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Material selection for environmental responsibility: the case of soft drinks packaging in Brazil

C.M.V.B. Almeida*, A.J.M. Rodrigues, F. Agostinho, B.F. Giannetti

Paulista University, Programa de Pós-Graduação em Engenharia de Produção, LaPROMA — Laboratório de Produção e Meio Ambiente, R. Dr. Bacelar, 1212, Cep 04026-002, São Paulo, Brazil

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ABSTRACT

The unprecedented scale of packaging waste in global soft drinks supply chains is attracting increasing attention due to its environmental, social and economic impacts. The selection of the most feasible packaging options is one of the key approaches towards reducing resources depletion and packaging disposal. From an environmental point of view, selection requires knowledge of all product life stages including the type and the amount of materials used and the manufacturing practices such as recycling and reuse. In this context, decision makers in industry are looking for assessment methods that address the problem as a whole and not only as a sum of parts for selecting the most appropriate and reliable option. This paper introduces environmental accounting based on emergy as a tool to assist materials selection. This tool can help decision makers in industry providing information on the environmental cost of each decision. Emergy has low cost compared to other methods that require extensive information databases and commercial software. To exemplify the application of the emergy as a tool for material selection, options for the production of soft drinks are compared. The results obtained for the Brazilian case make it possible to select refillable glass bottles as the best option according to the resources available in the country; establishing the best production model for the selected option and determining when and if a recycling stage should be implemented.

1. Introduction

Packaging in general has the characteristic of being immediately discarded after product consumption and must pursue environmental responsibility when designing, filling and importing. In general, environmental responsibility includes the amount of materials used, the type of material and the fabrication adopting practices such as recycling and reuse. Products such as soft drinks that satisfy a short-term need for the consumer produce a large amount of material to be reused, recycled or discarded. In this sector, the main packaging used are glass and PET (polyethylene terephthalate) bottles and aluminum cans. Glass partakes 12.3% of the Brazilian soft drinks market according to the Association of Soft Drink Industries (Abir, 2014), PET containers dominate with 79.8% while the aluminum cans are left with only 7.9% (CEMPRE, 2014). The return to glass bottles for the soft drink industry has been considered beneficial to the environment, and the main argument is that these packages are refillable, allowing reuse by dozens of times.

The choice of a more environmentally friendly package involves several aspects. The manufacture of the three packages is completely different and it would be necessary to account for the use of energy and auxiliary materials to estimate which one is least harmful to the environment. Allegedly, in the long run, the damage of the glass bottle would be lower, since they are produced only once and reused up to 40 times (Abividro, 2015) on average. Logistically it is stated that the PET bottles and aluminum cans are less detrimental because they are lighter, having a better weight/content relationship decreasing fuels consumption and CO_2 emissions during transportation (Amienyo et al., 2013). Both arguments are valid, but each one relates to only a part of the productive chain of the product.

Another crucial point at this stage is the after use destination of the packaging. All three materials are recyclable. The most recycled material in Brazil is aluminum with 91.5% (IBGE, 2010), and it is essential to mention that aluminum cans recycling in Brazil also generates jobs for more than 160 thousand people in activities that

* Corresponding author.
E-mail address: cmvbag@terra.com.br (C.M.V.B. Almeida).

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cover used cans collection to the scrap processing into new cans (Brazilian Aluminum Association, 2009). PET containers have a recycling rate of about 50%, while glass remains stable in recent years with 47%, according to data released by the Corporate Commitment to Recycling (CEMPRE, 2014).

Life cycle Assessment (LCA) has been widely used to examine and compare the environmental impacts of different disposal methods for food packaging, including laminated foils made from polyethylene and aluminum. Results shown that the environmental impacts from packaging material waste treatment were highest for landfill disposal, followed by incineration and recycling (Xie et al., 2016). Simon et al., 2015 analyzed six bottle collection systems for five different packaging materials. These authors observed that recycling allowed saving large amount greenhouse gas emission particularly in the case of aluminum can and glass bottles, and that even though refilling of bottles leads to decreasing greenhouse gas emission, it became less significant after a certain number of reuse.

In regard to the use of natural resources, glass is basically composed of sand, limestone, and soda ash. The PET bottle derives from petroleum, while aluminum cans are basically bauxite. All three packages are made of non-renewable resources and in that respect; it is difficult to establish the best option especially considering the short shelf-life of soft drinks packages. In particular, the overuse of non-renewable natural resources in human activities induces both resources depletion and increased production of waste, which can cause serious consequences for future generations.

Choosing the most feasible packaging options from an environmental point of view requires knowledge of all product life stages, in addition to considering the factors and levels of the components of the manufacturing process. In this context, decision makers in industry are looking for assessment methods that address the problem as a whole and not only as a sum of parts for selecting materials, as the need for altering the current non-sustainable product development practices turn out to be increasingly patent. As a result, techniques such as LCA attempt to quantify significant environmental variables, seeking to scientifically estimate resource consumption and environmental impact (Rebitzer et al., 2004). LCA has been used widely to quantify and evaluate the environmental impact of products (Andersson and Ohlsson, 1999), processes (Amienyo et al., 2013), and the consequences of packaging selection on the product life cycle (Munhoz et al., 2013; Meneses and Pasqualino, 2012). Authors also propose new indices for product design (Khan et al., 2004; Almeida et al., 2010a), methods combining costs, environmental impact and customer evaluation (Bovea and Vidal, 2004; Simon et al., 2015). For three olive packaging options, Simon et al. (2015) highlighted the importance of technologies for waste treatment and of national household waste collection rates of packaging design, concluding that increasing waste collection rates and recycling is crucial to improve packaging sustainability. In this LCA study, the packaging solution with the lowest environmental impact is made of plastic, in agreement with Almeida et al. (2010b) who found that, despite of the exceptional condition of aluminum recycling in Brazil, PET bottles were the best option. Both results (Simon et al., 2015; Almeida et al., 2010b) contradict the common suggestion for limiting the use of non-renewable and non-recyclable materials (Bertolucci et al., 2014).

Materials selection based on LCA has been explored for products such as asphalt wearing (Mladenovič et al., 2015), and for energy recovery to reduce the fossil fuel consumption (López-Sabirón et al., 2014). Based on LCA, Peças et al. (2013) proposed a method called "Materials Selection Engine" as a new selection procedure to overcome some of the limitations found in other methods. Cleary (2013) examined the argument that refillable packaging substitutes to single-use glass bottles for wines and spirits reduce environmental impacts. LCA results estimated using the ReCiPe impact assessment method showed that the refillable glass bottle had the lowest environmental impacts. Due to the numerous LCAs dealing with beverage packaging systems, von Falkenstein et al. (2010) published a 'meta-analysis' in an attempt to answer if it is possible to draw general conclusions about the environmental performance of beverage packaging alternatives from existing LCAs. Their result showed that there is still modest scientific agreement on the proper method for matching the environmental performance of products and process options.

Emergy synthesis is a powerful metric to introduce environmental concerns into the materials selection. Most the information needed to perform an emergy analysis is available in free databases, which makes emergy syntheses an attractive tool for small and medium enterprises (ISAER, 2016). Every step of the analysis is transparent, and discussions are supported by a scientific model based on the general systems theory model. This method avoids also the use of streamlined analysis that considers only one or two categories of impact. With a strong scientific basis, emergy provides information on the environmental loading of production processes and their sustainability. Moreover, emergy allows for accounting of additional and circulating flows that mimic natural ecosystems, and with the development of the method, several studies devoted to analyzing production processes were published (Cao and Feng, 2007; Giannetti et al., 2008).

This study introduces the use of emergy accounting for material selection checking the claim that refillable glass bottles reduce environmental impacts of the beverage value chain. Given the holistic nature of material selection for an environmentally friendlier option, this paper presents an alternative low cost method to provide a more systemic approach to be adopted in companies praxis.

2. Methods

Emergy accounting can be used to appraise the load imposed by a product to the environment. Considering that solar energy is the common basis of all energy flows within the biosphere, Howard T. Odum (1988) defined emergy as the quantity of solar energy necessary to obtain a product or energy flow in a specified process. The greater the emergy flow necessary to sustain a process, the greater the quantity of solar energy consumed and the larger the environmental cost. Emergy is associated with the memory of all the solar energy usage during a process, and is calculated in solar energy joules (sej) (Odum, 1996). The Unit Emergy Values (UEV) stand for the solar energy directly or indirectly required to obtain one unit of product or service, and the inverse of the UEV is called global productivity (GP) (Almeida et al., 2010b). This value provides information on the amount of product that can be fabricated per emergy invested (output/input; unit/sej). More competitive will be the process in which a smaller amount of emergy is needed to obtain a certain amount of product.

Indices obtained from emergy accounting make a distinction between renewable (R, such as sun, wind, water), non-renewable (N, such as minerals) and imported inputs (F, as electricity and fossil fuels) of the total emergy of the product, Y (Odum, 1996). The environmental loading ratio (ELR) was selected among the emergy indices for the estimation of environmental burden into the production process. ELR matches up the quantity of non-renewable and purchased emergy ($N + F$) to the quantity of local renewable emergy (R) (Brown and Ulgiati, 2004), providing a quantitative way for appraising the stress caused by, in this case, the packages fabrication (Eq. (1)). The higher ELR, the larger is the environmental stress or the load imposed to the environment by any human activity, including production systems.

$$ELR = (N + F)/R \quad (1)$$

EYR, the emergy yield ratio, is the quotient of the total emergy to the emergy of economics inputs, F, and stands for the emergy return on the economic investment (Eq. (2)). The EYR estimates the process capability to benefit from local resources. The lower the share of the economic input (F) the higher is this capability (Odum, 1996).

$$EYR = (R + N + F)/F \quad (2)$$

ESI, the environmental sustainability index indicates that it is better to have a higher emergy yield (EYR) per unit of environmental loading (ELR), as shown in Eq. (3) (Ulgiati and Brown, 2002).

$$ESI = EYR/ELR \quad (3)$$

The combination of ELR or ESI and GP pieces together information facilitating decision making, as shown by the emergy-based quadrants for decision making and material selection. For the same ESI value there are different combinations values EYR and ELR (Giannetti et al., 2012), and if the decision making is aimed to reduce the environmental burden, comparing the ELR to the global productivity can provide the desired response for regulators and policy makers (Fig. 1 A). If decision making is made within the company, the process yield must be taken into account, and the comparison between the ESI and GP can provide the most appropriate information for designers and engineers (Fig. 1 B).

To exemplify the use of the emergy accounting as a tool for material selection, an LCI comparing beverage packages was used (Valt, 2004, 2007). This LCI uses the same criteria and the same time interval for all options, ensuring the validity of comparisons for selecting materials. The LCI tables comprise the consumption of raw material and energy, the quantities of auxiliary materials and semi-manufactures, and the use of fuel for transport at each life cycle stage. Values of emergy per unit used are available in Supplementary Materials, Appendix A. Since the studied system includes a number of Brazilian States in both fabrication and recycling stages, the inputs for each flow were chosen taking into account the Brazilian limits. Water is considered a renewable input and crude oil and bauxite non-renewable ones. The amount of recycled PET considered (40% in weight) is in conformity with Mercosur (MERCOSUL/GMC/RES, 2008) and Brazilian regulations (Anvisa, 1998). The recycling rates of aluminum (Brazilian Aluminum Association, 2009) and glass (Abividro, 2015) are those practiced in the country in the same year. The functional unit (FU) is 1000 L of beverage corresponding to 3448 glass of 290 ml, 500 PET bottles of 2 L, and to 2857 aluminum cans, which represent the best-selling sizes in Brazil. Diesel used for transporting was taken into account as distances go over 1000 km. The five steps for decision making in material selection using emergy is summarized in Table 1.

3. Results

The energy system diagram (Fig. 2) combines information about the glass bottles production system, taking into account all driving energies included in the glass LCI (Valt, 2004, 2007).

Fig. 2 shows the indirect and direct environmental inputs and the main inputs for glass bottles production (electricity, materials, and fuels for transportation). Inputs are quantified (Table 2) for bottles produced exclusively with virgin materials (Glass), bottles produced using 25% of recycled materials without reuse (Glass-R), bottles reused 20 times without recycling (Glass-20), and bottles produced with reuse and recycling (Glass-20R). The complete tables for each glass bottle option are available in Appendix B.

The total emergy value considering reuse and recycling practices for the Glass-20R bottle production corresponds to 6% of the emergy invested to produce glass bottles exclusively from virgin materials (Table 2). The implementation of the reuse and recycling stages reflect directly on the extraction and glass production phases diminishing resources and energy usage. For the bottle produced only with virgin materials, 93% of the total emergy invested is associated to extraction and glass production stages. The key contributions to the total emergy are related to electricity (45%) and raw materials (42%) − sand, soda ash, limestone, dolomite, and feldspar. Chemicals and fuels contribute with 5%. The total emergy required for filling 1000 L beverage is of interest to those who purchase and fills the beverage containers while the GPs account for the amount of product that can be obtained per emergy invested being of interest to those who produces and sells the containers.

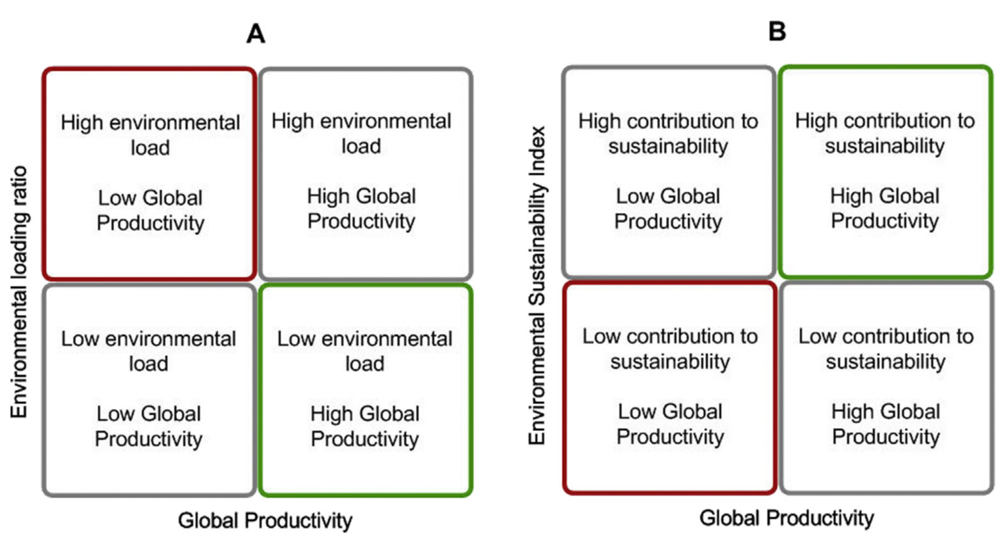

Fig. 1. Emergy-based quadrants for decision making and materials selection. Quadrants were colored in red and green to facilitate selection. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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Table 1
Five steps for decision makers for selecting materials using emergy synthesis.

Step	Action	Comments
#1	Get data	Data may be preferably collected at the system under study, but if needed, literature, public and academic sources may be used as a complement.
#2	Draw the energy diagram	Diagrams help to convert mental/verbal models to quantitative energy flows and to visualize the interactions among production stages.
#3	Build an emergy table	Each line representing the quantitative flows identified in the diagram. Calculate the total emergy by multiplying each flow by its respective UEV.
#4	Calculate the emergy indices	Indices give concise information about environmental stress, sustainability and global productivity of each material
#5	Compare materials using the emergy-based quadrants for decision making	Comparisons will allow material selection in a quantitative manner. Results presented in the quadrants for decision making help to assess the advantages or disadvantages of using a given resource taking into account environmental purposes.

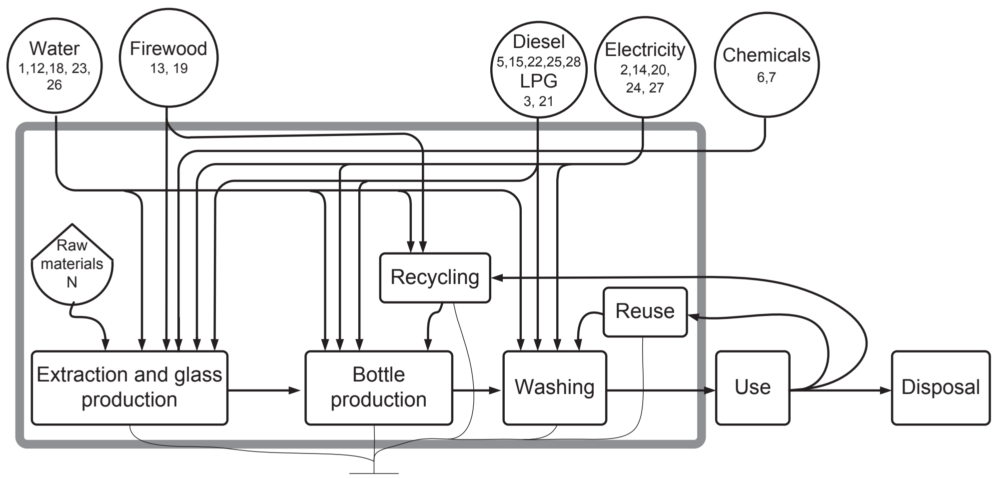

Fig. 2. Energy system diagram for glass bottles production using virgin, reused (20 times) and recycled materials (25% in weight). Numbers within the circles correspond to the lines in Table 2. Raw materials are represented in lines 7–11.

The GPs values confirm that the reuse can be the most advantageous solution. However, when considering the total resource usage, the inclusion of a recycling step increases the emergy inputs economy by 4%, which may be significant if one considers the total number of packages produced per year in the country.

Fig. 3 summarizes the emergy investment in each production step for the four glass bottles analyzed in Table 2. The introduction of a recycling stage brings no savings during the bottle production stage, but it reduces the use of new resources by 21% at the extraction stage. The production of Glass-20 bottles with or without recycling decreases the required emergy to extract and produce the glass by 95%, indicating that 20 reuses avoid the emergy need to produce a bottle from zero. It is also clear that recycling demands more emergy than reuse, but it is worthy to remark that adopting the reuse option also reduces the investment in the recycling step.

3.1. *Emergy accounting for materials selection*

The results obtained for the glass containers for soft drinks made clear that, in terms of the whole production chain, the most beneficial option to the environment is the production of Glass-20R (Table 3). However, in this market other options are widely used. The aluminum cans and PET bottles production were thoroughly analyzed elsewhere (Almeida et al., 2010b). The last column was included to represent the reuse rate of 40 times informed by the Brazilian Glass Association (Abividro, 2015).

Once the input flows to the packages production process have been identified and the GP of each process has been calculated (Table 3) a set of indices and ratios can be accordingly calculated (Table 4), using the R, N and F categorization of each flow.

A quick analysis of the results shown in Tables 3 and 4 makes clear that reuse practices improve almost all indicators. The GP values, which bring important information to the manufacturer, shows that less material and energy are used when the returnable bottles are produced. The ELR and the %R (Table 4) express the use of environmental services by a process, indicating a load on the environment. The higher ELR, the higher is the stress to the environment. The calculation of this indicator allows selecting the production mode that would bring less damage to the environment depending on the material available. For example, if the choice of material were bound with the use of virgin materials, the PET bottles would be the best choice. However, if recycling and reuse are available, the environmental load may be reduced in at least 85% by replacing PET-R bottles by Glass-20 bottles.

The EYR values for all materials do not exceed the value 1.4 (Table 4), indicating that all modes of production, regardless of the material used, are strongly dependent on the resources provided by the economy. This result is reflected in the values of ESI, which increases more than ten times when reuse practices are implemented.

3.2. *The trade-off between environmental load and productivity*

For the better visualization of results, and for a quick decision making, the values of ELR, ESI and GP were normalized in a scale from 0 to 1 and presented in four quadrants explained in Fig. 1.

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Table 2
Emergy and GP values for bottles produced exclusively with virgin materials (Glass), bottles produced using 25% of recycled materials without reuse (Glass-R), bottles reused 20 times without recycling (Glass-20), and bottles produced with reuse and recycling (Glass-20R).[a]

#	Item[a]	Solar emergy/$\times$ 10^{12} (sej/FU)			
		Glass	Glass-R	Glass-20	Glass-20R
Extraction and glass production					
1	Water	0.046	0.034	0.002	0.002
2	Electricity	3510	2630	175	132
3	LPG	10	7.6	0.5	0.4
4	Metals	0.007	0.003	0.000	0.000
5	Diesel	153	114	7.6	5.7
6	Sodium chloride	162	121	8.1	6.0
7	Sodium hydroxide	1060	795	53.2	39.8
8	Sand	1590	1200	79.6	59.8
9	Limestone	158	119	7.9	5.9
10	Dolomite	303	227	15.2	11.4
11	Feldspar	317	237	15.8	11.9
	Subtotals	**7263**	**5451**	**363**	**273**
Recycling					
12	Water		0.034		0.002
13	Firewood		0.003		0.000
14	Electricity		1580		79
15	Diesel		16.8		0.8
16	Sodium chloride		8.5		0.5
17	Broken glass				
	Subtotals		**1605**		**80**
Glass bottle production					
18	Water	0.041	0.041	0.002	0.002
19	Firewood	0.004	0.004	0.003	0.000
20	Electricity	303	303	9.0	15.1
21	LPG	21.8	21.8	1.1	1.1
22	Diesel	244	244	12.2	12.2
	Subtotals	**569**	**569**	**22**	**28**
Washing					
23	Water	0.01	0.01	0.01	0.01
24	Electricity	2.81	2.81	2.81	2.81
25	Diesel	3.05	3.05	3.05	3.05
	Subtotals	**6**	**6**	**6**	**6**
Reuse 20$\times$					
26	Water			0.191	0.191
27	Electricity			56.3	56.3
28	Diesel			61	61
	Subtotals			**117**	**117**
Glass bottles		7840	7630	509	505
GP/$\times$ 10^{-9} (seJ/g)		0.19	0.20	3.03	3.03

[a] The complete tables for each type of production are available in the Appendix B.

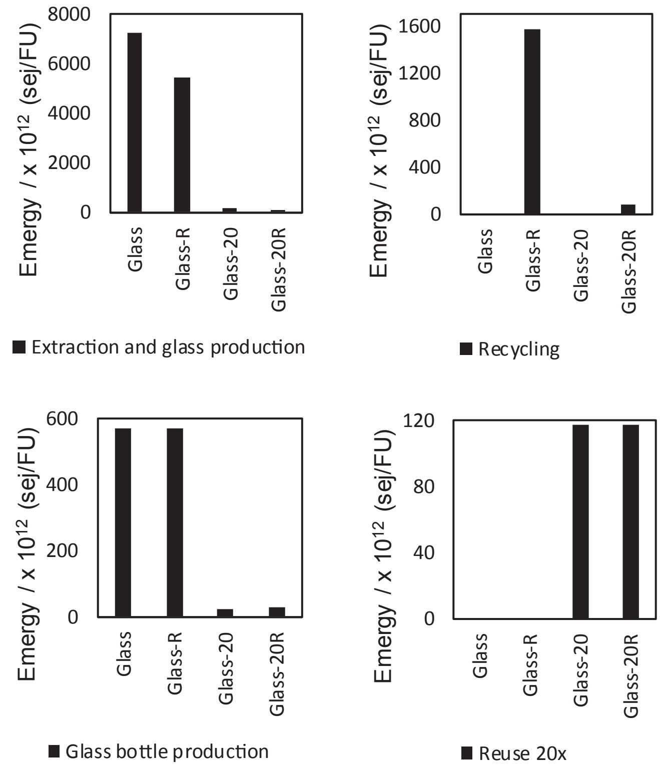

Fig. 3. Summary of the emergy requirements to produce four options of glass bottles: Glass (bottles produced with virgin material); Glass-R (bottles produced using 25% of recycled materials without reuse); Glass-20 (bottles reused 20 times without recycling); and Glass-20R (bottles produced with reuse and recycling).

Fig. 4 shows the relationship between ELR and GP considering the production mode used. Since PET can be recycled, the indices for various recycling rates according to the different Brazilian information sources were also included (Almeida et al., 2010b). Each point represents the values of ELR and GP for each material choice covering all the recycling rates reported by ABIPET (2008). There are no materials placed in top-right quadrant, which indicates that, among the materials available, reuse and recycling at higher rates can decrease environmental stress and maintain a higher global productivity.

The four quadrants shown in Fig. 4 illustrates the material selection based on the concern for the stress that each material can cause in the environment, considering that the decision maker is an environmental analyst or a public policies maker. The analysis of the emergy-based quadrants for decision making and materials selection makes clear that Al, Glass and Glass-R cause significant stress to the environment and offer low global productivity to manufacturers. Public policies and regulations should then encourage the use of materials which are positioned in the quadrant marked in green, which includes PET with more than 50% recycling rates, Glass-20, Glass-20R, and Glass-40R.

ESI combines a high environmental yield with a low environmental loading (Eq. (3)), and the analysis of the emergy-based quadrants for decision making can help designers and engineers in selecting a material considering the production yield (Fig. 5). In this case, materials positioned in the green quadrant are Glass-20, Glass-20R, and Glass-40R. The possibility to increase the PET recycling rate to 88.4% would increase the global productivity substantially, but the increase on the ESI value will be less important.

The analysis of the emergy-based quadrants may also help to improve the production process. If the decision lies on implementing or not a recycling stage on the production of Glass-20, the position of Glass-20R when compared to that of Glass-20 may indicate that the investment on a recycling stage may be postponed, and that would be more beneficial to invest on increasing the reuse practice. Among the possibilities presented in Fig. 5, the best option is to maximize the reuse of glass bottles. However, the results suggest that returnable PET-R88%, with the highest GP, is a potential competitor.

The results also support studies from other authors (Cleary, 2013; von Falkenstein et al., 2010) and the general acceptance of the community that reuse is better than recycling. The results are also in agreement with the idea that the more a material circulates within a production chain, the more this chain approximates the natural ecosystem, and the lower will be the stress imposed to the environment (Giannetti et al., 2004; Giannetti and Almeida, 2005). This analysis can be repeated and updated according to decision makers needs to evaluate, for example, changes in the production process, the adoption of new materials, the use of different energy sources, new suppliers or for the improvement of the environmental performance of the whole supply chain.

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Table 3
Emergy requirements (Y) and global productivity (GP) for the production of glass, PET, and aluminum packaging, considering reuse and recycling options[a].

Option	Virgin			Recycled			Reused	Reused & recycled	
	PET	Al	Glass	PET-R	Al-R	Glass-R	Glass-20	Glass-20R	Glass-40R
$Y/10^{12}$ (seJ/FU)	1460	4930	7840	930	1300	7630	509	505	440
$GP/\times 10^{-9}$ (seJ/g)	0.02	0.01	0.20	0.03	0.03	0.20	3.03	3.03	3.45

[a] FU, functional unit: 1000 L beverage (500 PET bottles of 2 L each, 2857 aluminum cans and 3448 glass bottles of 290 ml).

Table 4
Emergy indices for the production of glass, PET and aluminum packaging, considering reuse and recycling option[a]. R are the renewable inputs, N the non-renewable inputs, F the feedback from the economy.

Option	Virgin			Recycled			Reused	Reused &recycled	
	PET	Al	Glass	PET-R	Al-R	Glass-R	Glass-20	Glass-20R	Glass-40R
%R	<1	<1	<1	<1	<1	<1	<1	<1	1
%N	14	6	23	13	4	23	18	18	10
%F	86	94	77	87	96	77	82	82	89
ELR	22,500	100,000	78,500	18,300	30,000	61,300	2500	2400	1100
EYR	1.1	1.0	1.4	1.1	1.0	1.3	1.3	1.2	1.1
ESI	0.00005	0.00001	0.00002	0.00006	0.00003	0.00002	0.00052	0.00050	0.00100

Where: Environmental Loading Ratio (ELR), Emergy Yield Ratio (EYR) and Environmental Sustainability Index (ESI).
[a] FU, functional unit: 1000 L beverage (500 PET bottles of 2 L each, 2857 aluminum cans and 3448 glass bottles of 290 ml).

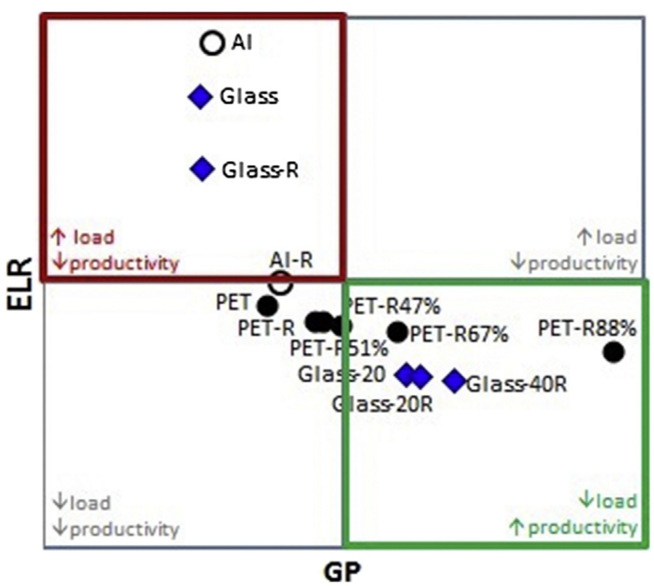

Fig. 4. ELR as a function of GP. Quadrants were colored in red and green to facilitate selection. Percentages indicate the recycling rate applied to each PET option (40, 47, 51, 67 and 88%, ABIPET, 2008). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

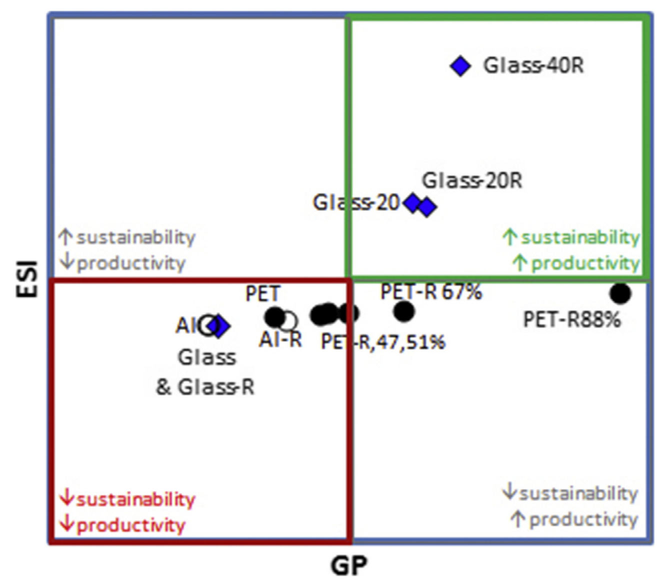

Fig. 5. ESI as a function of GP. Quadrants were colored in red and green to facilitate selection. Percentages indicate the recycling rate applied to each PET option (40, 47, 51, 67 and 88%, ABIPET, 2008). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4. Conclusions

The process of decision making seeks widespread consensus among the members of the scientific and industrial communities in providing indicators to deal with environmental issues. Decision makers prefer indicators that can provide quick and reliable decisions. However, there is also a consensus that there is no available tool that could provide single score sustainability indicators covering all environmental aspects. The emergy approach tries to get closer to this preference providing indicators of simple calculation and interpretation based on a strong scientific model. The introduction of emergy synthesis for materials selection with its respective rules, scale analysis and meanings provides a different snapshot of the soft drinks packaging productive chain that may be used by decision makers. The method has many strong points that can even help improve and complement other methods since it was shown that emergy synthesis can be easily integrated into the LCA framework.

Results obtained for the Brazilian case make possible to select the best option according to the resources available in the country; establish the best production model for the selected option and determine when and if a recycling stage should be implemented. The best choice among the options presented for each of the three materials is the production of Glass-40R bottles followed by PET-R and Al-R. In the long-term, considering that all three materials are based on the exploitation of non-renewable resources, the reuse solution also appears as the more feasible.

The introduction of emergy synthesis for materials selection could answer some fundamental questions concerning the materials selection, the benefits achieved for each recycling rate and the suitable rate of recycling and reuse to be used. For decision makers in industry, emergy results provide information on the environmental cost of each decision with relatively low cost compared to other methods. The procedure also outlines how decision makers can assess any production system, and if their main environmental responsibilities are being fulfilled, including obligations to reuse and/or recycle. From the perspective of environmental analysts and public policies makers, emergy synthesis provides information on the environmental stress imposed by a given production system to the environment, and could help to define and standardize indicators in a participatory way when wider perspectives are studied.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2016.04.130.

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