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Emergy as a tool for Ecodesign: evaluating materials selection for beverage packages in Brazil

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ABSTRACT

The life of a product begins with the initial product design concepts; the costs and potential impacts of a product are heavily influenced by the final design, the production processes, the economic and environmental costs of all raw materials. Additionally, both of these factors are very much affected by how the products are managed during and after consumer usage. Thus, there is an urgent need for a tool to facilitate the integration and assessment of environmental and economic demands into the product planning and development processes. The introduction of environmental accounting based on emergy as a tool to assist in product design is proposed. This complementary tool may be inserted into the conventional design methodology to facilitate in the selection of materials and processes as well as in the actual design of the products. To illustrate the application of the proposed method for material selection, PET (polyethylene terephthalate) bottles and aluminum cans for beverage packaging are compared. Despite the exceptional condition of aluminum recycling in Brazil, results show that the best option for beverage packages is the PET bottles.

1. Introduction

Worldwide environmental policy became more unpermissive in the last decades, and evolved from prescribing specific but limited end-of-pipe technologies to, in some cases, dictating systemic industry development routes and competitive structures. There are still technological, market, and environmental troubles ahead and little scientific consensus on the appropriate methodology for comparing the environmental performance of products and process alternatives.

There is also a growing focus on environmental reporting and use of environmental product declarations (EPDs), and a tendency that the environmental performance of products often is of importance when decisions made by the buyers take place [1], even though this is far from a general agreement [2]. Over the last decade, much attention has been paid to concepts such as Design for Environment, Extended Producer Responsibility, Responsible Chain Management, and Ecodesign [3–26], and with their application, many companies have improved the environmental performance of their products. According to Lagerstedt [27], Design for the Environment is a term used as synonym for several other names such as: Ecodesign, Sustainable Design, Green Design, Environmental Conscious Design, Life Cycle Design or Life Cycle Engineering and also Clean Design. This author [27] points out that although the phrasing may have different meanings, the concepts generally have the same objectives.

Ecodesign is one of the terms being used to describe the approach used by designers in the field of product design and manufacture. The life of a product starts with the initial design concept and the final cost of this product is determined at the design phase, being this cost associated to economic or environmental issues [28]. Thus, assuming that the impact of a product upon the environment is determined at the design phase it is easy to perceive the importance of Ecodesign. However, there is still a strong need for a tool to facilitate the integration and the assessment of environmental demands into the product development process.

Most of the works concerning Ecodesign offer guidelines, checklists and other tools that have been used in product design for a long time [29–44]. Checklists were adapted with the inclusion of environmental concerns such as recommendations against the use of toxic materials and unnecessary raw materials (dematerialization) or suggestions on energy consumption minimization at different production phases. Checklists and guidelines differ in complexity and structure. Some publications focus upon a special kind of product [30–33], others incorporate a life cycle assessment,

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emphasizing disassembly and recycling as central issues in Ecodesign [34–36]. There are also publications that concentrate on the reduction of resource exploitation and dematerialization [37–39], and several works have been published concerning Ecodesign, in the sense that it incorporates materials selection in order to reduce the environmental burdens of products [40–44]. In 2006, the Journal of Cleaner production published a special issue offering an overview of the subject area of Ecodesign [45].

In this context, designers are being forced to consider more holistic techniques for design and assess products and processes, as the need for changing the current non-sustainable product development practices becomes increasingly patent. As a result, techniques such as Life Cycle Assessment (LCA) and Materials Flow Analysis (MFA) are increasingly popular. Such techniques attempt to quantify critical environmental variables, seeking to scientifically evaluate environmental impact and resource consumption (Fig. 1).

The search for an assessment method or the combination of methods to monitor and evaluate production systems is a growing concern that attracts efforts from researchers all over the world. In an effort to quantify and compare the environmental impact of products and processes, there is also a great number of papers dealing with the application of LCA for this task [46–48]. As LCA offers the possibility to identify environmental impacts all over the production chain, it has been widely employed to calculate the environmental burden of a product life cycle, such as greenhouse gas emissions or ozone depletion. However, there are some shortcomings to deal with, especially at the design phase. At first, LCA data of a target product is only available after detail design. Hence, it is hard to quantify the environmental impact of products and processes before detail design, as LCA's impact is associated to the quantity of wastes and emissions, which may only be estimated at this phase. Secondly, although several studies dealing with LCA for materials have already been performed, LCA practitioners have a number of different weighting methods available, and the results of the different methods do not generally coincide because of a lack of standardization in conventional methodologies [49]. At this point, the ISO 14042 states that in an LCA study it may be desirable to use different weighting methods and conduct sensitivity analysis to assess the consequences they may have on the results of the LCA.

MFA [50–53] applies the concepts of industrial ecology [54,55] to study how materials and energy flow into, throughout, and out of a system. This method, developed at the Wuppertal Institute [53], can evaluate the environmental harm associated with the extraction or diversion of resources from their natural ecosystemic pathways. Material intensity factors (g/unit) are multiplied by each input (material or energy), respectively, accounting for the total amount of abiotic matter, water, air and biotic matter required in order to provide that input to the process in study (Fig. 1). MFA accounts physical units such as the quantity of materials, which result from the extraction, production, transformation, consumption, recycling, and disposal within a system [56]. The target of the analysis can be one single substance (such as carbon dioxide), a material (transformed naturally or technically) or a product. But there are also shortcomings as MFA assumes fundamentally that, for a given period, inter-sector flows from one sector to another are proportional to the total output of the receiving sector for that same time period.

These shortcomings arise in part from the difficulty for establishing metrics that completely represent a desirable environmental performance. Challenges arise especially on defining sustainability and which assessment method should be used to measure this sustainability. Up till now, various indicators quantifying product environmental performance have been proposed [57,58], but none of them was completely accepted by the scientific community [59].

Emergy accounting (EA) offers a promising metric to introduce environmental concerns into the Ecodesign methodologies. It counts with scientific basis and offers indices that can supply additional information on the environmental loading of a system and its sustainability. But, more importantly, emergy accounting fulfils the need for including the contribution of natural ecosystems, data relative to human labor and process implementation. With the development of EA [60,61], the aware of the impossibility of completely control, dispose or recycle all pollutants, suggests a strategy to calculate the emergy investment needed to dispose or recycle some of the wastes and pollutants. To complete the analysis, an additional emergy investment required by the biosphere to repair damages, dispersing or mitigating pollutants often released without control, can be also calculated [61], although some damages are very unlikely to be amendable. Even though this methodology is able to meet the main needs of ecodesigners, it has still found relatively limited use in environmentally conscious design.

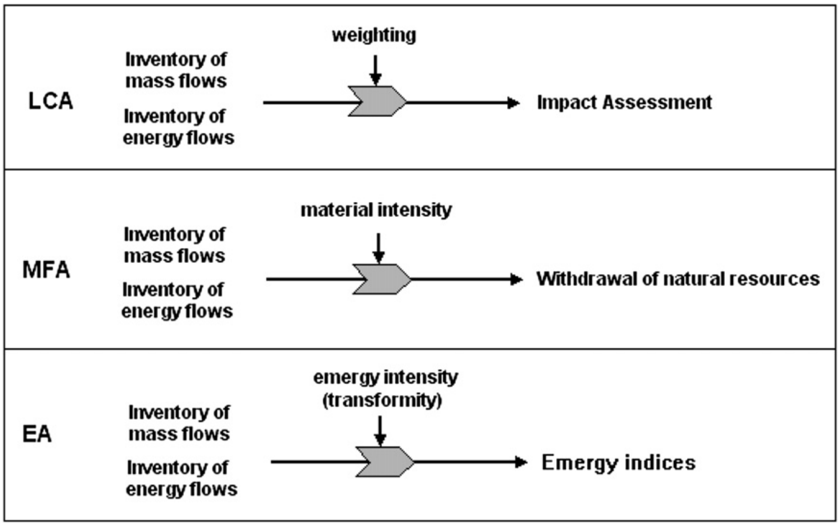

Fig. 1. Integration scheme of inventory phase with the assessment methods: LCA, life cycle assessment, which focuses mainly downstream flows; MFA, material flow analysis regarding only upstream flows, and EA, emergy accounting, with its central attention to upstream flows, but may include also downstream fluxes.

The purpose of this study is to introduce environmental accounting based on emergy as a tool to assist product design, through the use of emergy indices. The use of this simplified tool, easy to use, aims to support designer's decisions in the development/assessment of more sustainable products. This complementary tool may be inserted into the conventional design methodology with LCI or MFA inventories to facilitate the selection of materials and processes, the assessment of improvements and process changes or to guide decision making. To check the feasibility of the proposed tool using an LCI inventory, the production of PET bottles was compared with that of aluminum cans for beverage packaging in order to help designers regarding materials selection.

2. Method

2.1. Theoretical background

The concept of emergy can be used to assess the load imposed by a product to the environment. Emergy is in agreement with one of the principles of sustainability defined by Daly [62], namely, that a process is sustainable only if the resources consumed are used at a rate that does not exceed the rate at which they are renewed. Odum [63] defined emergy as the quantity of solar energy necessary (directly or indirectly) to obtain a product (good or service) or energy flow in a given process. Solar energy, despite being dispersed and low quality energy, is the common basis of all energy flows circulating within the biosphere. The greater the emergy flow necessary to sustain a process, the greater the quantity of solar energy consumed or in other words, the greater the environmental cost. Hence emergy represents the memory of all the solar energy consumed during the process. Emergy is measured in solar energy joules (sej) [64]. Solar transformity is the solar energy directly or indirectly necessary to obtain 1 J of another type of energy and emergy per unit (g) is the solar emergy needed to obtain one unit of a product (specific emergy). For systems with the same output, such as the 1000 L of beverage packaged, the lower the emergy per functional unit (emergy/FU, where FU = 1000 L), the higher is the efficiency of the system in the production [64]. It is worthy to note that this definition of efficiency includes all biosphere services, called from here of global efficiency. For designers, this approach may provide indicators of processes' efficiency and environmental stress. Indicators based on emergy accounting distinguish between renewable (R) and the non-renewable (N) resources, and imported inputs (F) of the total emergy of the output ($Y = N + R + F$).

Targeting the assessment of environmental demands into the product development process, the environmental loading ratio (ELR) was chosen among the emergy-based indicators. ELR compares the amount of non-renewable and purchased emergy ($N + F$) to the amount of local renewable emergy [65], that is, the total human-controlled emergy invested in the system divided by the annual free environmental emergy input, providing a quantitative means for assessing the PET and aluminum cans production balance (Eq. (1)).

$$\mathrm{ELR} = (N + F)/R \tag{1}$$

A high value of the ELR, often due to a high technological level in the use of resources, indicates high environmental stress, because local environmental cycles are overloaded. In the absence of investments from outside, the renewable emergy locally available would result in a full-grown ecosystem with ELR → 0 consistent with the limits imposed by the local environment. But, with anthropogenic intervention, the non-renewable imported emergy imposes a distance from the natural ecosystem, which can be indicated by the ratio $(N + F)/R$. The higher the ratio, the bigger is the distance between the system and the natural environment. Hence, ELR may be defined as a measure of the load inflicted to the environment by production systems or any other human activity.

In this work, besides the use of the traditional indices, the product ELR × emergy/FU and the ratio of ELR with the emergy per functional unit were analyzed in order to obtain a more complete assessment.

2.2. Introducing emergy accounting for Ecodesign use

The first step for applying any assessment method is data collection through an inventory of mass and energy flows (Fig. 1). Data collection and compilation are often the most work- and time-consuming steps in assessment methods, and must extend over all the production cycle (Fig. 2). But, independently of methodological choices regarding the assessment of a product system, for each process of the product system, a data set is imperative. For designers, a good option may lie on the use of data sets already published in the literature.

Among the common data sets found in the literature, LCIs (Life Cycle Inventories) are used by LCA practitioners to calculate, as well as to interpret, indicators of the potential impacts associated with emission and resource consumption. The aim of LCIs is to report the

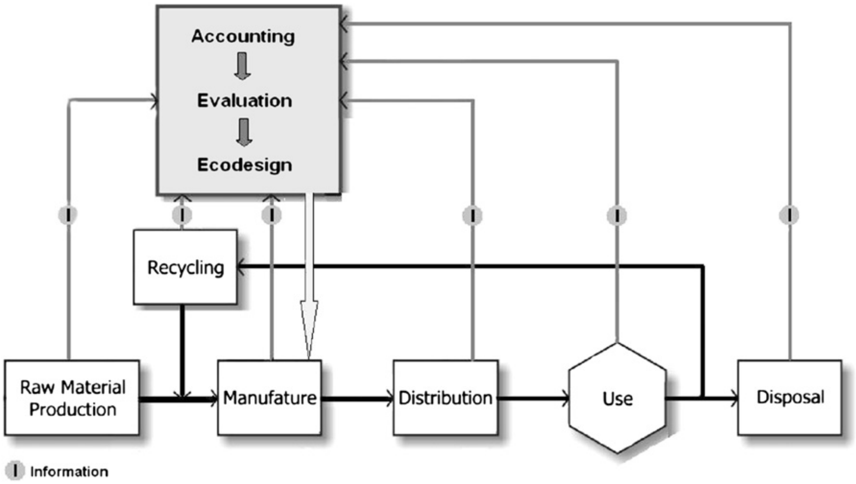

Fig. 2. Life cycle stages that provide feedback information to Ecodesign evaluation.

quantities of different resources required and emissions and wastes generated per functional unit of a given system. There are also public database initiatives, industry databases initiatives and LCA dedicated softwares, which cover the more commonly used goods and services for a number of products and processes [66].

LCIs commonly include the main raw materials and the use of water and energy, and special emphasis is given to the emissions released to the environment. Emergy accounting refers to the use of resources to produce a good or a service. It is worthy to mention that at the design phase of a given product, the designer using emergy accounting would be able to consider not only the resources used for operating the production life cycle, but also all materials, human labor and energy to implement and operate the production process. Data referring to the system releases may be also used to calculate the environmental services required for absorbing, diluting or decomposing these emissions and wastes. But, it is worthy to attention that, at the design phase, data relative to emissions may only be estimated.

The interactions of each stage of PET bottles and aluminum cans production with the Ecodesign activity may be established throughout the product's life cycle stages (Fig. 2). From these interactions, the designer gets important information for the development of the product or for the improvement of its environmental performance. It is important to note that designer's power to make changes in both production life cycles lies on the manufacture stage. However, his actions may indirectly affect the life cycle, both upstream and downstream.

The following are the steps recommended for designers for evaluating a system with emergy accounting using data collected from the literature:

1. Get a data set from the literature, from public, industrial or academic source.
2. Draw an energy diagram, which helps to convert mental/verbal models to quantitative energy fluxes and to visualize the interactions among production stages.
3. Set up an emergy evaluation table with a line item for each input.
4. Multiply 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, calculate the emergy indices. In this work, ELR is calculated in order to assess the environmental load of the product, but there are other indices which may help designers to assess the benefits of the economic use of an environmental resource, for example. For further information see Ref. [64].
6. To compare products or processes or to evaluate process' improvements, calculate the transformity or the emergy/unit of each product/process. The use of the product ELR × emergy/FU and the ratio of ELR with the emergy per functional unit may lead to more complete and reliable results.

To illustrate the use of the emergy accounting and the calculations for ELR, an LCI found in the literature [67,68] was taken. This example was chosen in order to enlighten the use of a literature data set and the use of quantitative results provided by emergy accounting during the product development. The selected LCI [67,68] compares beverage packages produced with PET and aluminum using virgin and recycled materials.

2.3. Case study

The LCIs of PET bottles and aluminum cans were taken as a Brazilian case study, and LCI information is based on literature data. A detailed description of the system, including the complete life cycle inventory data, can be consulted from Valt [67,68]. This approach was used to assess not only production systems and product options, but principally to aid designers to decide among materials alternatives, and to assess changes and improvements in each production process.

The inventory tables include the use of raw material, energy consumption, the use of semi-manufactures and auxiliary materials, and transport at each life cycle stage. Values of emergy per unit are shown in Table 1. Because of the size of the system, which covers several Brazilian States in both production and recycling stages, the type of the inputs for each flow was chosen considering Brazilian boundaries. Crude oil and bauxite are then considered non-renewable inputs and water a renewable input. The quantity of recycled PET assumed (40% in weight) is in agreement with Brazilian [69] and Mercosur [70] regulations. The quantity of recycled aluminum (80% in weight) is that practiced in the country in the same year [67]. The functional unit (FU) is 1000 L of beverage corresponding to 500 PET bottles of 2 L, and to 2857 aluminum cans. Diesel spent for transporting materials between stages was taken into account as distances exceed 1000 km (Fig. 3).

3. Results

3.1. PET bottles production

System diagrams illustrated in Figs. 4 and 5 were drawn to combine information about the system of interest and the LCI inventory [67,68]. The energy diagram ensures that all driving energies included in the PET life cycle inventory were taken into account. Fig. 4 shows the diagram for PET production from virgin materials, and Fig. 5 includes the recycling stage for producing PET-R bottles. Both diagrams were used to construct tables of data required for the emergy accounting.

As shown in Figs. 4 and 5, PET production operating inputs for 1000 L of beverage (electricity, materials, and fuels for transportation), as well as direct and indirect environmental inputs (water), are quantified in Tables 2 and 3, accordingly to the LCI data [67,68], assigned a suitable emergy per unit and converted to emergy values.

The calculated emergy per 1000 L of beverage of the PET bottle production life cycle is 9.26×10^{14} sej/FU, while the emergy per mass of the finished bottle is 3.70×10^{10} sej/g (Table 2). 93% of the total emergy invested for PET bottles production is associated to the first two life cycle stages. The major contributions to the total emergy are related to electricity (71%, being 30% sej/sej associated to petroleum extraction and 41% sej/sej to crude oil refining), and to the crude oil used as raw material (14% sej/sej). It is interesting to mention that in Brazil 95% of the electric energy is obtained from hydroelectric plants [76], and that this kind of energy has

Table 1
Values of emergy per unit and transformities used in this work.

Item	Type[a]	Emergy per unit		References
		(sej/g)	(sej/J)	
River water	R	2.03×10^5	4.26×10^4	[71]
Methanol	F		4.80×10^4	[72]
Coke	F		5.40×10^4	[73]
Crude oil	N		5.54×10^4	[74]
Diesel (transport)	F		6.60×10^4	[64]
Electric energy	F		1.65×10^5	[64]
Bauxite	N	8.55×10^8		[64]
Chemicals	F	2.65×10^9		[75]
Paint and varnish	F	3.00×10^9		[61]

[a] Types of inputs were classified accordingly to the boundaries set to the system.

Fig. 3. Distances between stages in the PET bottle production life cycle (right) and aluminum cans production life cycle (left). The white triangle marked in Bahia State shows the location of the PET recycling plant, 100 km distant from the perform production plant.

a renewable fraction of 70% sej/sej corresponding to the geopotential input [64].

Table 3 shows the total emergy per 1000 L of beverage of the PET-R bottle production. The value of 5.86×10^{14} sej/FU corresponds to 63% of the emergy invested to produce PET bottles exclusively from virgin materials, while the emergy per unit of the PET-R bottle 2.34×10^{10} sej/g indicates that the inclusion of recycled material in the PET bottle life cycle increases its global efficiency in approximately 37% sej/sej. The implementation of the recycling stage reflects directly on the extraction and refining phases diminishing the quantities of resources and energy use.

3.2. Aluminum cans production

System diagrams illustrated in Fig. 6 and show the diagram for aluminum cans (Al) production from virgin materials, and Fig. 7 includes the recycling stage (Al-R).

As shown in Figs. 6 and 7, aluminum can production operating inputs for 1000 L of beverage (electricity, materials, and fuels for transportation), as well as direct and indirect environmental inputs, are quantified in Tables 4 and 5, accordingly to the LCI data [67,68], assigned a suitable emergy per unit and converted to emergy values.

The calculated emergy per 1000 L of beverage of the aluminum cans production life cycle is 3.02×10^{15} sej/FU, while the emergy per mass of the finished can is 7.10×10^{10} sej/g (Table 4). The major contributions to the total emergy are related to electricity (86%, being 53% sej/sej associated to bauxite extraction and alumina production and 33% sej/sej to electrolysis and smelting stage), and to the bauxite used as raw material (6% sej/sej). It is worthy to note that 96% of the total emergy invested for Al cans production is associated to the first two life cycle stages.

Table 5 shows the total emergy per 1000 L of beverage of the Al-R can production. The value of 7.95×10^{14} sej/FU corresponds to 26% of the emergy invested to produce aluminum cans exclusively from virgin materials; while the emergy per unit of the Al-R can 1.87×10^{10} sej/g indicates that the inclusion of recycled material in the cans life cycle increases its global efficiency in approximately 47%sej/sej. The implementation of the recycling stage reflects directly on the extraction and ingots production phases diminishing the quantities of resources and energy use. It is important to mention that can recycling in Brazil also generates employment for over 160 thousand people in activities ranging from used cans collection to the scrap processing into new cans [77]. Brazil has been the world leader in beverage aluminum can recycling for four consecutive years, and, in 2004, a new record was achieved with 95.7% kg/kg of the cans returning to the production chain. This percentage corresponds to 121.3 thousands tons, or approximately 9 billion cans.

4. Discussion

Once the total number of input flows to the PET bottles and aluminum cans production process has been identified and the

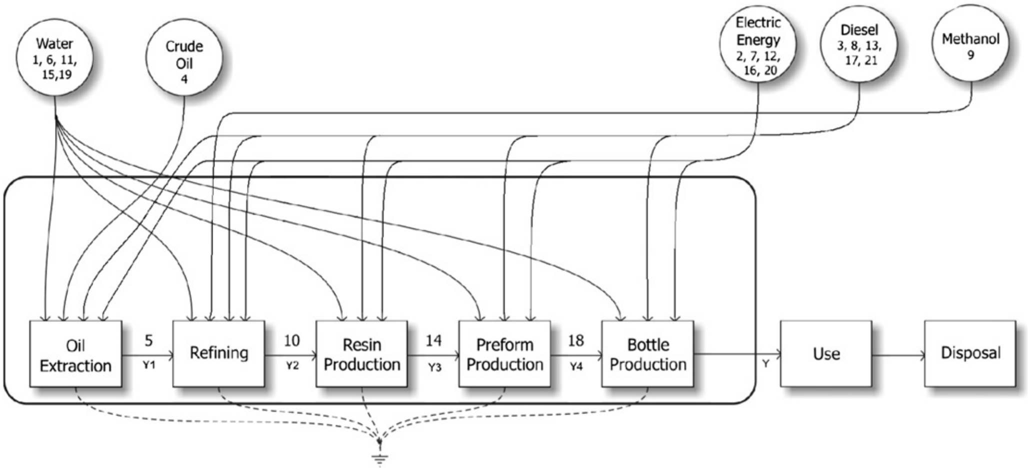

Fig. 4. Energy diagram for PET production using exclusively virgin materials. Each number within the circles or over arrows corresponds to a line in Table 2. Emergy fluxes 5, 10, 14 and 18 are presented in the table but do not contribute to the total emergy, as the only raw material entering the production chain is crude oil.

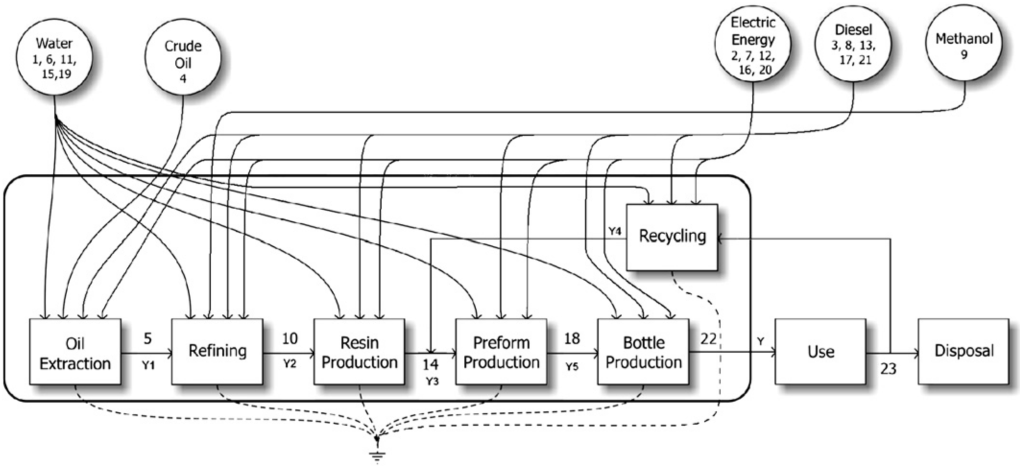

Fig. 5. Energy diagram for PET-R production using virgin and recycled materials. Each number within the circles or over arrows corresponds to a line in Table 3. Emergy fluxes 5, 10, 14, 18 and 22 are presented in the table but do not contribute to the total emergy, as the only raw material entering the production chain is crude oil.

emergy yield driving the process has been calculated (Tables 2, 3, 4 and 5) a set of indices and ratios can be accordingly calculated. Emergy indices have been shown to be particularly useful when studying processes under human control, where a sustainable pattern is not guaranteed and choices have to be supported by the careful consideration of many different parameters. The environmental loading ratio (Eq. (1)) expresses the use of environmental services by a system, indicating a load on the environment. The

Table 2
Environmental accounting for the PET bottle production (500 bottles).

#	Item[a]	Type	Unit	Amount	Emergy per unit[d] (sej/un)	Solar Emergy (sej)
Oil extraction						
1	Water	R	g	9.49×10^{4}	2.03×10^{5}	1.93×10^{10}
2	Electricity	F	J	1.69×10^{9}	1.65×10^{5}	2.79×10^{14}
3	Diesel (transport)	F	J	5.16×10^{8}	6.60×10^{4}	3.41×10^{13}
4	Crude oil	N	J	2.30×10^{9}	5.54×10^{4}	1.27×10^{14}
5	Petroleum	Y1	g	7.46×10^{4}	$\mathbf{5.90 \times 10^{9}}$	4.41×10^{14}
Refining						
6	Water	R	g	4.33×10^{4}	2.03×10^{5}	8.79×10^{9}
7	Electricity	F	J	2.27×10^{9}	1.65×10^{5}	3.74×10^{14}
8	Diesel (transport)	F	J	4.51×10^{8}	6.60×10^{4}	2.98×10^{13}
9	Methanol	F	J	2.07×10^{8}	4.80×10^{4}	9.93×10^{12}
10	DMT + MEG[b]	Y2	g	3.29×10^{4}	$\mathbf{2.60 \times 10^{10}}$	8.55×10^{14}
Resin production						
11	Water	R	g	5.54×10^{3}	2.03×10^{5}	1.12×10^{9}
12	Electricity	F	J	1.89×10^{8}	1.65×10^{5}	3.12×10^{13}
13	Diesel (transport)	F	J	1.19×10^{8}	6.60×10^{4}	7.82×10^{12}
14	PET Resin	Y3	g	2.60×10^{4}	$\mathbf{3.44 \times 10^{10}}$	8.94×10^{14}
Preform[c] production						
15	Water	R	g	1.96×10^{3}	2.03×10^{5}	3.98×10^{8}
16	Electricity	F	J	1.47×10^{7}	1.65×10^{5}	2.43×10^{12}
17	Diesel (transport)	F	J	4.52×10^{7}	6.60×10^{4}	2.98×10^{12}
18	Preformer	Y4	g	2.39×10^{4}	$\mathbf{3.76 \times 10^{10}}$	8.99×10^{14}
PET bottle production						
19	Water	R	g	4.50×10^{4}	2.03×10^{5}	9.14×10^{9}
20	Electricity	F	J	1.60×10^{8}	1.65×10^{5}	2.64×10^{13}
21	Diesel (transport)	F	J	1.06×10^{7}	6.60×10^{4}	6.98×10^{11}
	PET bottles	**Y**	**g**	$\mathbf{2.50 \times 10^{4}}$	$\mathbf{3.70 \times 10^{10}}$	$\mathbf{9.26 \times 10^{14}}$

[a] Items from lines 5, 10, 14 and 18 (over arrows in Fig. 4) were not accounted to avoid double-counting.

[b] DMT dimethyl terephtalate and MEG mono ethylene glycol.

[c] In the PET bottle life cycle, the PET resin is first molded into a "preform" using the Injection Molded Process. These preforms are produced with the necks of the bottles, including threads on one end. These preforms are fed after cooling into a blow molding machine.

[d] The values of emergy per unit calculated in this table (lines 5, 10, 14 and 18) only take into account inputs considered in the LCI used (water, electricity and diesel for transport). However, the value calculated for PET resin is comparable to that calculated for PVC (1.14×10^{10} sej/g [76]), confirming that the inputs considered are the main flows of PET production.

Table 3
Environmental accounting for the PET-R bottle production, 40% of recycled material in weight (500 bottles).

#	Item[a]	Type	Unit	Amount	Emergy per unit (sej/un)	Solar emergy (sej)
Oil extraction						
1	Water	R	g	5.69×10^{4}	2.03×10^{5}	1.16×10^{10}
2	Electricity	F	J	1.01×10^{9}	1.65×10^{5}	1.67×10^{14}
3	Diesel (transport)	F	J	3.10×10^{8}	6.60×10^{4}	2.04×10^{13}
4	Crude oil	N	J	1.38×10^{9}	5.54×10^{4}	7.65×10^{13}
5	Petroleum	Y1	g	4.48×10^{4}	$\mathbf{5.90 \times 10^{9}}$	2.64×10^{14}
Refining						
6	Water	R	g	2.60×10^{4}	2.03×10^{5}	5.28×10^{9}
7	Electricity	F	J	1.36×10^{9}	1.65×10^{5}	2.25×10^{14}
8	Diesel (transport)	F	J	2.71×10^{8}	6.60×10^{4}	1.79×10^{13}
9	Methanol	F	J	1.24×10^{8}	4.80×10^{4}	5.96×10^{12}
10	DMT + MEG[b]	Y2	g	1.97×10^{4}	$\mathbf{2.60 \times 10^{10}}$	5.13×10^{14}
Resin production						
11	Water	R	g	3.32×10^{3}	2.03×10^{5}	6.75×10^{8}
12	Electricity	F	J	1.13×10^{8}	1.65×10^{5}	1.87×10^{13}
13	Diesel (transport)	F	J	7.11×10^{7}	6.60×10^{4}	4.69×10^{12}
14	PET Resin	Y3	g	1.56×10^{4}	$\mathbf{3.44 \times 10^{10}}$	5.36×10^{14}
Recycling						
15	PET bottles (after use)		g	1.14×10^{4}		
16	Water	R	g	1.50×10^{4}	2.03×10^{5}	3.05E $\times 10^{9}$
17	Electricity	F	J	1.02×10^{8}	1.65×10^{5}	1.68×10^{13}
18	Diesel (transport)	F	J	1.09×10^{7}	6.60×10^{4}	7.17×10^{11}
19	Recycled PET Resin	Y4	g	1.04×10^{4}	$\mathbf{5.32 \times 10^{10}}$	5.54×10^{14}
Preform production						
15	Water	R	g	1.96×10^{3}	2.03×10^{5}	3.98×10^{8}
16	Electricity	F	J	1.47×10^{7}	1.65×10^{5}	2.43×10^{12}
17	Diesel (transport)	F	J	4.52×10^{7}	6.60×10^{4}	2.98×10^{12}
18	Preformers	Y5	g	2.39×10^{4}	$\mathbf{2.34 \times 10^{10}}$	5.59×10^{14}
PET bottle production						
19	Water	R	g	4.50×10^{4}	2.03×10^{5}	9.14×10^{9}
20	Electricity	F	J	1.60×10^{8}	1.65×10^{5}	2.64×10^{13}
21	Diesel (transport)	F	J	1.06×10^{7}	6.60×10^{4}	6.98×10^{11}
	PET-R bottles	**Y**	**g**	$\mathbf{2.50 \times 10^{4}}$	$\mathbf{2.34 \times 10^{10}}$	$\mathbf{5.86 \times 10^{14}}$

[a] Items from lines 5, 10, 14, 18 and 23 (over arrows in Fig. 5) were not accounted to avoid double-counting.

[b] DMT dimethyl terephtalate and MEG mono ethylene glycol.

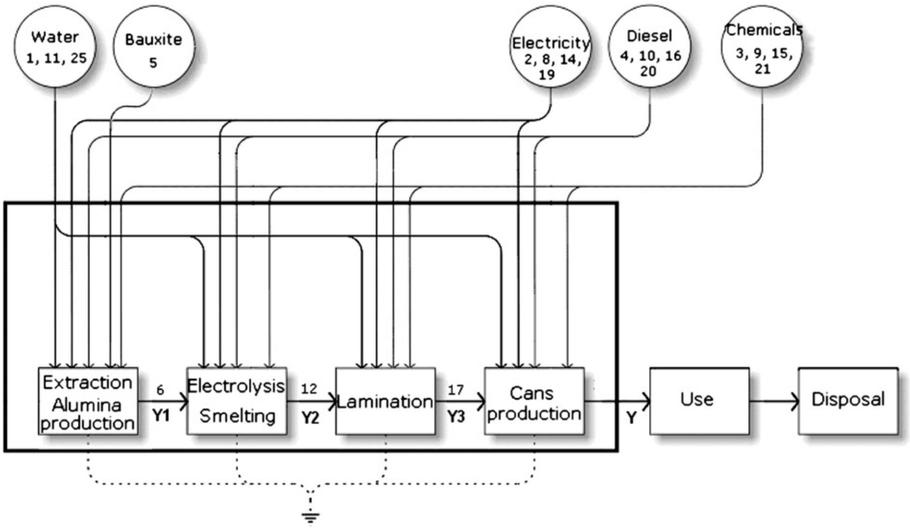

Fig. 6. Energy diagram for Al cans production using exclusively virgin materials. Each number within the circles or over arrows corresponds to a line in Table 4. Emergy fluxes 6, 12 and 17 are presented in the table but do not contribute to the total emergy, as the only raw material entering the production chain is bauxite.

lower the ratio, the lower is the stress to the environment. Table 6 summarizes results concerning the total emergy per functional unit, the emergy per gram and the environmental load that each production process imposes to the environment.

Recycled packages, besides the higher environmental efficiency, present a lower value for ELR. The result is in agreement with the idea that the more a material circulates within a production life cycle, the more this life cycle approximates the natural ecosystem, and the lower will be the stress imposed to the environment. In this way, the designer's decision for using recycled materials must be unquestionable for both cases. The result illustrates the case in which designers may intervene in a running process or make a decision at the project phase imposing the use of a recycled fraction. This decision made with support of emergy accounting, is now based on numeric data and on the information that the use of recycled materials reduces the environmental load of in approximately 19% for the PET bottles life cycle and ca. 72% for the production of aluminum cans. The values of specific emergy for PET-R bottles correspond to 63% of the invested emergy to produce PET bottles with virgin materials. The values for Al-R cans correspond to 26% of that used for the production of aluminum cans with virgin materials.

Table 6 shows three different points of view to the designer assessment of beverage packages production. The first, emergy per gram (of package), can be associated to the package producer point of view, as the idea is to produce 1 g of product with the minimum use of resources. The production of Al-R cans is environmentally more efficient than that produced with aluminum virgin materials or those produced with PET, recycled or not. The second indicator, emergy per UF, indicates the total emergy invested to supply 1000 L beverage to the customer, who wants to receive the packages with the minimum emergy use. This indicator would be better used by a designer working to the beverages producers, and in this case, the designer would choose among the four options the production using PET-R bottles, with specific emergy of 5.86×10^{14} sej/UF. However, from the biosphere point of view, the ELR value should determine the designer's decision towards the PET-R production. The product ELR × Emergy/FU gives a more complete and reliable

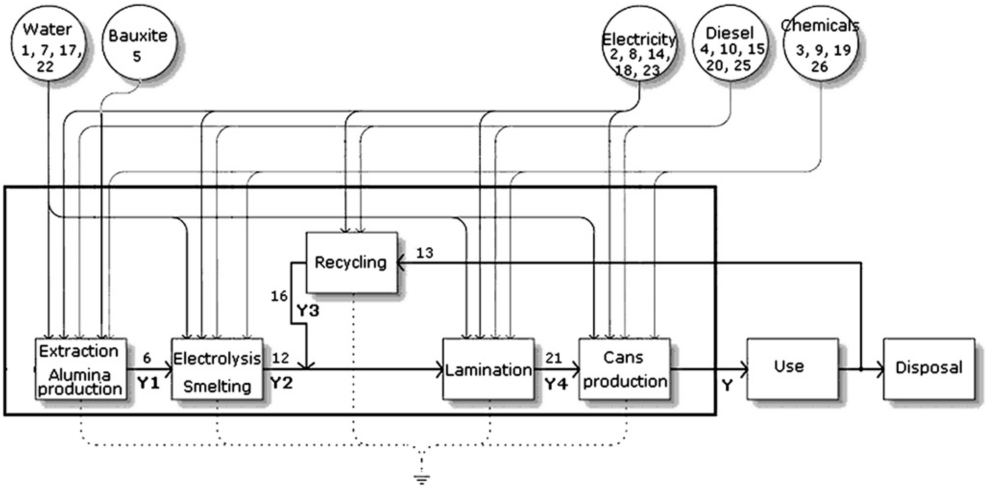

Fig. 7. Energy diagram for Al-R cans production. Each number within the circles or over arrows corresponds to a line in Table 5. Emergy fluxes 6, 12, 13, 16 and 21 are presented in the table but do not contribute to the total emergy, as the only raw material entering the production chain is bauxite.

Table 4
Environmental accounting for the Al cans production (2857 cans).

#	Item[a]	Type	Unit	Amount	Emergy per unit (sej/un)	Solar Emergy (sej)
Extraction and alumina production						
1	Water	R	g	1.68×10^{4}	2.03×10^{5}	3.41×10^{9}
2	Electricity	F	J	9.79×10^{9}	1.65×10^{5}	1.62×10^{14}
3	Chemicals	F	g	1.12×10^{4}	2.65×10^{9}	2.96×10^{13}
4	Diesel	F	J	4.79×10^{8}	6.60×10^{4}	3.16×10^{13}
5	Bauxite	N	g	1.95×10^{5}	8.55×10^{8}	1.67×10^{14}
6	Alumina	Y1	g	7.80×10^{4}	**2.36×10^{10}**	1.84×10^{15}
Electrolysis and smelting						
7	Water	R	g	5.03×10^{3}	2.03×10^{5}	1.02×10^{9}
8	Electricity	F	J	6.00×10^{9}	1.65×10^{5}	9.90×10^{14}
9	Chemicals	F	g	8.44×10^{3}	2.65×10^{9}	2.24×10^{13}
10	Diesel	F	J	4.74×10^{8}	6.60×10^{4}	3.13×10^{13}
11	Coke	F	J	1.13×10^{8}	5.40×10^{4}	6.10×10^{12}
12	Aluminum ingot	Y2	g	4.49×10^{4}	**6.44×10^{10}**	2.89×10^{15}
Lamination						
13	Water	R	g	1.12×10^{2}	2.03×10^{5}	2.27×10^{7}
14	Electricity	F	J	4.29×10^{8}	1.65×10^{5}	7.07×10^{13}
15	Chemicals	F	g	2.00×10^{-1}	2.65×10^{9}	5.30×10^{8}
16	Diesel	F	J	4.53×10^{7}	6.60×10^{4}	2.99×10^{12}
17	Aluminum sheets	Y3	g	4.61×10^{4}	**6.44×10^{10}**	2.97×10^{15}
Aluminum cans production						
18	Water	R	g	1.22×10^{5}	2.03×10^{5}	2.48×10^{10}
19	Electricity	F	J	2.96×10^{8}	1.65×10^{5}	4.88×10^{13}
20	Diesel	F	J	9.11×10^{7}	6.60×10^{4}	6.01×10^{12}
21	Paint and varnish	F	g	8.17×10^{2}	3.00×10^{9}	2.45×10^{12}
	Aluminum cans	**Y**	**g**	**4.26×10^{4}**	**7.10×10^{10}**	**3.02×10^{15}**

[a] Items from lines 6, 12 and 17 (over arrows in Fig. 6) were not accounted to avoid double-counting.

Table 5
Environmental accounting for the Al-R cans production, for 80% in weight of recycled material (2857 cans).

#	Item[a]	Type	Unit	Amount	Emergy per unit (sej/un)	Solar Emergy (sej)
Extraction and alumina production						
1	Water	R	g	4.22×10^{3}	2.03×10^{5}	8.57×10^{8}
2	Electricity	F	J	1.96×10^{9}	1.65×10^{5}	3.23×10^{14}
3	Chemicals	F	g	2.23×10^{3}	2.65×10^{9}	5.92×10^{12}
4	Diesel	F	J	9.56×10^{7}	6.60×10^{4}	6.31×10^{12}
5	Bauxite	N	g	3.90×10^{4}	8.55×10^{8}	3.33×10^{13}
6	Alumina	Y1	g	1.56×10^{4}	**2.37×10^{10}**	3.69×10^{14}
Electrolysis and smelting						
7	Water	R	g	1.01×10^{3}	2.03×10^{5}	2.05×10^{8}
8	Electricity	F	J	1.20×10^{9}	1.65×10^{5}	1.98×10^{14}
9	Chemicals	F	g	1.34×10^{3}	2.65×10^{9}	3.55×10^{12}
10	Diesel	F	J	9.48×10^{7}	6.60×10^{4}	6.26×10^{12}
11	Coke	F	J	2.26×10^{7}	5.40×10^{4}	1.22×10^{12}
12	Aluminum ingots	Y2	g	8.98×10^{3}	**6.44×10^{10}**	5.78×10^{14}
Recycling						
13	Post use aluminum cans	F	g	3.67×10^{4}		
14	Electricity	F	J	4.97×10^{8}	1.65×10^{5}	8.20×10^{13}
15	Diesel	F	J	3.97×10^{7}	6.60×10^{4}	2.62×10^{12}
16	Recycled aluminum	Y3	g	3.59×10^{4}	**1.85×10^{10}**	6.63×10^{14}
Lamination						
17	Water	R	g	1.12×10^{2}	2.03×10^{5}	2.27×10^{7}
18	Electricity	F	J	4.29×10^{8}	1.65×10^{5}	7.07×10^{13}
19	Chemicals	F	g	2.00×10^{-1}	2.65×10^{9}	5.30×10^{8}
20	Diesel	F	J	4.53×10^{7}	6.60×10^{4}	2.99×10^{12}
21	Aluminum sheets	Y4	g	4.49×10^{4}	**1.64×10^{9}**	7.37×10^{14}
Aluminum cans production						
22	Water	R	g	1.22×10^{5}	2.03×10^{5}	2.48×10^{10}
23	Electricity	F	J	2.96×10^{8}	1.65×10^{5}	4.88×10^{13}
25	Diesel	F	J	1.19×10^{8}	6.60×10^{4}	7.84×10^{12}
26	Paint and varnish	F	g	8.17×10^{2}	3.00×10^{9}	2.45×10^{12}
	Aluminum cans	**Y**	**g**	**4.26×10^{4}**	**1.87×10^{10}**	**7.94×10^{14}**

[a] Items from lines 6. 12, 13,16 and 21 (over arrows in Fig. 7) were not accounted to avoid double-counting.

evaluation, as the designer should seek for a low emergy use per functional unit combined with a low environmental load.

Despite the environmental load reduction of the overall life cycle (Table 6), designers may also evaluate the emergy use and the ELR of each stage, to prioritize/identify changes and to look for opportunities of improvement, as the sheer volume of materials processed through the life cycle continues to increase dissipative pollution.

The total emergy use for both life cycles can be compared. Fig. 8 shows the total emergy use for each stage of PET and aluminum beverage packages, and it is clear that the emergy use for packages production with recycled materials is sensibly lower than that of produced with virgin materials at all stages of the production cycle.

Fig. 9 shows the environmental loading ratio for each stage for both systems. As the proportion of the inputs needed to produce the intermediary products at stages preceding the recycled material entrance in the life cycle does not vary, ELR remains the same. Observing the stages of PET production, it is clear that a great stress is imposed to the environment at the crude oil extraction and refining stage, and during resin production. Aluminum cans production also presents a high stress at the first three stages (extraction, electrolysis/smelting and lamination). These are life cycle stages where designers have no influence, but the result may convince a designer to examine the best conditions to prescribe the use of recycled materials. The stress introduced by the recycling process can be noticed. The emergy invested in the recycling process represents 3% of the total emergy for PET and 11% for aluminum cans.

The designer has now a good picture of both production cycles, and may decide for the package producer choosing the lowest specific emergy, for the package consumer choosing the minimum emergy per UF or for the biosphere, selecting the production cycle with the lowest environmental load and highest efficiency (less emergy per functional unit).

At this point, one may suppose that the Brazilian designer would choose the biosphere option, selecting to produce beverage packages with PET-R bottles, which presents the lowest values for emergy per functional unit and for ELR.

According to the Ordinance No. 987, from 8 December 1998 from ANVISA [69] and Resolution No. 25, June 10, 1999 of Mercosur [70], the thickness of the PET virgin material layer in contact with the drink must be greater than 25 μm and the thickness of the recycled layer should not exceed 200 μm. The lowest thickness for PET bottles allowed by Resolution No. 25 is 225 μm. Then the limit for recycled PET inclusion is 199 μm of recycled PET and 26 μm of virgin material. In this way, the maximum percentage of recycled PET for beverage packing use is 88.44% in weight.

The recycling rates for PET, for the years 2003 and 2006, considered by Valt [67,68], were 40% kg/kg and 47% kg/kg respectively. But in 2006, ABIPET [78] published a report accounting the

Table 6
Specific emergy, emergy per functional unit (FU), environmental load ratio (ELR), and the product ELR × emergy/FU for PET bottles and aluminum cans production.

Product	Specific emergy $\times 10^{10}$ (sej/g)	Emergy per FU $\times 10^{14}$ (sej/FU)	ELR	ELR × emergy per FU $\times 10^{19}$ (sej/FU)
PET bottle	3.70	9.26	23,900	2.21
PET-R bottle	2.34	5.86	19,500	1.14
Al can	7.10	30.20	103,000	31.11
Al-R can	1.87	7.95	30.600	2.43

FU, functional unit: 1000 L beverage (500 bottles of 2 L each or 2857 aluminum cans).

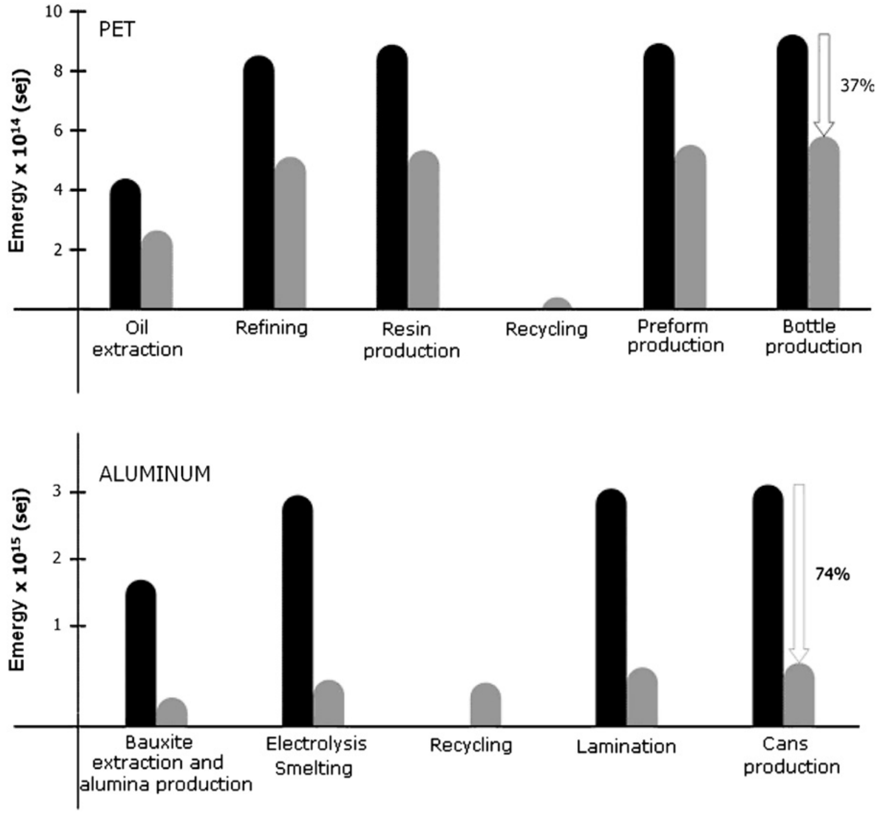

Fig. 8. Total emergy of the production life cycle of beverage packages production: with virgin materials (black) and with recycled materials (gray), for 1000 L of beverage.

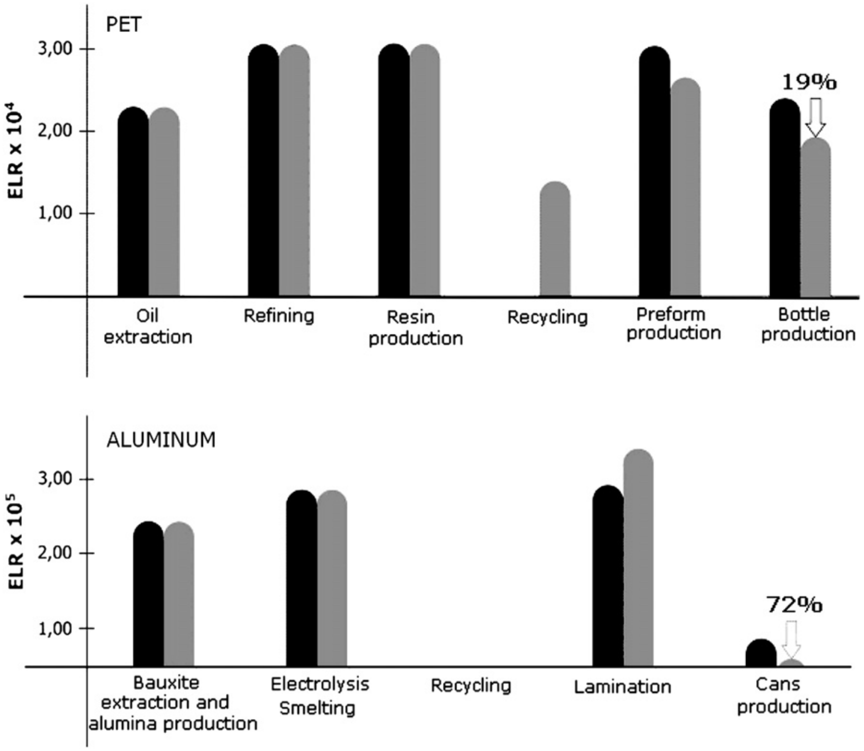

Fig. 9. Environmental load ratio of the production life cycle of beverage packages production: with virgin materials (black) and with recycled materials (gray), for 1000 L of beverage.

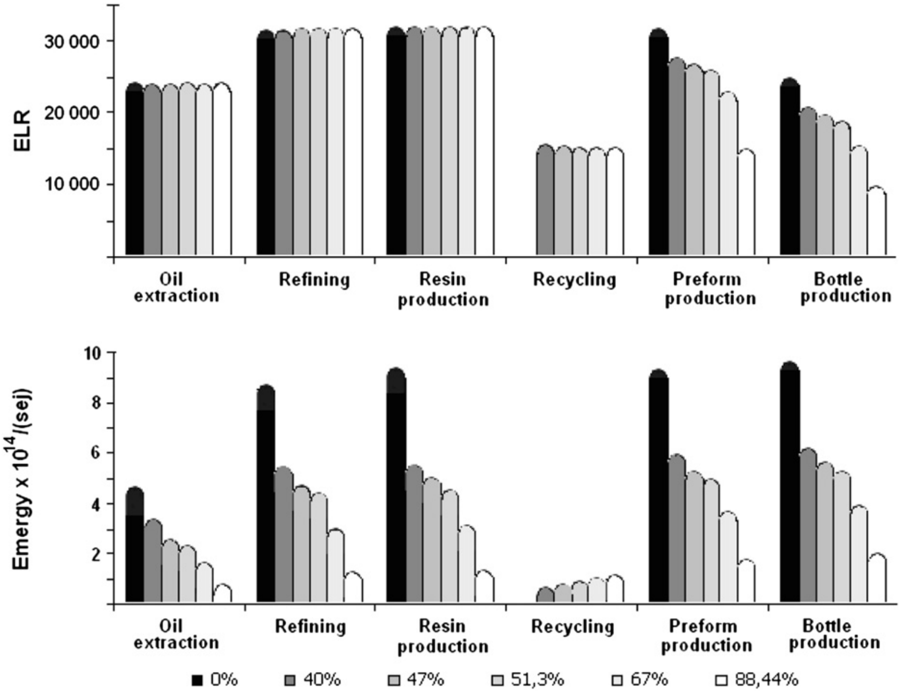

Fig. 10. ELR (top) and total emergy (bottom) of the production life cycle of PET bottles considering different rates of recycling.

recycling of 194 tons of post-consumer PET in this year, or the equivalent to 51.3% in weight of the total output.

Along with the data found in the literature [68–70,78], a commercially available PET bottle was evaluated. The 2 L PET bottle is 300 μm thick, and accordingly to the limits determined by ANVISA [69], it has a maximum layer of recycled material of 200 μm. Considering that all post-consumer PET in 2006 was constituted of this specific type of bottle, the recycling rate of PET bottles would be 67% kg/kg.

Fig. 10 shows the possibilities for PET recycling according to the different information found about PET recycling in Brazil. It is clear that the more PET is recycled, the less will be the environmental load and the less the use of resources. The emergy invested for the implementation of the recycling stage is very low in face of the savings related to the use of raw materials and other inputs. It is clear that the product ELR × Emergy/FU represents the correctness of each material selection under an environmental point of view. The lower the product ELR × Emergy/FU, the better the selection to be done, but a critical analysis permits to visualize that a small product alone does not satisfy a sufficient condition. However, supposing the designer is free to choose among aluminum cans (Al or Al-R) and all the possibilities shown for PET bottles in Fig. 10, it would be also possible, and safer, to analyze the ratio of ELR and the emergy/FU.

The ratio of ELR and the emergy per functional unit may bring more information. The inverse of the emergy per functional unit may be associated to the global productivity (GP) of each material [79].

Fig. 11 shows the relationship between ELR and the global productivity for aluminum (Al and Al-R) and for PET bottles. Each point represents the values of ELR and GP for each material choice covering all the recycling rates shown in Fig. 10.

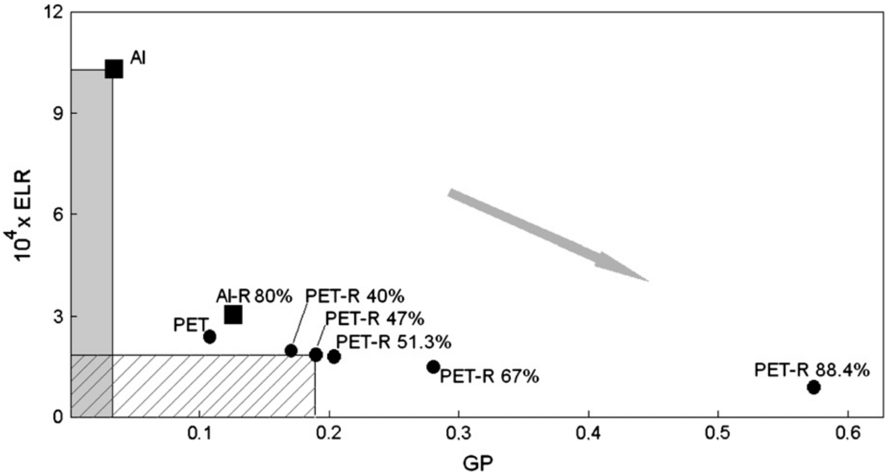

Fig. 11. ELR versus GP, where GP is the inverse of the emergy per functional unit (FU = 1000 L of beverage). The descendant arrow indicates the direction for better material selection.

The point corresponding to Al defines an area almost equal to that defined by the PET-R 47% point. However, it is clear that Al area is composed by a high ELR combined with a low global productivity, while the PET area is composed by a higher value for global productivity and a lower environmental load. In this way, the product ELR × emergy/FU would give similar values for the selection between these two options, but the analysis of Fig. 11 makes clear that Al and PET-R with 47% kg/kg recycling rate belong to opposite situations, and that the PET-R selection corresponds to the best option. PET selection still offers the possibility for increasing the recycling rate. Obviously, an increase of the recycling rate does not depend only on the designer's preferences. For aluminum, the maximum recycling rate was almost achieved, and in this case, improvements due to the increase of the recycling rate are almost accomplished. For PET, the analysis shows that there is still possibility to increase the PET recycling rate, and it also indicates that an increase from 67% to 88.4% (in weight) would increase the global productivity substantially, but the decrease on the ELR value will be less important.

With these results, the Brazilian designer is able to distinguish which would be the benefit to the environment depending on his material selection and on the recycling rate chosen.

5. Conclusions

The use of emergy accounting, through the calculation of the specific emergy, the emergy per functional unit and the ELR, was proposed as a tool for Ecodesign, and the usefulness of this tool was illustrated with an example regarding PET bottles and aluminum cans production with and without a recycling stage. This approach allows answering some basic questions regarding the materials selection, the appropriate rate of recycling to be used and the benefits achieved for each recycling rate.

The novelty of this approach is that it supplies quantitative indicators, based on a common unit (solar energy joules), which may be compared to those calculated for other processes and other products, independently of the weighting method.

With the use of emergy accounting designers may:

1. get a data set from the literature, from public, industrial or academic source. This procedure may facilitate data collection, although designers may collect their own data, if possible, including fluxes associated to human labor, to the system implementation phase and after use collection and landfilling.
2. identify the main fluxes of each production stage drawing the energy diagram. This procedure helps the designer to explore the system in study, with a deeper awareness of the variables to be considered.
3. by setting up an emergy evaluation table, identify the production stages of higher impact, the resources with higher use and the contribution of the implementation of the recycling stage. Designers will be also capable to assess the effect of a change done in the manufacture stage (as the inclusion of a recycling stage or the dematerialization of the product) and identify improvements on the entire production chain.
4. with the value of the emergy per unit (UF or g), identify the best material option and the most advantageous recycling rate possible to supply the desired product with the minimum resource use.
5. with the values of ELR, designers may assess the environmental load that the product causes on the biosphere and select the best option among materials to guarantee the minimum damage possible to the environment.
6. With the product ELR × emergy/FU and the ratio ELR/emergy per functional unit designers may have an accurate and more reliable analysis for material selection and for the determination of the best recycling rate to be used.

The main conclusion is that emergy accounting is very valuable for incorporating environmental aspects in the development of more sustainable products. However, a reflection on what would be a more sustainable product and what would be the contribution of Ecodesign for the achievement of this product is needed.

The best choice among the four options presented is the production of PET-R bottles for this Brazilian case study. PET-R bottles cause less damage to the environment than aluminum cans, and despite the reduction of the environmental load achieved by the implementation of a recycling stage, the environmental load of the PET-R bottles production is still very high, indicating that this process, as many others under human control, contributes to the reduction of the carrying capacity of the earth beyond an acceptable limit. The PET production life cycle is based on the use of a non-renewable resource and as the carrying capacity of the earth is exceeded, the whole system will be stressed over time, going into decline and finally collapsing.

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