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Identifying improvements in water management of bus-washing stations in Brazil

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A B S T R A C T

Bus-washing stations play a great role in an urban metropolis daily life. On working days, 15,064 vehicles circulating in Sao Paulo are washed at the end of each day, and transport companies consume approximately 2,200,000 m^3 of water per year in this activity. This study compares three bus-washing systems operating in São Paulo. Two of these companies use the conventional washing system, using water of artesian wells and disposing the effluent in the public network or in water bodies. The third company uses a rainwater catchment system together with a treatment plant for water reuse. The environmental accounting in emergy concerns to the efficiencies of bus-washing processes, the calculation of emergy indicators, and the potential for the improvement of the three systems. The results of the environmental accounting suggest that the wastewater reuse and the rainwater collection improve the environmental performance of bus-washing activity. The comparison of the environmental cost of the wastewater treatments showed that the best environmental option is the installation of a wastewater treatment plant within the companies for internal water reuse. Opportunities of rainwater catchment and shampoo reduction were also evaluated, showing that there are considerable environmental gains for the companies and for the region of São Paulo. A first opportunity of improvement was applied to companies B and C by installing a rainwater catchment system, decreasing the indice of environmental load from 900 to 170. For companies A and B, there is an opportunity to reduce the use of shampoo during operation in 20% in weight, which leads to an increase of the global productivity of 12%. Global productivity of companies B and C may increase 20% by the installation of a wastewater treatment plant, but to achieve a performance comparable to that of Company A, reuse of the treated water must be implemented.

1. Introduction

Urban development and increasing water demand are putting stress on existing water resources. Large Brazilian cities present critical condition of sustainability due to overloads of domestic and industrial discharge, combined with a strong demand for water. In São Paulo, 4.1 billion liters of water is consumed per day, by 18.2 million people. The average consumption of water in the city of São Paulo is close to 221 L of water per capita per day, while the UN (United Nations Organization) recommends that consumption is around 110 L (UN Report, 2006).

São Paulo, where the use of water approaches and in some cases exceeds the limits of sustainability, tolerates growing water stresses, both in terms of water scarcity and quality deterioration. World wide this kind of situation has prompted many municipalities to look for a more efficient use of water resources, including a more widespread acceptance of water reuse practices (Bixioa et al., 2006), and focusing on supplementary water sources such as rainwater collecting systems (Villarreala and Dixonb, 2005).

Although wastewater reuse has been recognized as a promising strategy for relieving water scarcity and reducing the impacts on the environment, the actual reuse of treated wastewater is rather limited in both developed and developing countries. For developed countries, a high proportion of the wastewater is treated, especially in large cities, but the reuse ratio is low (Hochstrat et al., 2005). This occurs partly because most of the developed countries have relatively rich water resources, wastewater treatment is mainly driven by environmental concerns, and the economic gains of reuse of treated wastewater are comparatively less important. In developing countries, on the other hand, wastewater treatment rate is low, and part of the wastewater from industries and part of sewage are released without any treatment. In many countries, as China (Chu et al., 2004), existing wastewater treatment plants (WWTPs) are generally profitless and depend on public funds for operation. In many countries and regions where water is not sufficient to

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meet the demand, wastewater is often used directly for irrigation, causing health concerns. For these countries and regions, enhancing wastewater treatment capacity and the reuse of recovered wastewater are relevant for reduce water scarcity and decrease environmental and health risks. In São Paulo, Sabesp (Basic Sanitation Company of the State of São Paulo) has adopted the water reuse since the 80s in its own facilities for cleaning equipments or maintenance of its areas. In the present days, 780 million liters of water per month are reused, and the exceeding production was extended to private companies and public cleaning, which use about 34 million liters of water per month through those practices (Sabesp, 2008).

Despite of reusing the wastewater is not a new concept, wastewater reuse draws world attention as an essential part of water resources management, due to two major forces: scarcity of freshwater resources and intensified environmental concerns (Angelakis et al., 2003; Asana and Cotruvo, 2004; Chatila, 2004). Recovered wastewater can be used for many purposes, including agricultural irrigation, ground-water recharge, car and bus washing, toilet flushing, urban lawn watering and recreational amenities, road cleaning, etc. Of all the users of recovered wastewater, agricultural irrigation has been by far the major user in many areas where wastewater is reused. This is mainly because of the large water use in irrigation, relatively low quality requirement, and relatively low cost of infrastructure for the irrigation water supply.

Systematic modeling of the costs and benefits of wastewater treatment and the optimal scale of the reuse was performed under various aspects such as food production (Liub et al., 2005), technological issues (Al-Odwani et al., 2007; Coombes et al., 1999; Casania et al., 2005), urban applications (Ernsta et al., 2007; Kalavrouziotisa and Apostolopoulos, 2007), industrial applications (You et al., 2001; Rosia et al., 2007), socio-economic acceptance (Hadjer et al., 2005; Friedlera et al., 2006) and institutional conditions (Yang and Abbaspour, 2007; Siracusa and La Rosa, 2006; Björklund et al., 2001). However, studies of the environmental performance of wastewater reuse are rather rare in the literature (Lundin and Morrison, 2002; Tal, 2006).

The concept of deriving beneficial uses from reuse water coupled with increasing pressures on water resources has promoted the emergence of washing water reclamation, recycling, and reuse as integral components of water resource management. The inherent benefits associated with reclaiming treated bus-washing water for reapplication prior to discharge or disposal include preservation of higher quality water resources, environmental protection, and economic advantages.

Bus-washing stations play a great role in an urban metropolis daily life. On working days, 15,064 buses circulating in São Paulo (SPTRANS, 2007) are washed at the end of each day. At the transport companies of the city, the washing system operates 24 h a day and the average consumption of water per bus is 400 L (Santa Brígida, 2007). Thus, companies consume approximately 2,200,000 m^3 of water per year in this activity.

In São Paulo, there are 60 companies for urban transportation operating with 450 lines, which transport daily 1.5 million passengers (EMTU, 2008). In conventional processes of bus-washing in the city, the main water used comes from artesian wells (Milaré, 1991), not following the guidance of the Economic and Social Council of the United Nations (Braga, 2002) that suggests the use of reused water. This large quantity of water contains hazardous pollutants such as detergents and dust in the wastewater, which may eventually end up in the rivers causing severe damage to the aquatic life environment.

Bus-washing stations are among the activities that consume large quantities of fresh water on daily basis and can benefit from recycling programs and rainwater catchment systems, as garage roofs represent an important percentage of the large impermeable companies' covered areas, hence offering a significant possibility for rainwater collection (Barbagello et al., 2001; He et al., 2001; Durham et al., 2002; Tsagarakis and Georgantzis, 2003). However, despite their potential, water reclamation, reuse, and recycling technologies remain greatly underused in this sector.

This study aims to establish a systematic framework to compare three bus-washing systems operating in São Paulo. Two of these companies use the conventional washing system, using water of artesian wells and disposing the effluent in the public network or in water bodies. The third company uses a rainwater catchment system together with a treatment plant for water reuse. The analysis concerns to the following issues:

(1) Comparison of the productivities of three bus-washing processes
(2) Calculation of emergy indicators for the three processes
(3) Evaluation of the potential for the environmental improvement of the systems

The paper is organized as follows: Section 2 provides an overview of companies' bus-washing systems operation. Section 3 describes briefly the methodology employed. Results and discussion are provided in Section 4. Summary of the findings and main conclusions are given in Section 5.

2. Companies and bus-washing systems description

Companies were identified as A, B and C. Buses of Company B circulate only in São Paulo and provide services to the municipality. Buses of Company C provide transport services to other cities in the state of Sao Paulo, and Company A has both types of services: urban buses and tourism buses.

Company A operates in the sector of urban buses. On working days, 3% of the fleet remains in preventive maintenance. All the buses are washed daily after their use. The company holds new facilities, designed for recycling the water used in washing process and to collect rainwater, in order to minimize the use of the artesian well. As the covered area of the company is considerably large, it is used to rainwater collection, which is used in the bus-washing process. The bus-wash drain is conducted by gravity to a sand box and then is stored in a reservoir, which feeds WWTP (Waste Water Treatment Plant). The reuse water produced by the WWTP is driven by gravity to another reservoir, and is ready to feed the washing system through pumping. The sludge generated is dried, collected manually and sent to a deposit within the company area. The quantity of reuse water produced is limited by the WWTP dimensions.

Company B operates in the sector of urban buses, from which 8% remain in preventive maintenance. Buses are also washed daily after use. The washing sector is not covered. All the water used in the system comes from an artesian well. After bus-wash, the water used is captured in a sand box, and discarded in a river located in the company's limits. Company C operates in the tourism sector. Daily 6% of the total fleet remains in maintenance. Wash drain is captured by a sand box and subsequently discarded in the public network. All the water used in the system comes from an artesian well. Table 1 shows the main characteristics of the three companies.

Fig. 1 shows annual water flows for each company. Losses from all processes are released to the environment. Note that losses of Company A, are higher than the total need of Company B. From the total value of 23,156 m^3, 16,540 m^3 are losses that occur during the washing process and are released to the environment, while the rest (6616 m^3) is reuse water, which cannot

Table 1
Main characteristics of the three companies studied.

	Company A	Company B	Company C
Urban buses	634	200	230
Total companies' area/(m^2)	50,000	20,000	20,000
Built area/(m^2)	3000	500	3150
Rainwater collection	Yes	No	No
Washing system operation/(h/day)	24	24	24
Water consumption/(L/bus)	400	300	500
WWTP	Yes	No	No

return to the system due to the size reservoirs constructed for this task.

3. Methodology

Data collected refers to the companies' operation 2005. Values of the transformities and specific emergies are mostly taken from the literature (see Tables 3–5), and are relative to the 9.44 baseline. Services were not accounted and values relative to money were avoided, as prices include subjective evaluations and the analysis takes into account only technological aspects. In this study the water of artesian wells extracted by far exceeds the recharge of water generated on the systems area and the water is regarded as a non-renewable resource which is depleted faster than it is renewed. All results are shown as function of the washed area and per bus (functional unit = 1 m^2 of washed bus surface). The considered useful life of facilities is 25 years according to Thomson Report (2004).

3.1. Emergy accounting

3.1.1. Conceptual background

Emergy accounting is a technique which determines the value of nature to the human's economy. "Emergy is the available energy of one kind (measured in solar emergy joule, sej) previously used up directly and indirectly to make a service or product" (Odum, 1996). Emergy accounting has logic of memorization rather than of conservation, different from other energy (Brown and Herendeen, 1996), exergy (Sciubba and Ulgiati, 2005), or thermoeconomic (Lazzaretto, 2009) based analysis. Emergy's definition, despite of being very general, stimulated a new mathematical approach to the differential calculus (Giannantoni, 2006), as it considers whatever other form of available energy, and in order to account for energy quality (transformity) associated to any form of exergy, some special algebraic rules have to be taken into account (Brown and Herendeen, 1996) and a special mathematical formulation was required (Giannantoni, 2002). Transformities, expressed in sej/J, are used to "transform" a given form of energy into emergy, by multiplying the given energy to its correspondent transformity (Brown and McClanahan, 1996).

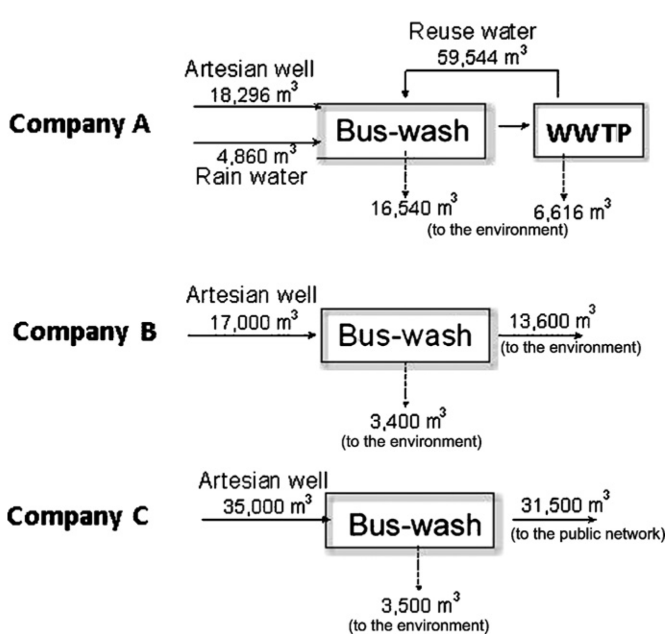


Fig. 1. Annual water flows for bus-washing processes of the three companies. Losses from all companies go to the environment. Company B wastewater is released directly to the environment, while wastewater of Company C goes to the public network for treatment.

The following the steps were observed for evaluating bus-washing systems with emergy accounting:

1. Field data survey.
2. Drawn of energy diagrams, which help to convert mental/verbal models to quantitative energy fluxes.
3. Set up of emergy evaluation tables with a line item for each input.
4. Multiplication of the amount relative to each flow by its respective emergy/unit or transformity to get the total emergy flow per functional unit.
5. For interpretation, emergy indices were calculated, and ternary diagrams were constructed.
6. Comparison among bus-washing systems, or to evaluate process' global productivity, and opportunities for improvement.

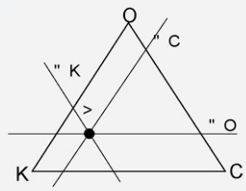
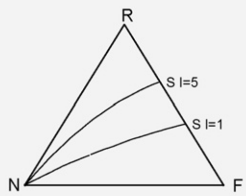
3.2. Emergy indices

Emergy accounting separates renewable (R) from non-renewable inputs (N) and local ($I = N + R$) from external inputs (F). These distinctions make it possible to define several emergy-based indicators that can provide decision support tools (Brown and McClanahan, 1996). These indicators (transformity, environmental loading ratio (ELR), emergy yield ratio (EYR), and environmental sustainability index (ESI)) cover all the aspects of the environmental sustainability issues, regarding resource use. Transformity is defined as the total emergy required to produce a joule of product or service. The inverse of the transformity is a measure of global productivity, G_p (Eq. (1)) (Bonilla et al., 2010). More productive will be the system in which less emergy is needed to produce a given amount of product, or in this paper to produce a square meter of washed bus. The increase of global productivity was defined considering the global productivity (G_p) of the actual system and the global productivity of the improved system (G'_p) according to Eq. (2).

$$G_p = \frac{1}{\text{total emergy/washed area}} \tag{1}$$

$$\left(1 - \frac{G_p}{G'_p}\right) \times 100 \tag{2}$$

Table 2
Properties of emergy ternary diagrams functioning as auxiliary tools for emergy accounting.

Properties	Illustration	Description
Resource flow lines		Ternary combinations are represented by points within the triangle, the relative proportions of the elements being given by the lengths of the perpendiculars from the given point to the side of the triangle opposite the appropriate element. These lines are parallel to the triangle sides and are very useful to compare the use of resources by products or processes.
Sustainability lines		The graphic tool permits to draw lines indicating constant values of the sustainability index (SI). The sustainability lines depart from the *N* apex in direction to the *RF* side allowing the division of the triangle in sustainability areas, which are very useful to identify and compare the sustainability of products and processes.

EYR is the ratio of total emergy ($Y=R+N+F$) to the emergy purchased on the market (F). This index shows how efficaciously the system uses the available local resources. It is worthy to attention that an increase of the value of this indice indicates an improvement of the system performance, but this improvement depends on the availability of local resources (Raugei et al., 2005). ELR is the ratio of all non-renewable emergy ($N+F$) to the renewable emergy (R). This index is high for systems with a high technological level and/or with high environmental stress. EIR shows the relation between the emergy of the economic inputs (F) with those provided by the environment, renewable or not (I), and ESI (or SI) arises from the ratio of EYR to ELR, which is a sustainability function for a given process or economy. The fact that it is preferable to have a higher emergy yield per unit of environmental loading defines this index that evidences if a process offers a profitable contribution to the user with a low environmental pressure (Brown and Ulgiati, 2002).

3.3. Ternary diagrams

Giannetti et al. (2006) developed a graphical tool that produces a triangular diagram with three variables associated with percentages in emergy. The ternary diagram was referred by Gasparatos et al. (2008) as a necessary step when performing an emergy evaluation, as it facilitates the communication of the results and the decision making process. The sum of R, N and F is always 100%. With this restriction, it is possible to represent three variables in two dimensions. Each vertex of the triangle is associated with a flow (R, N and F), and the sides of the triangle represent binary combinations. Combinations of three fluxes are represented by points inside the triangle, and the relative proportions of the elements are given by the lengths of the perpendiculars from the given point to the side of the triangle opposite to the appropriate vertex. The use of the ternary diagrams' properties provides additional information on the dependence of the system on a particular type of flow (R, N or F), on the system's efficiency concerning the use of reserves and on the support of the environment, necessary to the system operation. Table 2 shows the ternary diagrams' properties used in this paper.

The graphic tool permits to draw three lines shown in Table 2 indicating constant values of the sustainability index. These lines are presented independently and the value of ESI or SI may be fixed by the user ($SI>0$). The sustainability lines depart from the N apex in direction to the RF side allowing the division of the triangle in sustainability areas, which are very useful to identify and compare the sustainability of products and processes. When $SI<1$ products and processes are not sustainable in a long term. Systems presenting $1<SI<5$ may have a sustainable contribution to the economy for medium periods and processes with $SI>5$ can be considered sustainable in a long term (Brown and McClanahan, 1996).

The graphical tool allows you to compare companies, products, processes and services, evaluate improvements and monitor the performance of the system over time. With the aid of diagrams, one can evaluate the performance of given system and its interactions with the environment. A full description of the graphical tool is found in Almeida et al. (2007) and Giannetti et al. (2006). Examples of application are also found in Barrella et al. (2005), Giannetti et al. (2007), Agostinho et al. (2008), Cai et al. (2008), and Almeida et al. (2010).

4. Results and discussion

System diagrams illustrated in Fig. 2 were drawn to combine information about the systems of interest from various sources, and to organize data gathering efforts. The energy diagrams ensure that all driving energies from the economy, the environment and interactions are included (Odum, 1996). Diagrams are used to construct tables of data requirements for the emergy accounting. Construction inputs divided by plant lifetime, annual operating inputs (labor, electricity, machinery, human services), as well as direct and indirect environmental inputs, are quantified in Tables 3–5.

The emergy of Company A washing system equals 1.38×10^{17} sej/year, as shown in Table 2. For the operation, it is necessary to integrate the waste water treatment plant (WWTP), therefore, the total system emergy will be the sum of these two emergies, which results in the amount of 1.81×10^{17} sej/year. The largest flows that contribute to the company's total emergy are labor (37%), shampoo (12%) and electricity (12%). It is worthy to note that the concrete infrastructure contributes with 13% of the total emergy, and the system of wastewater reuse and rainwater catchment contributes with 3% of the total emergy, even considering a useful life of 25 years.

Tables 4 and 5 account all inputs required for the bus-washing systems of Companies B and C, respectively.

The largest emergy contributions for the bus-washing system of Company B are labor (70%), electricity (8%) and shampoo (6%). The services of the environment to degrade the shampoo present in the effluent discarded represent approximately 7% of the total emergy. At Company C, the major contributions come from the effluent treatment performed the public network (23%) and labor (53%).

Table 3
Environmental accounting in emergy of company A washing system (data on a yearly basis).

#	Item	Unit	Type	Amount [a]	Emergy per unit/(sej/unit)	Solar emergy/(sej/year)	%/(sej/sej)	Refs.[b]
Bus-washing process								
Construction phase								
1	Concrete	g	F	1.22×10^7	1.54×10^9	1.88×10^{16}	10	Brown and Buranakarn (2003)
2	Machinery	g	F	1.28×10^5	4.10×10^9	5.25×10^{14}	<1	Geber and Björklund (2001)
3	Steel	g	F	1.02×10^6	2.77×10^9	2.83×10^{15}	2	Brown and Buranakarn (2003)
4	PVC	g	F	2.34×10^4	5.87×10^9	1.37×10^{14}	<1	Geber and Björklund (2001)
5	Rubber	g	F	5.82×10^3	4.30×10^9	2.50×10^{13}	<1	Odum (1996)
6	Copper	g	F	3.39×10^6	7.34×10^8	2.49×10^{15}	1	Brown and Ulgiati (2002)
7	Water (artesian well)	g	N	2.70×10^4	4.10×10^9	1.11×10^{14}	<1	Buenfil (2001)
Operating phase								
8	Sun	J		3.23×10^{14}	1.00	[c]		By definition
9	Evaporation[d]	g	R	4.14×10^9	1.45×10^5	6.00×10^{14}	<1	Buenfil (2001)
10	Water (artesian well)	g	N	1.83×10^{10}	2.25×10^5	4.12×10^{15}	2	Buenfil (2001)
11	Water (rain)	g	R	4.86×10^9	1.57×10^5	7.63×10^{14}	<1	Buenfil (2001)
12	Water (reuse)	J		2.45×10^{11}	1.78×10^5	[c]		Calculated[e]
13	Human labor	J	F	1.58×10^{10}	4.30×10^6	6.79×10^{16}	37	Calculated[f]
14	Annual electricity input	J	F	8.12×10^{10}	1.65×10^5	1.34×10^{16}	7	Odum (1996)
15	Chemicals[g]	g	F	8.27×10^6	2.65×10^9	2.19×10^{16}	12	Odum (1996)
16	Sand	g	F	2.60×10^6	1.00×10^9	2.60×10^{15}	1	Odum (1996)
Indirect environmental inputs								
17	Oxygen for losses oxidation[h]	g	R2	1.65×10^6	1.00×10^9	1.65×10^{15}	1	Brown and Ulgiati (2002)
	Bus-wash emergy				1.38×10^{17}	76		
WWTP								
Construction phase								
18	Concrete	g	F1	3.53×10^6	1.54×10^9	5.43×10^{15}	3	Brown and Buranakarn (2003)
19	Machinery	g	F1	1.17×10^4	4.10×10^9	4.80×10^{13}	<1	Geber and Björklund, 2001
20	Steel	g	F1	6.23×10^5	2.77×10^9	1.73×10^{15}	1	Brown and Buranakarn (2003)
21	Copper	g	F1	1.85×10^4	7.34×10^8	1.36×10^{13}	<1	Brown and Ulgiati (2002)
Operating phase								
22	Human labor	J	F1	3.82×10^9	4.30×10^6	1.64×10^{16}	9	Calculated[e]
23	Chemicals	g	F1	4.20×10^6	2.65×10^9	1.11×10^{16}	6	Geber and Björklund (2001)
24	Annual electricity input	J	F1	5.32×10^{10}	1.65×10^5	8.78×10^{15}	5	Odum (1996)
	WWTP emergy					4.36×10^{16}	24	
Total emergy		sej				1.81×10^{17}		

[a] Quantities of materials used for the construction of the washing systems were calculated from construction drawings and estimated by local measurements. Quantities used for the operation of the washing systems were calculated by local measurements.
[b] References for emergy per unit.
[c] Emergies corresponding to sun and reuse water were not considered to avoid double-counting.
[d] Admitted as 5% vol. of each bus wash.
[e] WWTP total energy = 59,544 $m^3 \times 1$ kcal/$m^3 \times 4186$ J/kcal.
[f] Brazil's total emergy = (2.77×10^{24} sej/year)/(1.80×10^8 hab/day $\times 1.26 \times 10^7$ J/hab $\times$ 285 days).
[g] 1% of the total volume, dilution 1:100, v/v.
[h] The amount of oxygen for losses oxidation was related to the quantity of shampoo present in the effluent, as follows: $C_{24}H_{45}O_6SN{\cdot}H_2O + 46O_2 \rightarrow 24CO_2 + 47/2H_2O + SO_2 + NO_2$, thus 46 mol (1,472 g) of oxygen are needed to oxidize 1 mol of shampoo (493 g), and the theoretical oxygen demand will be: TOD = (1472/493) = 2.985 $g_{O2}/g_{shampoo}$.

The services of the environment to degrade the shampoo present in the effluent discarded represent 0.13% of the total emergy.

The company that employs more emergy to wash one square meter of bus surface, even without treating its effluents, is the Company B. This result indicates that in global scale the ability of this company to produce one square meter of washed bus may be enhanced. The more effective company in the use of resources is Company A.

It is interesting to note that the water that comes from the artesian well, which is the main input for the three companies, corresponds to approximately 3% of the total emergy required for the systems operations. Fig. 3 shows a comparison between the assessment at local scale (mass balance) and at global scale (emergy balance).

At local scale, when the mass balance is performed, water appears as the main input, and the importance of the reuse water is promptly recognized (Fig. 3, top). It is clear that the reuse of water is a main issue in this kind of activity. The intrinsic benefits associated with reclaiming treated bus-washing water for reapplication prior to discharge may be also summoned, as they involve preservation of higher quality water resources, environmental protection, and economic advantages. However, these benefits are not accounted quantitatively when local scale assessment is adopted.

At global scale, when not only the quantity but also the quality of the inputs is considered, new insights appear. Emergy accounting allows including other forms of available energy entering a given system in order to account for the energy quality (transformity) contributing to the product. In this way, emergy accounting permits to connect in the same assessment the contribution inputs apparently incomparable, such as labor, electricity and water. Transformities are used to "transform" a given form of energy into emergy, but they also give a measure of the energy quality. A high value of transformity means that there was a great work (from nature and from mankind) to bring a given input to the production process, and that the environmental stress caused by this input production is higher than the environmental load driven by an input with lower transformity.

Fig. 3 (bottom) shows the emergy balance for all three washing systems operations. Despite of the low quantity in mass used, shampoo (high transformity) appears as a great resource consumer,

Table 4
Environmental accounting in emergy of company B washing system (data on a yearly basis).

#	Item	Unit	Type	Amount[a]	Emergy per unit/(sej/unit)	Solar emergy/(sej/year)	%/(sej/sej)	Refs.[b]
Bus-washing process								
Construction phase								
1	Concrete	g	F	1.61×10^6	1.54×10^9	2.49×10^{15}	2	Brown and Buranakarn (2003)
2	Machinery	g	F	2.70×10^4	4.10×10^9	1.11×10^{14}	<1	Geber and Björklund (2001)
3	Steel	g	F	5.58×10^5	2.77×10^9	1.57×10^{15}	1	Brown and Buranakarn (2003)
4	PVC	g	F	8.25×10^3	5.87×10^9	4.84×10^{13}	<1	Geber and Björklund (2001)
5	Rubber	g	F	4.27×10^3	4.30×10^9	1.84×10^{13}	<1	Odum (1996)
Operating phase								
6	Sun	J		7.66×10^{13}	1.00	[c]		By definition
7	Evaporation[d]	g	R	8.51×10^8	1.45×10^5	1.23×10^{14}	<1	Buenfil (2001)
8	Water (artesian well)	g	N	1.70×10^{10}	2.25×10^5	3.83×10^{15}	3	Buenfil (2001)
9	Human labor	J	F	1.98×10^{10}	4.30×10^6	8.51×10^{16}	70	Calculated[e]
10	Annual electricity input	J	F	6.09×10^{10}	1.65×10^5	1.00×10^{16}	8	Odum (1996)
11	Shampoo[f]	g	F	2.76×10^6	2.65×10^9	7.31×10^{15}	6	Odum (1996)
12	Sand	g	F	2.60×10^6	1.00×10^9	2.60×10^{15}	2	Odum (1996)
Indirect environmental inputs								
13	Oxygen for effluent oxidation[g]	g	R2	8.24×10^6	1.00×10^9	8.24×10^{15}	7	Brown and Ulgiati (2002)
Total emergy		sej				1.22×10^{17}		

[a] Quantities of materials used for the construction of the washing systems were calculated from construction drawings and estimated by local measurements. Quantities used for the operation of the washing systems were calculated by local measurements.
[b] References for emergy per unit.
[c] Emergies corresponding to sun was not considered to avoid double-counting.
[d] Admitted as 5% vol. of each bus wash.
[e] Brazil's total emergy = (2.77×10^{24} sej/year)/(1.80×10^8 hab/day $\times$ 1.26×10^7 J/hab $\times$ 285 days).
[f] 0.65% of the total volume, dilution 1:40, v/v.
[g] The amount of oxygen for losses oxidation was related to the quantity of shampoo present in the effluent, as follows: $C_{24}H_{45}O_6SN{\cdot}H_2O + 46O_2 \rightarrow 24CO_2 + 47/2H_2O + SO_2 + NO_2$, thus 46 mol (1472 g) of oxygen are needed to oxidize 1 mol of shampoo (493 g), and the theoretical oxygen demand will be: TOD = (1472/493) = 2.985 $g_{O2}/g_{shampoo}$.

and the reduction of its use may reveal an opportunity to improve the environmental performance of the systems beyond the local scale.

Comparing the values of emergy per unit invested in the effluent treatment, done by the company or the environment, it is observed that Company C employs more resources than the other two companies (Table 6). The use of the public network to treat effluents decreases the investment within the company, but increases the emergy investment in the region where the company is inserted, that is, Company C shares its costs of operation with its neighborhood, which has to deal with the impacts caused by the operation of a private company. The emergy appropriated by Company C from the neighborhood corresponds to 23% of the total emergy of its washing system. This result suggests that Company C should

Table 5
Emergy accounting of company C washing system (data on a yearly basis).

#	Item	Unit	Type	Amount[a]	Emergy per unit/(sej/unit)	Solar emergy/(sej/year)	%/(sej/sej)	Refs.[b]
Bus-washing process								
Construction phase								
1	Concrete	g	F	9.32×10^6	7.34×10^8	6.84×10^{15}	3	Brown and Buranakarn (2003)
2	Machinery	g	F	2.61×10^4	4.10×10^9	1.07×10^{14}	<1	Geber and Björklund (2001)
3	Steel	g	F	1.61×10^6	2.77×10^9	4.46×10^{15}	2	Brown and Buranakarn (2003)
4	PVC	g	F	8.25×10^3	5.87×10^9	4.84×10^{13}	<1	Geber and Björklund (2001)
5	Rubber	g	F	2.14×10^3	4.30×10^9	9.20×10^{12}	<1	Odum (1996)
Operating phase								
6	Sun	J		1.71×10^{14}	1.00	[c]		By definition
7	Evaporation[d]	g	R	1.75×10^9	1.45×10^5	2.54×10^{14}	<1	Buenfil (2001)
8	Water (artesian well)	g	N	3.50×10^{10}	2.25×10^5	7.88×10^{15}	4	Buenfil (2001)
9	Human labor	J	F	2.64×10^{10}	4.30×10^6	1.14×10^{17}	53	Calculated[e]
10	Annual electricity input	J	F	1.24×10^{11}	1.65×10^5	2.05×10^{16}	10	Odum (1996)
11	Shampoo	g	F	2.80×10^6	2.65×10^9	7.42×10^{15}	3	Odum (1996)
12	Sand	g	F	2.60×10^6	1.00×10^9	2.60×10^{15}	1	Odum (1996)
13	Treatment on public network	g	F2	1.32×10^{11}	3.80×10^5	5.02×10^{16}	23	Geber and Björklund (2001)
Indirect environmental inputs								
14	Oxygen for losses oxidation	g	R2	2.80×10^5	1.00×10^9	2.80×10^{14}	<1	Brown and Ulgiati (2002)
Total emergy						2.14×10^{17}		

[a] Quantities of materials used for the construction of the washing systems were calculated from construction drawings and estimated by local measurements. Quantities used for the operation of the washing systems were calculated by local measurements.
[b] References for emergy per unit.
[c] Emergies corresponding to sun was not considered to avoid double-counting.
[d] Admitted as 5% vol. of each bus wash.
[e] Brazil's total emergy = (2.77×10^{24} sej/year)/(1.80×10^8 hab/day $\times$ 1.26×10^7 J/hab $\times$ 285 days).

Table 6
Emergy and emergy per unit for effluent treatment of companies A, B and C.

		Company A	Company B	Company C
Total treatment (F + F1 + R2)	sej/year	4.52×10^{16}	8.24×10^{15}	5.02×10^{16}
Emergy per washed area	sej/m^2 year	2.08×10^{9}	1.60×10^{9}	4.34×10^{9}
Emergy per bus	sej/bus	9.42×10^{11}	2.14×10^{12}	3.05×10^{12}

Data calculated from Tables 2–4.

compensate the society, as the resources diverted for its operation cannot be used by this society for other uses. The case of Company C exemplifies that the joint use of economic and environmental assessments could be adequate motivation for the reduction of the capital appropriation (social and natural), as described by Garret Hardin in the Tragedy of Commons (Hardin, 1968).

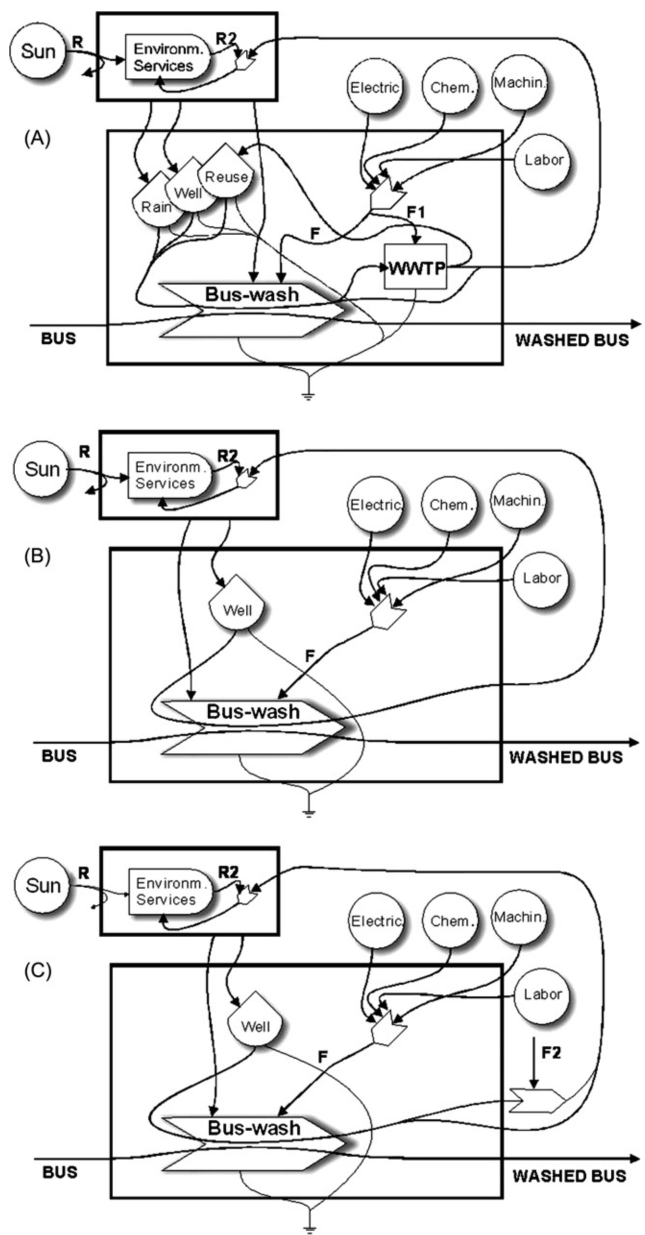


Fig. 2. Energy system diagrams of companies A, B and C. Water outputs of bus-wash processes are diluted and recycled by nature, by means of a renewable emergy investment, R2. Company A uses purchased inputs (F1 as responsibility of the company) to produce reuse water and to improve effluent quality. Company C use purchased inputs outside its limits (F2 as responsibility of the State of São Paulo). Effluent treatment of Company B only counts with renewable inputs of the environment (R2).

4.1. Emergy indices and ternary diagrams

Indices calculated from the emergy accounting depend not only on the value of the flows, but also on their quality (Table 7). Fluxes R, N and F have their usual meaning, and all fluxes are identified in Fig. 2.

Flux R2 corresponds to the nature's renewable emergy investment to treat the effluents imposed, intentionally or not, to the environment. Flux F1 is associated to purchased inputs employed to produce reuse water (as responsibility of the company), and flux F2 to purchased inputs taken from the region of São Paulo for company's effluent treatment. It is worthy to mention that the inclusion of fluxes R2 and F2 implies an increase in the spatial scale as the effluent treatment is performed outside the companies' borders. Also, the R2 flux implies in an increase of the time scale, as the indirect environmental services do not treat the effluent at the same rate of a WWTP. R2 and F2 are inflicted by the companies to the environment and to the region, respectively, and are considered environmental costs. On the contrary, flux F1 corresponds to an emergy investment made to avoid the improper use of the region's emergy. Note that F1 is associated to R fluxes and F2 and R2 are always summed to F fluxes.

The emergy yield ratio (EYR) is a measure of the ability of a process to exploit local resources by investing outside resources. In this case, EYR measures the ability to provide a clean bus with less investment coming from the economy, which Company A accomplishes by reusing wastewater and collecting rainwater. The emergy investment ratio (EIR) shows the relation between the emergy of the economic inputs (F) with those provided by the environment (R + N) renewable or not. F1 was included as it is used to avoid indirect services improperly imposed to the environment. Company A has the lower value, and is able to compete and prosper in the market, while companies B and C should rethink its resource use. The environmental loading ratio (ELR) expresses the use of environmental services by a system, indicating a load on the environment. The lower the ratio, the lower is the stress to the environment. Company A, using properly the environmental services has also the lower value. Finally, ESI arises from the ratio of EYR to ELR, as a sustainability function for a given process or economy. The fact that it is preferable to have a higher emergy yield per unit of environmental loading defines this index that evidences if a process offers a profitable contribution to the user with a low environmental pressure. For companies B and C, the ESI is lower than 0.001. This result should not be surprising, since the only renewable flow (evaporation) to these systems corresponds to less than 1% of their total emergy requirements. Including the F1 flow, Company A becomes more sustainable, non-exploiting environmental services for its effluent treatment.

Fig. 4 shows the performance of the three companies in the ternary diagram. Observe that the investment for the economic operation is the largest Company B and that the use of non-renewable resources (water from artesian wells) is similar in the three companies. For all three companies, local resources (N + R) represent a small fraction in relation to resources paid (F1). Com-

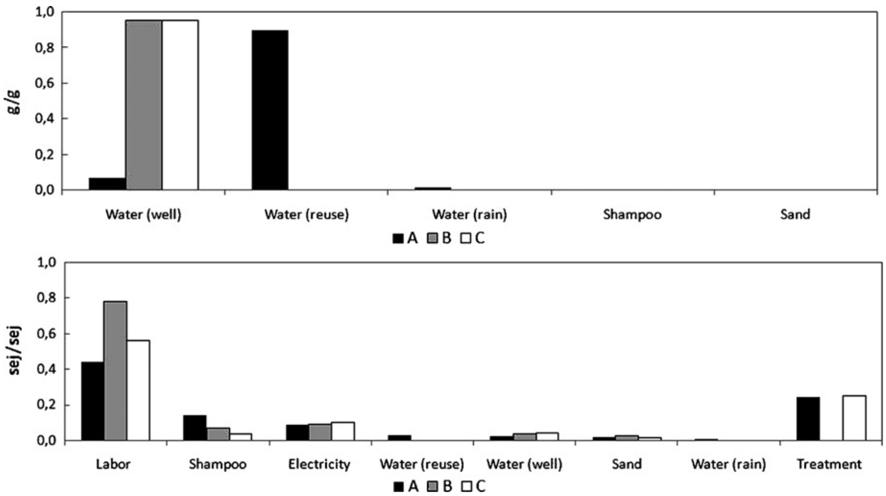


Fig. 3. Mass balance (top) and emergy balance (bottom) of the operation phase for companies A, B, and C.

Table 7
Emergy indices of companies A, B and C.

Indices	Equations	Company A	Company B	Company C
Emergy yield ratio	EYR = (R + R2 + N + F + F1 + F2)/(F + F2)	1.37	1.03	1.04
Emergy investment ratio	EIR = F/(R + N + F1)	2.69	29.82	25.34
Environmental load ratio	ELR = (R2 + N + F + F2)/(R + F1)	3.04	985.20	842.82
Environmental sustainability indice	ESI = EYR/ELR	0.45	(*)	(*)

(*)Values of ESI for companies B and C are less than 0.001.

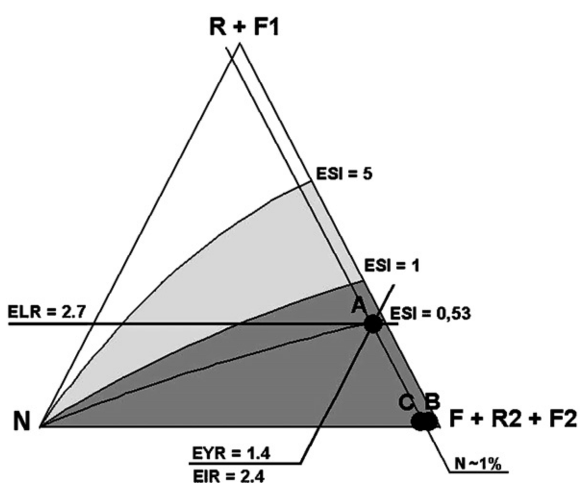


Fig. 4. Ternary diagram of companies A, B and C, where R2 is the renewable emergy investment to oxidize effluents and losses. F1 and F2 are purchased inputs, being F1 provided by Company A to produce reuse water and to improve effluent quality, and F2 is provided by the region to treat Company's C effluents.

pany A improves its performance investing F1 fluxes, and it is the company that more approaches the line for ESI = 1, which is associated to an environmental performance close to a condition of medium term sustainability. The F2 flux of Company C (23%) included as environmental cost is responsible by its inferior environmental performance.

4.2. Improvements opportunities

The analysis was performed based on the assumption that human labor, which has the major contribution to the total emergy of all three companies, should not decrease. A first opportunity of improvement may be applied to companies B and C by installing a rainwater catchment system. Company B has a covered area of 2300 m^2 and Company C, 3700 m^2. Thus, according to the precipitation recorded in the period of one year in Sao Paulo (and the available covered area), the rainwater that can be captured by Company B is 3.73×10^9 g/year, and Company C may collect 6.00×10^9 g/year. Fig. 5 shows that the uptake of rainwater by the two companies could reduce their environmental burden by approximately five times.

For companies A and B, there is also an opportunity to reduce the use of shampoo during operation in 20% in weight, to use the same

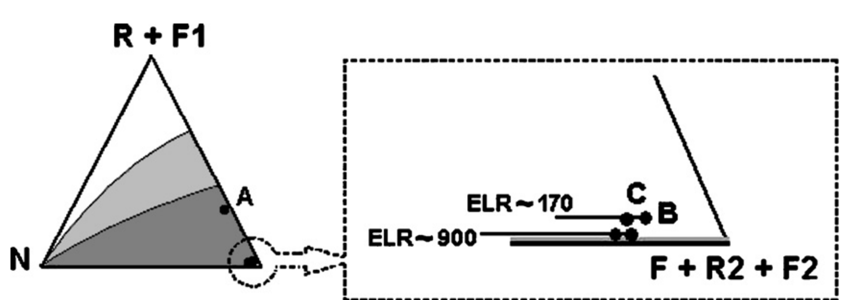


Fig. 5. Ternary diagram of companies A, B and C, assuming companies B and C with a rainwater catchment system.

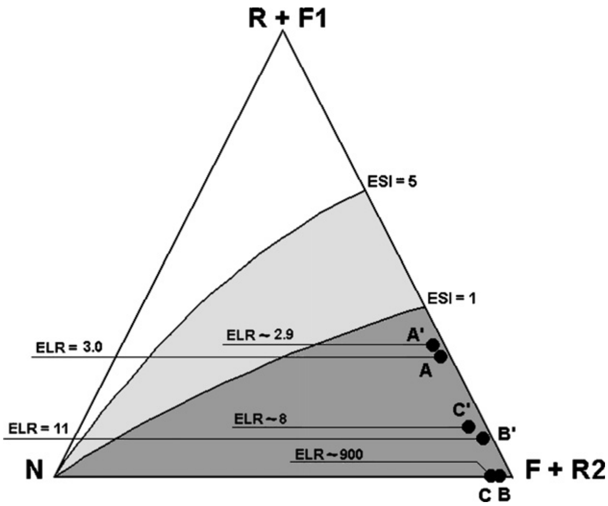


Fig. 6. Ternary diagram of companies A, B and C, assuming the collection of rainwater by companies B and C, the reduction of shampoo use by companies A and B, and the implantation of a WWTP in companies B and C, without water reuse.

quantity used by Company C (Table 8). The reduction in shampoo use decreases ELR of Company A from 3.0 to 2.8. There is also an increase in the ESI and EYR. The main improvement due to shampoo reduction is noticed on the value of emergy per square meter ($G_p = 1/8.36 \times 10^9$ sej/m^2; $G'_p = 1/7.76 \times 10^9$ sej/m^2, Eq. (1)) indicative of an increase of the global productivity of 12%. ELR of Company B also decreases with decreasing shampoo use, but the main reduction is due to the collection of rainwater. It is worthy to attention that diminishing a resource use increases the global productivity of the systems, while the change of a non-renewable flow for a renewable one reflects directly on the indices values.

Despite of the improvements accomplished admitting the rainwater collection at companies B and C, their emergy indices are still far from that of Company A. Thus, it was admitted the installation of WWTP in companies B and C. The amount of resources needed to install the WWTP was established assuming that the necessary inputs are proportional to the volume of water used by each company. In this case, not only a significant reduction of environmental load of the two companies (Fig. 6), as well as the improvement of all the other indicators (Table 9). Point A′ in Fig. 6 shows the improvement achieved by the reduction of shampoo for Company A, and points B′ and C′, the position in the ternary diagram assuming the collection of rainwater, the shampoo reduction and the WWTP implementation in Company B. Point C′ results from rainwater catchment and WWTP installation.

As G_p of Company C was $1/1.86 \times 10^{10}$ sej/m^2 and G'_p equals $1/1.55 \times 10^{10}$ sej/m^2, the global productivity (Eq. (1)) of the company increases about 20% with the implementation of a WWTP replacing the treatment at the public network, but it is worthy to note that, as reuse was not considered, companies B and C do not still reach the indices achieved by Company A. For this, the reuse of water must be implemented. This result corroborates the idea that end of pipe treatments is not sufficient to improve the environmental performance of a system.

5. Concluding remarks

This study, provided a systematic framework for evaluating the environmental performance of bus-washing systems, and was completed successfully showing that reclamation of water used in bus-wash stations are effective and successful in creating a new and reliable water supply that can be used for several washes. The environmental costs and benefits of wastewater treatment and reuse were estimated, and potential improvements were evaluated using emergy accounting.

The results of the environmental accounting suggest that the wastewater reuse and the rainwater collection improve the environmental performance of bus-washing activity. The comparison of the environmental cost of the wastewater treatments showed that the best environmental option is the installation of a WWTP within the companies for internal water reuse. Opportunities of rainwater catchment and shampoo reduction were also evaluated, showing that there are considerable environmental gains for the companies and for the region of São Paulo. Given the increasing water scarcity and the environmental concerns in São Paulo, policies regarding water management should pay more attention to encouraging the reuse of treated wastewater in an integrated freshwater and wastewater management system within the companies.

Improved water use efficiency in its simplest form means lowering the water needs to achieve a unit of production in any given activity. In this context, Company C would be the most efficient as it uses 3 L of water to wash 1 m^2 of bus surface, in contrast with companies B (3.3 L/m^2) and A (3.8 L/m^2), which use more water to the same sake. However, in an environmental resource context,

Table 8
Emergy indices for companies A, B and C, assuming the collection of rainwater by companies B and C, and the reduction of shampoo use by companies A and B.

		A	B	C	A shampoo	B rain + shampoo	C rain
EYR		1.37	1.03	1.04	1.40	1.03	1.04
EIR		2.69	29.82	25.34	2.53	32.00	26.68
ELR		3.04	985.20	842.82	2.86	168.13	177.73
ESI		0.45	(*)	(*)	0.49	0.01	0.01
Emergy/area	sej/m^2	8.36×10^9	2.37×10^{10}	1.86×10^{10}	7.46×10^9	2.33×10^{10}	1.84×10^{10}
Emergy/bus	sej/bus	9.42×10^{11}	2.14×10^{12}	3.05×10^{12}	8.43×10^{11}	2.10×10^{12}	3.02×10^{12}

(*) Values of ESI for companies B and C are less than 0.001.
Columns in grey resume previous data to facilitate comparisons.

Table 9
Emergy indices for companies A, B and C, assuming the collection of rainwater by companies B and C, the reduction of shampoo use by companies A and B, and the implantation of a WWTP in companies B and C, without water reuse.

		A	B	C	A′ shampoo	B′ rain + shampoo + WWTP	C′ rain + WWTP
EYR		1.37	1.03	1.04	1.40	1.12	1.17
EIR		2.69	29.82	25.34	2.56	8.42	5.79
ESI		0.45	0.00	0.00	0.49	0.10	0.15
Emergy/area	sej/m^2	8.36×10^9	2.37×10^{10}	1.86×10^{10}	7.46×10^9	2.31×10^{10}	1.55×10^{10}
Emergy/bus	sej/bus	9.42×10^{11}	2.14×10^{12}	3.05×10^{12}	8.43×10^{11}	2.09×10^{12}	2.54×10^{12}

Columns in grey resume previous data to facilitate comparisons.

the productivity concept includes considerations of total resources requirements and resources quality. Any effort to improve bus-washing operations should be consistent with maintaining or improving the system as a whole. Here, it is worthy to distinguish that the traditional assessment of efficiency is limited to the companies' boundaries, while the emergy assessment expands the companies' limits, including the biosphere as a whole. Thus, in emergy's point of view, Company A is the most efficient as it has the lower emergy per unit (8.36×10^9 sej/m^2) and the lower environmental load, ELR = 3.04, compared with ELR = 985 of Company B and ELR = 842 of Company C.

The opportunity of improvement pointed for companies B and C by installing a rainwater catchment system, decreases the indice of environmental load from 900 to 170. For companies A and B, an opportunity to reduce the use of shampoo during operation was identified, leading to an increase of its productivity of 12%. Global productivity of companies B and C may increase 20% by the installation of a wastewater treatment plant. This increase represents an opportunity to reduce the use of resources, and consequently the ecological footprint of the companies. Thus, a higher number of systems would be globally supported, as companies decrease their neighborhood exploitation.

The definition of bus-washing productivity includes not only any measure that reduces the amount of water used per unit, but also the use of all other resources needed to the process operation. Therefore, there are two concepts to be differentiated: the efficiency and the global productivity. The first refers to the systems optimization on the basis of the first and second principles of thermodynamics. The second, evaluated by emergy accounting, refers to the optimization of the system in terms of use of resources deriving from the environment and economy. Using the second concept of optimization procedure, one may understand the sustainability of the systems as "durable or lasting" (Giannantoni, 2006), as resources are evaluated regarding the way for driving systems (already optimized in terms of energy use efficiency) to contribute to the global efficiency or to the survival of the whole system (biosphere) for a longer time.

It is important to emphasize that the discussions within companies about the concept of sustainability to compare and/or to classify systems are centered in human activities. On the other hand, humans tend to adjust the attention to different scales, as it is easy to manage and understand small parts of the global system defining boundaries and limits. However, this anthropocentric view sometimes hinders the understanding that the concept of a sustainable subsystem in an un-sustainable global system is fundamentally defective. Labels such as sustainable companies must be seen as indications of benefic contributions to the global system.

The better position of Company A in the ternary diagram indicates a high environmental yield combined with a low environmental load. The biosphere sustainability is then less affected by operational processes of Company A, and the graphical representation of the sustainability lines indicate the contribution of each system to the global sustainability and may, therefore, be used as an important guide to conceptual progress.

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