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A combined tool for environmental scientists and decision makers: ternary diagrams and emergy accounting

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Abstract

Ternary diagrams are presented as graphic tools to assist environmental accounting and environmental decision-making based on emergy analysis [Odum HT. Environmental accounting – emergy environmental decision making. John Wiley & Sons; 1996. 370 pp. [1]]. Beyond the unquestionable advantages of graphic interpretation over table analysis, the use of ternary diagrams or phase diagrams, widely used for physical chemistry evaluation of three component systems, permits the use of phase diagram properties to assess the dependence of the system upon renewable and non-renewable inputs, the environmental support for dilution and abatement of process emissions and the system efficiency. The prompt visualization of the emergy accounting data makes possible to compare processes and systems with and without ecosystem services, to evaluate improvements and to follow the system performance over time. With the aim of ternary diagrams, aspects such as the interaction between systems and the interactions between systems and the environment can be readily recognized and evaluated.

Keywords: Emergy analysis; Emergetic sensibility; Graphic tool; Sustainability; Environmental indicators and ternary diagram

1. Introduction

Environmental indicators based on emergy accounting can be calculated and used to evaluate the relationships among components of anthropogenic systems and the resources needed to produce goods and services, such as industrial products, of these systems [1]. These indices and ratios depend upon the fraction of renewable and non-renewable inputs and on purchased inputs locally available or imported from outside the system. Taking into account the carrying capacity of the environment, indices can provide valuable information about the development and operation of economic systems within this environment. Emergy based indices provide practical information about the quality of inputs and outputs, the thermodynamic efficiency of the system, and especially about the interaction between the system and environment in which it is inserted.

Environmental assessment based on emergy takes into account the rate of natural resources use, their efficient exploitation, the carrying capacity of the environment and the production of wastes and pollutants, which determine the global sustainability of a system. The indices and ratios that arise from emergy analysis are able to account for both ecological and economic contribution and their use may enable international comparability. However, a lack for a clear and uniform representation of these indices can make the confrontation of different data troublesome and intricate.

Several models have been proposed to represent graphically environmental indicators. The ISSE index (Integrated Italian Sustainability Index) was introduced

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by the Institute of Sustainable Development and is based on three pillars: welfare, environmental quality and resource use [2]. A multidimensional vector presentation is used to show the role of each index component being the ISSE index the average of three values. This representation uses a normalization approach that introduces the concept of distance to target. Values of welfare, environment and resource use indexes and can be followed through a time series represented in a circle. Jalal and Rogers [3] developed a graphical representation of the change of the environment using the concept of environmental elasticity, defined by the ratio between the aggregate environmental change and the aggregate economic change. The graphical representation shows four quadrants in which systems or countries are located in an economic–environmental space to illustrate the use of the diagrams. In the first quadrant, economic and environmental changes are both positive and this is the most preferred situation. The third quadrant represents the worst situation when economic and environmental changes are both negative. The principal merit of the environmental elasticity is its dynamism. It uses data from two points at a time to compute economic and environmental changes for both aggregates within a time period.

The environmental diamond is another graphical representation that focuses the state of the environment in a given lapse of time. In a simple version, the diamond shows how the environment depends on the four principal environmental components: air, water, land and ecosystem [3]. The environmental diamond, constructed with selected appropriate variables, namely, energy consumption, population with safe drinking water, fertilizer use and forest cover, is drawn on the Cartesian system of axes using relative values. The result is a square diamond where the overlay data values reflect the situation of individual systems, such as countries or regions.

A graphical representation of the indices obtained by emergy accounting was also reported [4,5]. Ulgiati and Brown have plotted the ratios $N/F = \upsilon$ (NI) and $R/F = \eta$ (ETA) to the economic investment F, being N the local non-renewable resource flow and R the renewable resource flow. Three-dimensional plots representing the indices environmental loading ratio (ELR), environmental yield ratio (EYR) and sustainability index (SI) against υ and η, called exploit functions, were used to evaluate the amount of investment required to exploit a local renewable or non-renewable resource. The resulting surfaces can provide additional information about the indices and it is possible to simulate conditions where the amount of inputs is changed.

Ternary diagrams have been used to represent Life Cycle Assessment results graphically [6]. The sides of the mixing triangle were associated to three weighting factors: W_{EQ}, the weighting factor for the damage to ecosystem quality, W_{HH}, the weighting factor for the damage to human health and W_R, the weighting factor for the damage to energy resources, each one varying from 0 to 100%. The graphical representation can be used to assess two product alternatives based on their emissions to the environment and on the corresponding damages. Lines of indifference are calculated by determining points where the eco-index is equal for both products. A freeware tool that calculates and draws such triangles with indifference lines can be downloaded from http://www.pre.nl/ecoindicator99.

In this work, ternary diagrams are presented as graphic tools to assist environmental accounting and environmental decision-making based on emergy analysis. Ternary diagrams are here called tools instead of graphical representation because they offer not only possibilities for data interpretation, but also permit data treatment. The use of ternary diagrams, widely in areas such as chemistry, geology and metallurgy, permits the use of the inherent properties of triangular diagrams to assess the dependence of the system upon renewable and non-renewable inputs, the environmental support for dilution and abatement of process emissions and the system efficiency. The prompt visualization of the emergy accounting data makes it possible to compare processes and systems with and without ecosystem services, to evaluate improvements and to follow the system performance over time. With the aim of ternary diagrams, aspects such as the interaction between systems and the interactions between systems and the environment can be readily recognized and evaluated.

2. Emergy accounting

Odum claims in the introduction of his book that: “A science-based evaluation system is now available to represent both the environmental values and economic values with a common measure. EMERGY, spelled with an ‘m’, measures both the work of nature and that of humans in generating products and services” [1]. Emergy is the energy memory or the total energy embodied in any product or service. It is defined as the sum of all inputs of energy needed directly or indirectly to make any product or service [1]. The use of a common basis (solar equivalent joules, seJ) permits to account all the energy contributions to obtain a certain product or service. The relationship between emergy and energy is given by the transformity (seJ/J), which is the emergy needed to obtain 1 J of a product or service, directly or indirectly. In some cases, it is convenient using emergy per unit, such as mass, to transform the accounted quantities in emergy.

The values of emergy and transformity are path dependent, that is, they are susceptible to the material and energy used at each step of the production process.

The transformities of ecological services and products have been estimated by Odum [1,7], but the transformities of industrial products and services depending on selected raw material must be evaluated case by case. A typical emergy flow diagram for an industrial process is shown in Fig. 1.

The emergy flows represent three categories of resources: R as renewable resources, N as non-renewable resources and the inputs from the economy, F. All three categories are fundamental for the emergy accounting and for the understanding of the system interactions with the environment. The R and N flows are provided by the environment and are economically free, but while the renewable resources can be replaced at least at the same rate as they are consumed, the non-renewable resources are depleted faster than their ability of recuperation. The economic inputs, F, are provided by the market and related to fluxes that are accounted by the economy. The outputs, Y, may include products, services and also emissions that are released to the environment.

The vast majority of studies employing emergy analysis include the three types of resources, but recently some researchers have quantified the environmental support for dilution and abatement of process emissions [8], evaluated the human work to treat industrial and urban wastes [9–11].

Most man made systems are based on the misuse of locally available resources, R and N, and on an imported emergy investment F. The emergy flows, shown in Fig. 1, permit to calculate different indices that can help to examine and supervise a production system. A complete inventory of the emergy based indicators cannot be provided here, but complete information can be found in [1,12–15]. In this paper four indicators will be defined to assist the discussion: the environmental loading ratio (ELR), the emergy yield ratio (EYR), the emergy investment ratio (EIR) and the emergy index of sustainability (SI).

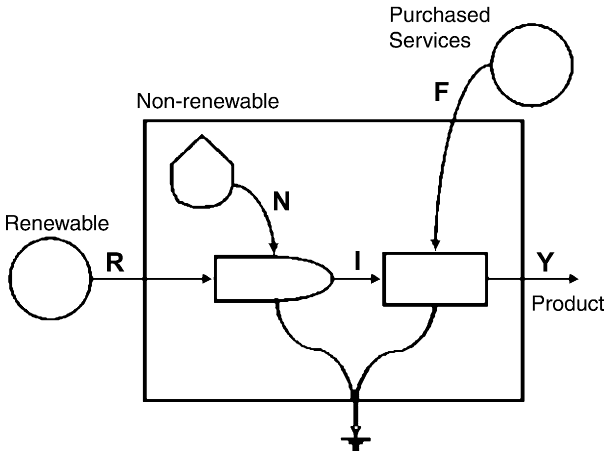


Fig. 1. Emergy flow chart for local renewable emergy inputs (R), local non-renewable inputs (N), purchased inputs from outside the system (F) and system yield ($Y = R + N + F$).

The ELR is an indicator of the stress of the local environment due to the production activity. It is the ratio of the economic inputs (F) and local non-renewable emergy (N) to free environmental emergy, R (Eq. (1)).

$$\mathrm{ELR}=\frac{N+F}{R} \tag{1}$$

Eq. (1) shows that the lower the portion of renewable emergy used the higher the pressure on the environment.

The emergy yield ratio, EYR, is the ratio of the emergy of the output to the emergy of economics inputs, F, and represents the emergetic return on economic investment (Eq. (2)).

$$\mathrm{EYR}=\frac{Y}{F}=\frac{R+N+F}{F} \tag{2}$$

This indicator computes the process ability to profit from local resources. The lower the portion of the economic input (F) the higher is this ability. However, this index does not differentiate local and imported resources.

The EIR shows the relation between the emergy of the economic inputs with those provided by the environment, renewable or not (Eq. (3)).

$$\mathrm{EIR}=\frac{F}{N+R} \tag{3}$$

The 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 (Eq. (4)) [4].

$$\mathrm{SI}=\frac{\mathrm{EYR}}{\mathrm{ELR}}=\frac{Y/F}{(N+F)/R} \tag{4}$$

3. Phase diagrams

Phase diagrams are used to describe equilibrium situations in which two or more phases of matter exist together in pure substances or in solutions. They are widely used in the physical sciences, especially in the fields of metallurgy, materials science, geology, and physical chemistry. The ternary diagrams were proposed by Gibbs and Roozeboom for the analysis of mixed components [16].

Most commonly, three fractions or proportions add to 1, or three percents add to 100. The constant sum constraint means that there are just two independent pieces of information. Hence, it is possible to plot observations in two dimensions within a triangle. This type of diagram is three-dimensional but is illustrated in two dimensions for ease of drawing and reading. Triangular plots appear under various names in the literature, including trilinear, triaxial, three-element maps, ternary, reference triangles, percentage triangles and mixing triangles.

An emergetic ternary diagram has three components, *R*, *N* and *F* (Fig. 2). These components can be represented in an equilateral triangle; each corner represents an element, and each side a binary system; 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 to the appropriate element (Fig. 2a). Hence, the "composition" of any point plotted on a ternary diagram can be determined (or any point can be plotted) by reading from zero along the basal line (axis) at the bottom of the diagram to 100% at the vertex of the triangle. In Fig. 2b the point A represents a system composed by three inputs: 16% of *F*, 62% of *N* and 22% of *R*. This device is possible because the sum of such perpendiculars is independent of the position of the point.

Ternary diagrams show important properties. When two different ternary compositions, represented by points P and Q within the triangle, are mixed, the resulting composition will be represented by a point X called here "simergic" point (see Section 3.1), which lies at some point on the segment PQ (Fig. 2c).

Another important property of triangular diagrams is the significance of a straight line joining an apex to a point on the opposite edge (Fig. 2d). Any point along the indicated line represents a composition that is progressively poorer in *N*, as it passes from A to B, but *R* and *F* remain present at the same initial proportion. Therefore, if one wishes to represent the changing composition of a system A as %*N* diminishes, all that is necessary is to draw a line from the apex *N* passing through point A. Any ternary system formed by adding or subtracting *N* from the former composition lies at some point of this line, called here "sensitivity line" (see Section 3.1).

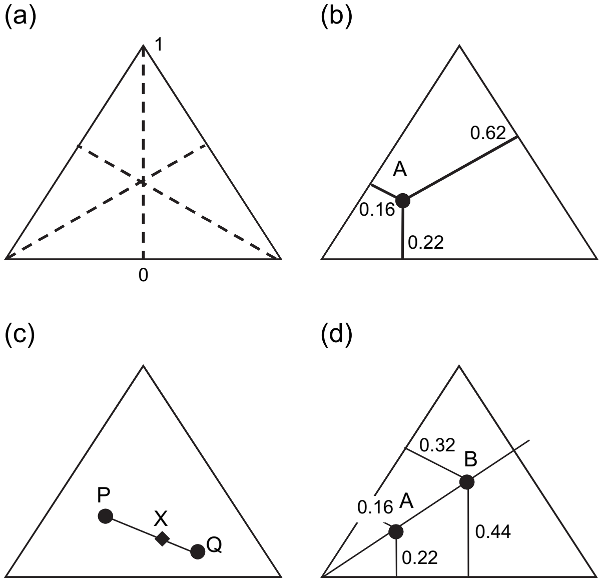


Fig. 2. Representation of (a) a ternary diagram, (b) a general A system, (c) an *X* system composed by the combination of P and Q systems and (d) the sensitivity line.

3.1. Methodology

An application composed by two Excel archives was developed with routines written using Visual Basic for Applications. Each apex of the ternary diagram was related to a resource flux: *R* (renewable), *N* (nonrenewable) and *F* (purchased). In order to exploit the basic properties of the diagrams, relative values were calculated and used instead of absolute ones, which do not alter indexes values. In this way, a point on the interior of the triangle can describe any product, process or service.

One of the Excel archives is used for data entrances, with capacity to present 10 products simultaneously, and capable to compute 50 items for each product or service (Fig. 3).

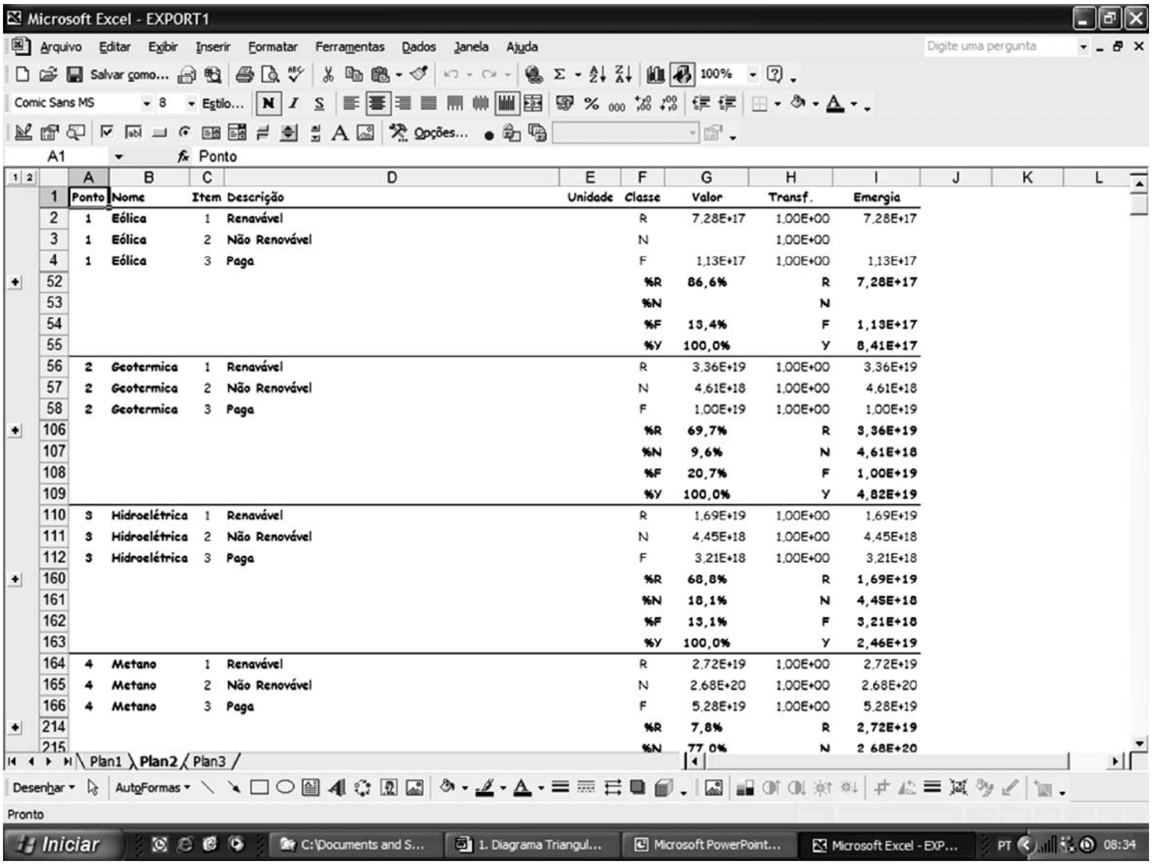
The second archive captures the data, performs the needed calculations and plots the results in the ternary diagram presenting a point for each product or process (Fig. 4). Each point can be selected or unselected according to the analysis to be performed and the size of each point can be proportional to the total emergy of the product that it represents. The triangular coordinates were chosen with *R* coincident with the *y*-axis of the Cartesian system and at the bottom of the triangle. *N* lies on the left apex and *F* on the right apex.

Auxiliary lines were defined and can be selected or unselected to facilitate analysis: resource flow lines, sustainability lines, sensitivity lines and the symergy point (Figs. 2 and 5).

3.1.1. Resource flow lines

These lines can be selected to indicate constant values for each resource flow (*R*, *N* or *F*). These lines are parallel to the triangle sides and are very useful to compare the use of resources by products or processes (Fig. 5a). As the sum of *R*, *N* and *F* equals 100%, the indices EYR and EIR can be related to the component *F* and the corresponding line *F*, parallel to the RN side, is representative of the values of both indices as follows:

$$\mathrm{EYR} = \frac{100}{F} \qquad (6)$$



	A	B	C	D	E	F	G	H	I
1	Ponto	Nome	Item	Descrição	Unidade	Classe	Valor	Transf.	Emergia
2	1	Eólica	1	Renavável		R	7,28E+17	1,00E+00	7,28E+17
3	1	Eólica	2	Não Renovável		N		1,00E+00	
4	1	Eólica	3	Paga		F	1,13E+17	1,00E+00	1,13E+17
52						%R	86,6%	R	7,28E+17
53						%N		N	
54						%F	13,4%	F	1,13E+17
55						%Y	100,0%	Y	8,41E+17
56	2	Geotermica	1	Renavável		R	3,36E+19	1,00E+00	3,36E+19
57	2	Geotermica	2	Não Renovável		N	4,61E+18	1,00E+00	4,61E+18
58	2	Geotermica	3	Paga		F	1,00E+19	1,00E+00	1,00E+19
106						%R	69,7%	R	3,36E+19
107						%N	9,6%	N	4,61E+18
108						%F	20,7%	F	1,00E+19
109						%Y	100,0%	Y	4,82E+19
110	3	Hidroelétrica	1	Renavável		R	1,69E+19	1,00E+00	1,69E+19
111	3	Hidroelétrica	2	Não Renovável		N	4,45E+18	1,00E+00	4,45E+18
112	3	Hidroelétrica	3	Paga		F	3,21E+18	1,00E+00	3,21E+18
160						%R	68,8%	R	1,69E+19
161						%N	18,1%	N	4,45E+18
162						%F	13,1%	F	3,21E+18
163						%Y	100,0%	Y	2,46E+19
164	4	Metano	1	Renavável		R	2,72E+19	1,00E+00	2,72E+19
165	4	Metano	2	Não Renovável		N	2,68E+20	1,00E+00	2,68E+20
166	4	Metano	3	Paga		F	5,28E+19	1,00E+00	5,28E+19
214						%R	7,8%	R	2,72E+19
215						%N	77,0%	N	2,68E+20

Fig. 3. Excel archive for data entrances.

$$\mathrm{EIR} = \frac{F}{100 - F} \tag{7}$$

In the same way, the environmental loading can be expressed by the fraction of renewable emergy used by a process.

$$\mathrm{ELR} = \frac{100 - R}{R} \tag{8}$$

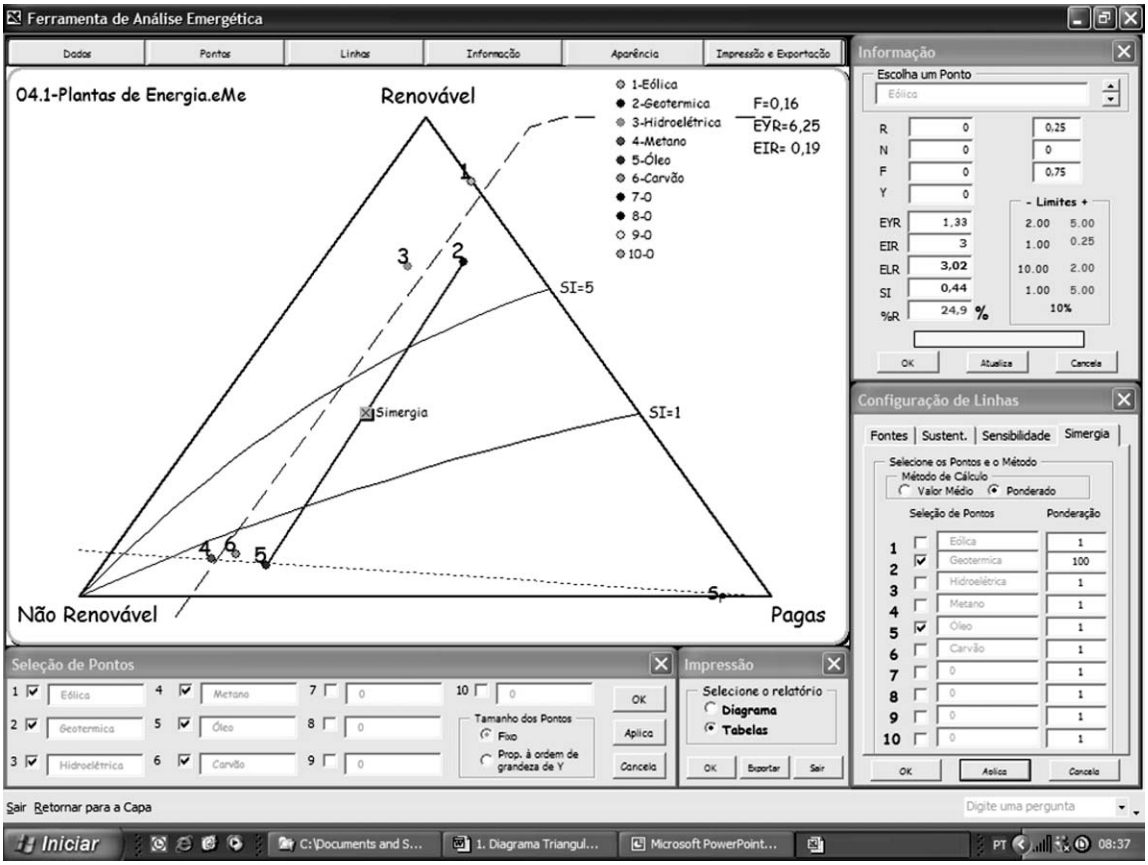
According to Ulgiati and Brown [8], EYR values below 5 denote primary materials, such as cement and steel, and secondary energy resources. Primary energy resources usually have EYR > 5 and processes with environmental yield ratio less than 2 do not contribute as energy source and are associated to consumables or manufacturing processes. Similar analysis can be made using the R component associated to ELR. Low values of ELR (nearly 2) indicate low environmental impact or processes having a large area to dilute their total impact. When ELR > 10, there is a high environmental loading and when $3 < \mathrm{ELR} < 10$, the impact is considered moderate. For extremely high values of ELR, the non-renewable inputs and/or the purchased inputs predominate suggesting that the offer of local renewable inputs is not enough to supply the process demands. In Fig. 5a it can be observed that the economic investments for products A and B are similar, but R and N quantities differ substantially.

3.1.2. Sustainability lines

The graphic tool permits to draw three lines shown in Fig. 5b indicating constant values of the sustainability index. These lines are presented independently and the value of SI may be fixed by the user (SI > 0). The sustainability lines depart from the N apex in direction of 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, point G, products and processes are not sustainable in a long term [8]. Systems presenting $1 < \mathrm{SI} < 5$, point E, may have a sustainable contribution to the economy for medium periods and processes with SI > 5 can be considered sustainable in a long term, point D.

3.1.3. Sensitivity lines

The graphic tool permits the presentation of three sensibility lines, shown in Fig. 2d, along which one can follow the variation of a given resource flux (R, N or F). Any point along the line represents a condition in which



Informação

Escolha um Ponto: Eólica

			- Limites +	
R	0	0,25		
N	0	0		
F	0	0,75		
Y	0			
EYR	1,33		2.00	5.00
EIR	3		1.00	0.25
ELR	3,02		10.00	2.00
SI	0,44		1.00	5.00
%R	24,9 %		10%	

Configuração de Linhas

Fontes | Sustent. | Sensibilidade | Simergia

Selecione os Pontos e o Método

Método de Cálculo: ○ Valor Médio ● Ponderado

		Seleção de Pontos	Ponderação
1	☐	Eólica	1
2	☑	Geotermica	100
3	☐	Hidroelétrica	1
4	☐	Metano	1
5	☑	Óleo	1
6	☐	Carvão	1
7	☐	0	1
8	☐	0	1
9	☐	0	1
10	☐	0	1

Seleção de Pontos

1 ☑ Eólica
2 ☑ Geotermica
3 ☑ Hidroelétrica
4 ☑ Metano
5 ☑ Óleo
6 ☑ Carvão
7 ☐ 0
8 ☐ 0
9 ☐ 0
10 ☐ 0

Tamanho dos Pontos: ● Fixo ○ Prop. à ordem de grandeza de Y

Impressão

Selecione o relatório: ○ Diagrama ● Tabelas

Fig. 4. Archive for data capture, calculations and plot presentation.

the other two fluxes remain present in the same initial proportion. This kind of analysis may be especially useful to simulate changes regarding the resource fluxes in an operating system.

3.1.4. Simergic point

There is still the possibility to present a point, called simergic point, which represents the resulting composition of a system composed by more than one product or process (Fig. 2c). The simergic point can be used to determine the characteristics of a whole sector or a set of products. Its significance depends on the understanding that the resource fluxes are independent. The location of this point on the triangle provides a prompt recognition of the effects of a sector or an industrial park on the environment, which is only possible with the application of the diagram properties and the use of the graphic tool presented.

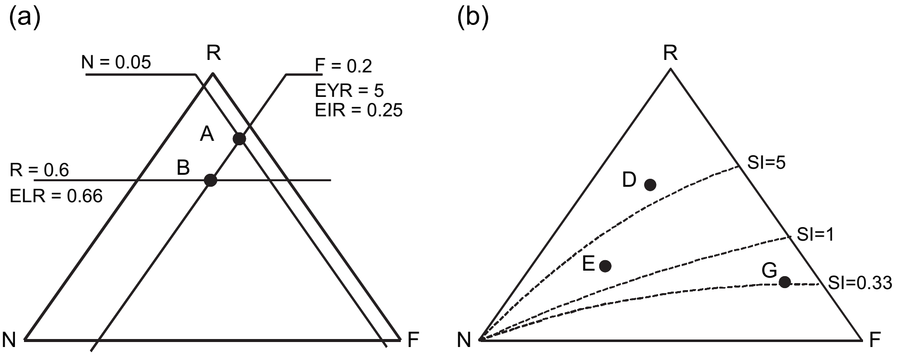


Fig. 5. Auxiliary lines: (a) resource flow lines and (b) sustainability lines.

4. Example of application

The graphic tool produces a triangular plot of three variables with constant sum. The following hypothetical example is shown to indicate some of the flexibility of the ternary diagram applied to emergy accounting. For this, suppose we have 10 systems, driven by a different share of emergy inputs as shown in Table 1. With the hypothetical values of emergy assigned to each point, the percentage of R, N, and F were calculated. Table 2 shows the indices calculated from the values shown in Table 1.

Assuming that points 1–10 represent different production processes of a given industrial sector, the observations in Tables 1 and 2 give a series of information that can be used to compare each process with the others. For example, processes 2 and 3 use the same relative amount of renewable resources. The environmental yield of process 2 is better than that of process 3, the SI index of process 2 is higher than that of process 3 and the environmental loading is the same for both processes. The economic investment of process 2 is 3.5 times lower than the economic input of process 3, but process 2 uses six times more non-renewable resources than process 3. This kind of comparison becomes more and more intricate as the number of processes increases.

The representation of points 2 and 3 on the ternary diagram permits the prompt visualization of the results and facilitates the comparison between the processes (Fig. 6a).

In Fig. 6b points 1–4, 6 and 8 are represented with the resource flow lines $R = 60\%$, $N = 5\%$ and $F = 20\%$ and the sustainability lines for SI = 1 and SI = 5. It is easy to note that processes 1, 3 and 8 use the same percentage of local non-renewable resources, but the sustainability of process 1 is higher. Process 3 may have a sustainable contribution for a medium period, but process 8 will not sustain its operation for a long term. In the same way, processes 6 and 8 use equal amount of renewable resources (20%), but process 6 is more sustainable, despite of their equivalent environmental loading. In this case, the economic investment and the use of little portion of non-renewable resources favour the sustainability of this process.

Table 2
Emergy indices calculated from Table 1

	ELR	EYR	EIR	SI
1	0.25	6.67	0.18	26.67
2	0.67	10.00	0.11	15.00
3	0.67	2.86	0.54	4.29
4	1.50	5.00	0.25	3.33
5	1.50	2.00	1.00	1.33
6	4.00	5.00	0.25	1.25
7	4.00	1.67	1.50	0.42
8	4.00	1.33	3.00	0.33
9	9.00	10.00	0.11	1.11
10	9.00	1.25	4.00	0.14

Processes 4 and 6 can also be compared in Fig. 6b. Both processes use the same percentage of economic investment for their operation, but the difference in the amount of renewable resources determines the higher sustainability of process 4.

Fig. 7 shows the use of the sensitivity lines. The line joining the apex N to point 9 passes also on point 6. Any point along this line represents a process operating progressively with lower quantities of non-renewable resources, as it passes from 9 to 6, with R and F remaining present at the same initial proportion. Therefore, it is possible to improve the sustainability of process 9, changing the quantities of non-renewable resources and maintaining the proportion between the economic investment and the quantity of renewable resources. It is also easy to note that a decrease of purchased services of process 8 may enhance its sustainability to be equivalent or higher to that of process 5. In the same way, the line joining the R apex to point 7 indicates that especial attention should also be given to the use of renewable resources to improve its sustainability. Clearly, the sensitivity lines show to decision makers the way to accomplish economic–environmental targets. Returning to processes 6 and 9, two points may be emphasized. First, if process 6 exists,

Table 1
Hypothetical emergy values and percentage of resource flows

Point	Total emergy (seJ/year)	Annual emergy flow					
		R (seJ)	%R	N (seJ)	%N	F (seJ)	%F
1	6.4×10^{20}	5.1×10^{20}	80	3.2×10^{19}	5	9.6×10^{19}	15
2	8.0×10^{19}	6.4×10^{19}	60	0.4×10^{19}	30	1.2×10^{19}	10
3	7.5×10^{19}	4.5×10^{19}	60	3.7×10^{18}	5	2.7×10^{19}	35
4	6.0×10^{19}	2.4×10^{19}	40	2.4×10^{19}	40	1.2×10^{19}	20
5	5.0×10^{19}	2.0×10^{19}	40	5.0×10^{18}	10	2.5×10^{19}	50
6	5.5×10^{19}	1.1×10^{19}	20	3.3×10^{19}	60	1.1×10^{19}	20
7	2.4×10^{20}	4.8×10^{18}	20	4.8×10^{19}	20	1.4×10^{20}	60
8	7.2×10^{19}	7.2×10^{18}	20	3.6×10^{18}	5	5.4×10^{19}	75
9	7.8×10^{19}	7.8×10^{18}	10	6.2×10^{19}	80	7.8×10^{18}	10
10	6.5×10^{19}	6.5×10^{18}	10	6.5×10^{18}	10	5.2×10^{19}	80

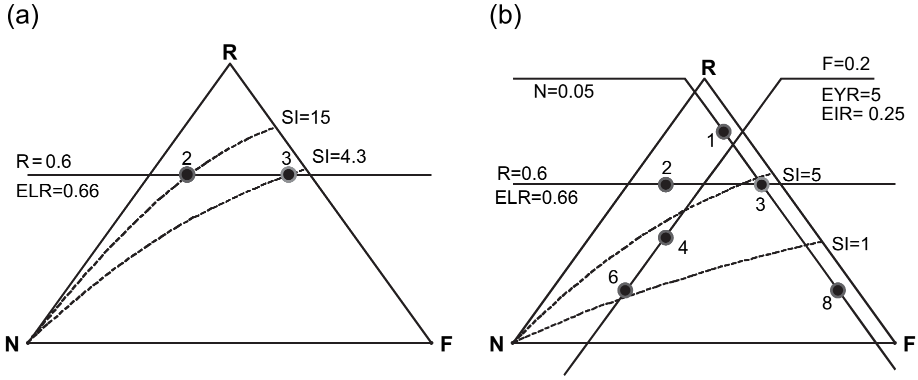


Fig. 6. Representation of hypothetical processes shown in Table 1.

there must be a way or technology to improve the performance of process 9 at least to equalize that of process 6. Second, the line indicates a hierarchy for action. Instead of randomly changing all variables to enhance system 9 functionality; the priority is clearly the reduction of the use of non-renewable resources.

Diagrams of Fig. 8 illustrate an application of the ternary diagram property, which leads to the simergic point. This point represents the resulting composition of a system composed by more than one product or process. The simergic point is used to determine the characteristics of a whole sector or a set of products, in this case formed by processes 1, 2, 6, 7 and 10. The location of this point on the triangle provides a prompt recognition of the effects of the set chosen. The SI index of the set is localised between 1 and 5 (SI = 4.5), indicating that this sector is sustainable for medium term (Fig. 8a). As the total quantity of products provided from each process can vary drastically, there is also the possibility of taking into account the weight of each process regarding their *Y* values, their outputs. For example, each one of these processes could represent a power plant with different energy production. Fig. 8b shows the simergic point obtained considering that processes 2, 6 and 10 produce equal quantities of a generic product. The production of process 1 is eight times higher and process 7 has capacity to produce three times more than process 2. Even with the participation of process 7 in the sector, with a bad environmental performance (SI = 0.42), its association with the other three processes, especially process 1, guarantees the sustainability of the sector as a whole for long periods. The sustainability index for this combination was calculated as being 7.2. It is also evident that the sector in question should invest in processes like 1 or 2 for future expansions of the system.

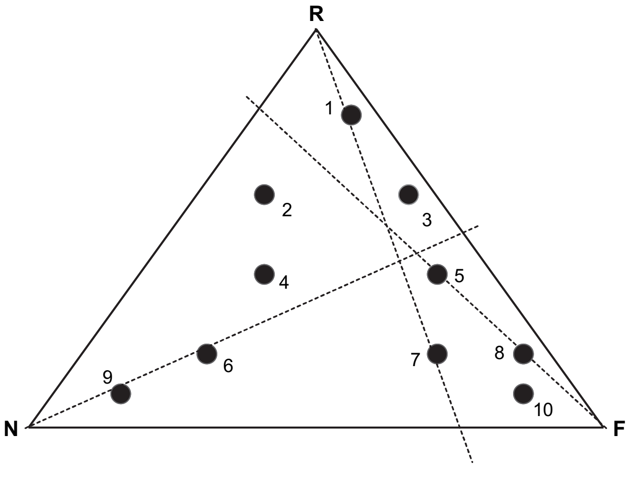


Fig. 7. Ternary diagrams illustrating the use of the sensibility lines.

5. Discussion and concluding remarks

Adopting emergy based ternary diagrams provides a better understanding of the actual contribution of given inputs and the global sustainability of production processes and especially industrial sectors. Ternary diagrams allow one to rank and to assess significant differences that can be immediately evaluated. The use of the triangle based on emergy accounting and emergy indices to assess production processes and industrial sectors permits, not only to evaluate the actual situation of a given process, but also to identify critical parameters that may be changed to improve the environmental performance of the whole system.

The triangle properties, especially the sensitivity lines and the simergic point, complement the emergy based analysis and permit monitoring the present state of a system by means of well-defined sustainability indicators and forecasting the system's behaviour according to changes in its driving forces. With the use of sensitivity lines, one can assess a process; identify the main driving force to enhance its sustainability, to diminish the environmental loading and to evaluate the need of

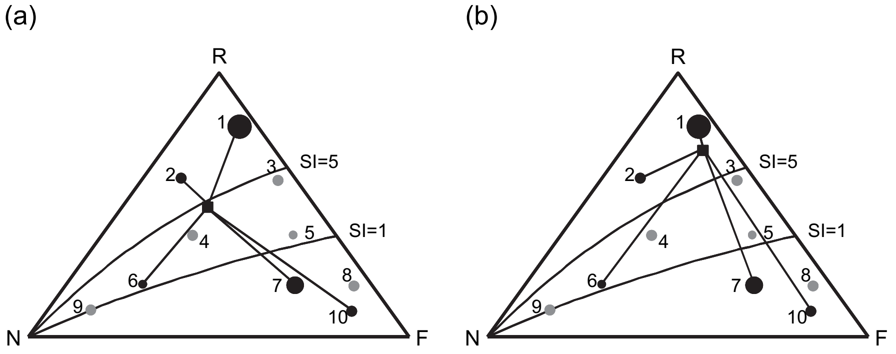


Fig. 8. Ternary diagrams illustrating: (a) the resulting combination of points 1, 2, 6, 7 and 10 and (b) the resulting combination of points 1, 2, 6, 7 and 10, taking into account the total yield of each process.

economic investment or change of inputs. It is possible to follow the effects of any economic or technological change and to determine the real consequences of these actions. For example, if emergy is invested in removing emissions using technology, this emergy can be accounted and the position of the point will change in the interior of the triangle. Analogously, if environmental services are needed to absorb and dispose the same emissions, performance of a production process becomes more time and location dependent. When the free services of the environment are accounted [4], a shift of the point in the diagram will be also noticed, showing the actual condition of the system under evaluation. The introduction of the simergic point permits to go further. The calculation of the simergic point, taking into account the production capacity of each component of an industrial sector, permits to evaluate not only the sector as a whole, but principally to identify the processes with inferior environmental performance and the areas where investment is necessary. The best alternatives can be simulated and analysed. In the decision-making process regarding sustainability of economic development, governments and society will have a powerful tool to establish policies and to choose alternatives concerning the environment.

On the other hand, when emergy analysis is carried out concerning processes' emissions and considering the investment in the waste treatment, an approach such as that used by Tiezzi and Marchettini [17] could be an interesting alternative. The emergy analysis of the municipal solid waste collection was performed comparing the emergy of collection (fuel and labor, which represents 70–80% emergy of the collection system) with the total emergy of material production; in order to assess how much "utility" is extracted from management strategy. The representation of this approach, based on three parameters, on the ternary diagram should improve the discussion of the results and the conclusions by the use of sensitivity lines and the simergic point.

The same reasoning could be applied to Life Cycle Assessment. In this case, emissions are accounted and allocated in three main categories (for example: ecosystem quality, human health and energy resources). Locating the categories at the triangle apexes may permit to assess processes and evaluate the total damage of a set of products or industrial sectors.

Emergy based ternary diagrams may well be seen as progress compared to methods that result in a list of interventions or an impact score profile. Such a tool for graphical analysis allows a transparent presentation of the results and may serve as an interface between emergy scientists and decision makers, provided the meaning of each line in the diagram is carefully explained.

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