mg/yr) is enough to have an overall net positive emergy return for all materials, i.e. an m-RYR higher than one.
- (iii) The SCWTP demands about twice emergy investment than Sanitary landfill (6.30E+13 sej/Mg and 3.18E+13 sej/Mg respectively). However, it must be highlighted that this emergy correspond to infra-structure and operation phases exclusively, disregarding the emergy of recovered material and energy.
- (iv) The SCWTP is a better alternative than Sanitary landfill (with or without electricity generation) under an emergy accounting perspective. While the SCWTP is able to supply to society about 3.13E+14 sej/Mg of treated USW, the Sanitary landfill and the Sanitary landfill with electricity generation have an emergy

deficit of $-3.18\text{E}+13$ seJ/Mg and $-3.60\text{E}+13$ seJ/Mg of treated USW.

Even that not evaluated in this work, there is a potential of good performance for economic, social and also direct (or local) environmental aspects as outcome of the SCWTP. Economic advantage exists due to materials recovered and sale to market, in which the revenue is managed by a cooperative of workers. Social advantages are related to high demand of workers (usually non-qualified labor, i.e. people with low education level) and the inclusion of these marginalized people into the society again; they fell as citizens again. Environmental issue is mainly related to threat of water bodies and soil contamination with hazardous products. Taking all this into account and also the results obtained in this work, we believe that SCWTP should be strongly promoted by public policies, however, we also emphasize firstly that the USW amount must be reduced, and secondly that abiotic fraction must be separated from the biotic fraction in the origin (i.e. at houses) before send them to public USW management facilities.

Acknowledgements

We are grateful to Department of Public Services of São Paulo Municipality, specifically to Mr. Rogério Seiji Guibu of Department of Urban Cleaning due to expended time in supplying essential information for this work. Special thanks to Eli Santos Araújo due to his collaboration on raw data obtainment, and to financial support of the Vice-Reitoria de Pós-Graduação e Pesquisa da Universidade Paulista (UNIP).

Appendix A. Calculation procedure of Tables 2 and 3

Note #1 (Concrete) – It includes infrastructure; Constructed area = 5000 m^2 ; Concrete used = 100 kg/m^2 ; Lifetime = 30 yr; Functional unit = $1.890\text{ Mg raw waste/day}$; Annual working days = 260 day/yr ; Conversion = $(\text{m}^2) (\text{kg/m}^2) (\text{yr})^{-1} (\text{day/yr})^{-1} (\text{Mg raw waste/day})^{-1}$; Total = $3.39 \times 10^{-2}\text{ kg/Mg raw waste}$; Specific energy = $2.59 \times 10^{12}\text{ seJ/kg}$ (Buranakarn, 1998).

Note #2 (Steel) – It includes infrastructure, machines and trucks; Amount of steel = $4.30 \times 10^6\text{ kg}$; Lifetime = 30 yr; Functional unit = $1.890\text{ Mg raw waste/day}$; Annual working days = 260 day/yr ; Conversion = $(\text{kg}) (\text{yr})^{-1} (\text{day/yr})^{-1} (\text{Mg raw waste/day})^{-1}$; Total = $2.92 \times 10^{-1}\text{ kg/Mg raw waste}$; Specific energy = $1.13 \times 10^{13}\text{ seJ/kg}$ (Brown and Ulgiati, 2004a).

Note #3 (Electricity, primary separation process) – Total amount = $1.16 \times 10^1\text{ kWh/Mg raw waste}$; Percentage used = 30%; Conversion = $(\text{kWh/Mg raw waste}) (30\%) (1.000\text{ W/kW}) (3600\text{ s/h})$; Total = $1.25 \times 10^7\text{ J/Mg raw waste}$; Transformity = $2.52 \times 10^5\text{ seJ/J}$ (Brown and Ulgiati, 2004a).

Note #4 (Electricity, composting process) – Total amount = $1.16 \times 10^1\text{ kWh/Mg raw waste}$; Percentage used = 70%; Conversion = $(\text{kWh/Mg raw waste}) (70\%) (1000\text{ W/kW}) (3600\text{ s/h})$; Total = $2.92 \times 10^7\text{ J/Mg raw waste}$; Transformity = $2.52 \times 10^5\text{ seJ/J}$ (Brown and Ulgiati, 2004a).

Note #5 (Water) – Used only for temperature and humidity control of composting process; Total amount = $0.38\text{ m}^3/\text{Mg raw waste}$; Gibbs free energy = 5000 J/kg ; Conversion = $(\text{m}^3/\text{Mg raw waste}) (1000\text{ kg/m}^3) (\text{J/kg})$; Total = $1.90 \times 10^6\text{ J/Mg raw waste}$; Transformity = $6.89 \times 10^4\text{ seJ/J}$ (Brown and Ulgiati, 2004a).

Note #6 (Diesel) – Including raw waste collection and transportation until the waste treatment plant; Total amount = $452,000\text{ L/yr}$; Functional unit = $1890\text{ Mg raw waste/day}$; Annual working days = 260 day/yr ; Conversion = $(\text{L/yr}) (\text{Mg raw waste/day})^{-1} (\text{day/yr})^{-1} (0.85\text{ kg/L}) (10,000\text{ kcal/kg}) (4,186\text{ J/kcal})$;

Total = $3.27 \times 10^7\text{ J/Mg raw waste}$; Transformity = $1.81 \times 10^5\text{ seJ/J}$ (Brown et al., 2011).

Note #7 (Labor, primary separation process) – Total workers = 356 workers; annual working hours = 1840 h/worker/yr ; Annual working days = 260 day/yr ; functional unit = $1890\text{ Mg raw waste/day}$; conversion = $(\text{workers}) (\text{h/worker/yr}) (\text{day/yr})^{-1} (\text{Mg raw waste/day})^{-1}$; Total = $1.33\text{ h/Mg raw waste}$; specific energy = $7.21 \times 10^{12}\text{ seJ/h}$ (Brown and Ulgiati, 2004a).

Note #8 (Labor, primary separation and composting processes) – Total workers = 470 workers; Annual working hours = $1,840\text{ h/worker/yr}$; Annual working days = 260 day/yr ; Functional unit = $1,890\text{ Mg raw waste/day}$; Conversion = $(\text{workers}) (\text{h/worker/yr}) (\text{day/yr})^{-1} (\text{Mg raw waste/day})^{-1}$; Total = $1.76\text{ h/Mg raw waste}$; Specific energy = $7.21 \times 10^{12}\text{ seJ/h}$ (Brown and Ulgiati, 2004a).

Note #9 (Services) – It includes infra-structure and machines repairs and phone bill; Maintaining costs = $752,000\text{ R\$/yr}$; Real per dollar ratio = $1.70\text{ R\$/USD}$; Annual working days = 260 day/yr ; Functional unit = $1,890\text{ Mg raw waste/day}$; Conversion = $(\text{R\$/yr}) (\text{R\$/USD})^{-1} (\text{day/yr})^{-1} (\text{Mg raw waste/day})^{-1}$; Total = $9.00 \times 10^{-1}\text{ USD/Mg raw waste}$; Energy per money ratio = $1.17 \times 10^{13}\text{ seJ/USD}$ (Sweeney et al., 2007).

Note #10 (Cost for paper transformation) – It includes electricity and water demand to make the paper sorted at waste treatment plant ready to be used again by the paper industry; Cost = $45.78\text{ USD/Mg paper}$ (IPEA, 2010); Recovered material = $5.25 \times 10^{-3}\text{ Mg paper/Mg raw waste}$; Conversion = $(\text{USD/Mg paper}) (\text{Mg paper/Mg raw waste})$; Total = $2.40 \times 10^{-1}\text{ USD/Mg raw waste}$; Energy per money ratio = $1.17 \times 10^{13}\text{ seJ/USD}$ (Sweeney et al., 2007).

Note #11 (Cost for glass transformation) – It includes electricity and water demand to make the glass sorted at waste treatment plant ready to be used again by the glass industry; Cost = $15.21\text{ USD/Mg glass}$ (IPEA, 2010); Recovered material = $2.08 \times 10^{-3}\text{ Mg glass/Mg raw waste}$; Conversion = $(\text{USD/Mg glass}) (\text{Mg glass/Mg raw waste})$; Total = $3.16 \times 10^{-2}\text{ USD/Mg raw waste}$; Energy per money ratio = $1.17 \times 10^{13}\text{ seJ/USD}$ (Sweeney et al., 2007).

Note #12 (Cost for iron&steel transformation) – It includes electricity and water demand to make the iron&steel sorted at waste treatment plant ready to be used again by the iron&steel industry; Cost = $112.09\text{ USD/Mg iron&steel}$ (IPEA, 2010); Recovered material = $1.11 \times 10^{-2}\text{ Mg iron&steel/Mg raw waste}$; Conversion = $(\text{USD/Mg iron&steel}) (\text{Mg iron&steel/Mg raw waste})$; Total = $1.24 \times 10^0\text{ USD/Mg raw waste}$; Energy per money ratio = $1.17 \times 10^{13}\text{ seJ/USD}$ (Sweeney et al., 2007).

Note #13 (Cost for plastic transformation) – It includes electricity and water demand to make the plastic sorted at waste treatment plant ready to be used again by the plastic industry; Cost = $14.33\text{ USD/Mg plastic}$ (IPEA, 2010); Recovered material = $1.02 \times 10^{-2}\text{ Mg plastic/Mg raw waste}$; Conversion = $(\text{USD/Mg plastic}) (\text{Mg plastic/Mg raw waste})$; Total = $1.46 \times 10^{-1}\text{ USD/Mg raw waste}$; Energy per money ratio = $1.17 \times 10^{13}\text{ seJ/USD}$ (Sweeney et al., 2007).

Note #14 (Cost for aluminum transformation) – It includes electricity and water demand to make the aluminum sorted at waste treatment plant ready to be used again by the aluminum industry; Cost = $115.75\text{ USD/Mg aluminum}$ (IPEA, 2010); Recovered material = $3.13 \times 10^{-4}\text{ Mg aluminum/Mg raw waste}$; Conversion = $(\text{USD/Mg aluminum}) (\text{Mg aluminum/Mg raw waste})$; Total = $3.63 \times 10^{-2}\text{ USD/Mg raw waste}$; Energy per money ratio = $1.17 \times 10^{13}\text{ seJ/USD}$ (Sweeney et al., 2007).

Note #15 (Cost for compost transformation) – There is no additional cost for compost transformation because it gets out of waste treatment plant ready to be used on agricultural land.

Note #16 (Paper) – Annual amount of recovered paper = 2580 Mg paper/yr; Annual working days = 260 day/yr; Functional unit = 1890 Mg raw waste/day; Conversion = (Mg paper/yr) (1000 kg paper/Mg paper) (day/yr)⁻¹ (Mg raw waste/day)⁻¹; Total = 5.25×10^0 kg paper/Mg raw waste; Specific energy = 6.52×10^{12} seJ/kg (Sinisgalli, 2000).

Note #17 (Glass) – Annual amount of recovered glass = 1020 Mg glass/yr; Annual working days = 260 day/yr; Functional unit = 1890 Mg raw waste/day; Conversion = (Mg glass/yr) (1000 kg glass/Mg glass) (day/yr)⁻¹ (Mg raw waste/day)⁻¹; Total = 2.08×10^0 kg glass/Mg raw waste; Specific energy = 3.63×10^{12} seJ/kg (Buranakarn, 1998).

Note #18 (Iron&steel) – Annual amount of recovered iron&steel = 5440 Mg iron&steel/yr; Annual working days = 260 day/yr; Functional unit = 1890 Mg raw waste/day; Conversion = (Mg iron&steel/yr) (1000 kg iron&steel/Mg iron&steel) (day/yr)⁻¹ (Mg raw waste/day)⁻¹; Total = 1.11×10^1 kg iron&steel/Mg raw waste; Specific energy (steel) = 1.13×10^{13} seJ/kg (Brown and Ulgiati, 2004a).

Note #19 (Plastic) – Annual amount of recovered plastic = 4990 Mg plastic/yr; Annual working days = 260 day/yr; Functional unit = 1890 Mg raw waste/day; Conversion = (Mg plastic/yr) (1000 kg plastic/Mg plastic) (day/yr)⁻¹ (Mg raw waste/day)⁻¹; Total = 1.02×10^1 kg plastic/Mg raw waste; Specific energy (plastic PVC) = 9.83×10^{12} seJ/kg (Buranakarn, 1998).

Note #20 (Aluminum) – Annual amount of recovered aluminum = 154 Mg aluminum/yr; Annual working days = 260 day/yr; Functional unit = 1890 Mg raw waste/day; Conversion = (Mg aluminum/yr) (1000 kg aluminum/Mg aluminum) (day/yr)⁻¹ (Mg raw waste/day)⁻¹; Total = 3.13×10^{-1} kg aluminum/Mg raw waste; Specific energy = 2.10×10^{13} seJ/kg (Buranakarn, 1998).

Note #21 (Compost) – Annual amount of compost produced = 237,000 Mg compost/yr; Annual working days = 260 day/yr; Functional unit = 1890 Mg raw waste/day; Conversion = (Mg compost/yr) (1000 kg compost/Mg compost) (day/yr)⁻¹ (Mg raw waste/day)⁻¹; Total = 4.82×10^2 kg compost/Mg raw waste; Specific energy = 2.13×10^{11} seJ/kg (Bastianoni et al., 2001).

References

- Abrelpe, 2010. Panorama dos resíduos sólidos no Brasil, 2010 (Overview of solid waste in Brazil, 2010). Available at <http://www.abrelpe.org.br/Panorama/panorama2010.pdf> [accessed 16.4.12.].
- Agostinho F, Diniz G, Siche R, Ortega E. The use of energy assessment and the geographical information system in the diagnosis of small family farms in Brazil. *Ecological Modelling* 2008;210:37–57.
- Agostinho F, Ambrosio LA, Ortega E. Assessment of a large watershed in Brazil using energy evaluation and geographical information system. *Ecological Modelling* 2010;221:1209–20.
- Almeida CMVB, Barrella FA, Giannetti BF. Emergetic ternary diagrams: five examples for application in environmental accounting for decision-making. *Journal of Cleaner Production* 2007;15:63–74.
- Almeida CMVB, Frimaio GS, Bonilla SH, da Silva CC, Giannetti BF. An evaluation of a MSW-to-energy system using eEnergy synthesis. *International Journal of Environment and Sustainable Development* 2012;11:258–73.
- Amponsah NY, Lacarrière B, Jamali-Zghal N, Le Corre O. Impact of building material recycle or reuse on selected energy ratios. *Resources, Conservation & Recycling* 2012;67:9–17.
- Amponsah NY, Le Corre O, Lacarrière B. Recycling flows in energy evaluation: a mathematical paradox? *Ecological Modelling* 2011;222:3071–81.
- Bastianoni S, Morandi F, Flamini T, Pulselli RM, Tiezzi EBP. Energy and energy algebra explained by means of ingenious set theory. *Ecological Modelling* 2011;222:2903–7.
- Bastianoni S, Marchettini N, Panzieri M, Tiezzi E. Sustainability assessment of a farm in the Chianti area. *Journal of Cleaner Production* 2001;9:365–73.
- Björklund J, Geber U, Rydberg T. Energy analysis of municipal wastewater treatment and generation of electricity by digestion of sewage sludge. *Resources, Conservation & Recycling* 2001;31:293–316.
- Brazilian Energy Balance, 2011. Empresa de Pesquisa Energética, Ano base 2010, Rio de Janeiro. Available at <https://ben.epe.gov.br/downloads/Relatorio.Final.BEN.2011.pdf> [accessed 28.5.12.].
- Brown MT. Areal empower density, unit energy values and emformation. In: Proceedings of the 3rd biennial energy analysis research conference. Gainesville, USA: University of Florida; 2005. p. 303–16.
- Brown MT, Herendeen R. Embodied energy analysis and EMERGY analysis: a comparative view. *Ecological Economics* 1996;19:219–35.
- Brown MT, Ulgiati S. Energy-based indices and ratios to evaluate sustainability: monitoring economies and technology toward environmentally sound innovation. *Ecological Engineering* 1997;9:51–69.
- Brown MT, Buranakarn V. Emery indices and ratios for sustainable material cycles and recycles option. *Resources Conservation & Recycling* 2003;38:1–22.
- Brown MT, Ulgiati S. Energy analysis and environmental accounting. *Encyclopedia of Energy* 2004a;2:329–54.
- Brown MT, Ulgiati S. Energy quality, emery, and transformity: H.T. Odum's contributions to quantifying and understanding systems. *Ecological Modelling* 2004b;178:201–13.
- Brown MT, Protano G, Ulgiati S. Assessing geobiosphere work of generating global reserves of coal, crude oil and natural gas. *Ecological Modelling* 2011;222:879–87.
- Buranakarn, V., 1998. Evaluation of recycling and reuse of building materials using the energy analysis method. PhD thesis. University of Florida, Gainesville, USA.
- Cherubini F, Bargigli S, Ulgiati S. Life cycle assessment of urban waste management: energy performances and environmental impacts. The case of Roma, Italy. *Waste Management* 2008;28:2552–64.
- Cherubini F, Bargigli S, Ulgiati S. Life cycle assessment (LCA) of waste management strategies: landfilling, sorting plant and incineration. *Energy* 2009;34:2116–23.
- Dijkema GJP, Reuter MA, Verhoef EV. A new paradigm for waste management. *Waste Management* 2000;20:633–8.
- Giannetti BF, Bonilla SH, Almeida CMVB. An energy-based evaluation of a reverse logistics network for steel recycling. *Journal of Cleaner Production* 2012. <http://dx.doi.org/10.1016/j.jclepro.2012.05.024>.
- Giannetti BF, Ogura Y, Bonilla SH, Almeida CMVB. Emery assessment of a coffee farm in Brazilian Cerrado considering in a broad form the environmental services, negative externalities and fair price. *Agricultural Systems* 2011;104:679–88.
- Giannetti BF, Barrella FA, Almeida CMVB. A combined tool for environmental scientists and decision makers: ternary diagrams and emery accounting. *Journal of Cleaner Production* 2006;14:201–10.
- Global Footprint Network, 2010. Living Planet Report, 2010, Biodiversity, biocapacity and development. Available at <http://www.footprintnetwork.org/press/LPR2010.pdf> [accessed 14.6.12.].
- Hall CAS, Day Jr JW. Revisiting the limits to growth after peak oil. *American Scientist* 2009;97:230–7.
- IBGE, 2008. Pesquisa Nacional de Saneamento Básico 2008 (“National survey of basic sanitation for public health, 2008”), Instituto Brasileiro de Geografia e Estatística. Available at <http://www.ibge.gov.br/home/estatistica/populacao/condicaoedevida/pnsb2008/PNSB.2008.pdf> [accessed 26.5.12.].
- IBGE, 2010. Cidades (“Statistics for Brazilian Cities”), Instituto Brasileiro de Geografia e Estatística. Available at <http://www.ibge.gov.br/cidadesat/link.php?codmun=355030> [accessed 18.6.12.].
- IPCC, Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA, editors. Contribution of working group III to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom/New York, NY, USA.: Cambridge University Press; 2007.
- IPEA, 2010. Pesquisa sobre pagamento por serviços ambientais urbanos para gestão de resíduos sólidos (“Report on the payment of urban environmental services for solid waste management”), Instituto de Pesquisa Econômica Aplicada, Dirur, Brasília. Available at http://agencia.ipea.gov.br/images/stories/PDFs/100514_relatspsau.pdf [accessed 16.5.12.].
- Leão S, Bishop I, Evans D. Spatial-temporal model for demand and allocation of waste landfills in growing urban regions. *Computers, Environment and Urban Systems* 2004;28:353–85.
- Lei Estadual 12300, 2006. Política Estadual de Resíduos Sólidos (“Statewide policies for solid waste management”). Available at <http://www.ambiente.sp.gov.br/wp/cpla/files/2011/05/PERS.pdf> [accessed 10.7.12.].
- Lino FAM, Ismail KAR. Energy and environmental potential of solid waste in Brazil. *Energy Policy* 2011;39:3496–502.
- Luchi F, Ulgiati S. Energy and emery assessment of municipal waste collection – a case study. In: Proceedings of the 1st biennial energy analysis research conference. Gainesville, USA: University of Florida; 2000. p. 303–16.
- Marchettini N, Ridolfi R, Rustici M. An environmental analysis for comparing waste management options and strategies. *Waste Management* 2007;27:562–71.
- Meadows D, Meadows D, Randers J. Limits to Growth: The 30-Year Update. White River, VT: Chelsea Green Publishers; 2004.
- Mendes MR, Aramaki T, Hanaki K. Assessment of the environmental impact of management measures for the biodegradable fraction of municipal solid waste in São Paulo city. *Waste Management* 2003;23:403–9.
- Odum HT. Environmental accounting, emery and decision making. John Wiley & Sons INC; 1996.
- Odum, H.T., Brown, M.T., Brandt-Williams, S., 2000. Handbook of emery evaluation, Folio#1, Introduction and Global Budget. Center for Environmental Policy, University of Florida, Gainesville, USA. Available at <http://www.emergysystems.org/folios.php> [accessed 10.8.12.].

- Política Nacional de Resíduos Sólidos, 2010. Lei n. 12.305, de 2 de Agosto de 2010 ("Nationwide policies of solid waste management"). Available at http://www.planalto.gov.br/ccivil_03/_ato2007-2010/2010/lei/l12305.htm [accessed 11.5.12].
- Reyes-López JA, Ramírez-Hernández J, Lázaro-Mancilla O, Carreón-Díazconti C, Garrido MML. Assessment of groundwater contamination by landfill leachate: a case in México. *Waste Management* 2008;28:S33–9.
- Rugani B, Pulselli RM, Niccolucci V, Bastianoni S. Environmental performance of a XIV Century water management system: an emergy evaluation of cultural heritage. *Resources, Conservation & Recycling* 2011;56:117–25.
- Sinisgalli, P.A.A., 2000. Análise de fluxo energético: aplicação ao caso da cadeia produtiva da celulose ("Emergy synthesis of cellulose production chain"). In: Jacobi, P.R. (organizador), *Ciência Ambiental: os desafios da interdisciplinaridade*. São Paulo, Annablume, Fapesp, 388pp.
- Sweeney S, Cohen MJ, King DM, Brown MT. Creation of a global emergy database for standardized emergy synthesis. In: Brown MT, editor. *Proceedings of the 4th biennial emergy research conference*. Gainesville, FL: Center for Environmental Policy; 2007. Available at <http://www.emergysystems.org/nead.php> [accessed 14.5.12].
- Themelis NJ, Ulloa PA. Methane generation in landfills. *Renewable Energy* 2007;32:1243–57.
- Tiezzi, E. (research coordinator), 1998. *Analisi di sostenibilità ambientale del trattamento dei rifiuti nel comune di modena* ("Environmental sustainability assessment of solid urban waste management in Modena, Italy"). Dipartimento di Scienze e Tecnologie Chimiche e dei Biosistemi, Università di Siena. Report not published.
- Tilley D. Dynamic accounting of emergy cycling. *Ecological Modelling* 2011;222:3734–42.
- Ulgiati S, Bargigli S, Raugi M. Dotting the I's and crossing the T's of emergy synthesis: material flows, information and memory aspects, and performance indicators. In: *Proceedings of the 3rd biennial emergy conference, emergy synthesis 3*. Gainesville, USA: University of Florida; 2004.
- UNEP. *Waste and climate change: global trends and strategy framework*. Osaka/Shiga: United Nations Environmental Programme, Division of Technology, Industry and Economics, International Environmental Technology Centre; 2010.
- Yuan F, Shen L, Li Q. Emergy analysis of the recycling options for construction and demolition waste. *Waste Management* 2011;31:2503–11.
- Zhang XH, Deng S, Jiang W, Zhang Y, Peng H, Li L, Yang G, Li Y. Emergy evaluation of the sustainability of two industrial systems based on wastes exchanges. *Resources, Conservation & Recycling* 2010;55:182–95.