Ecological Modelling 393 (2019) 98–106

Contents lists available at ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel

Contribution of the Paraconsistent Tri-Annotated Logic to emergy accounting and decision making

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ARTICLE INFO

Keywords:
Emergy
Paraconsistent annotated logic
Decision-making
Hydropower
Sustainability index

ABSTRACT

The process of decision-making is a complex task that can become more challenging if the information provided by indicators is contradictory. Emergy accounting is an environmental accounting methodology that has been used to guide environmental decision making. In this paper we propose a comprehensive tool to support decision-making in emergy accounting. Paraconsistent Logic is a non-classic logic, which can aid in decision-making when the investigator is confronted with contradictory results. Paraconsistent Tri-Annotated Logic (PL3v) is proposed as a decision tool to compare different systems and allow selection of those alternatives with the best performance from the standpoint of sustainability defined in emergy terms. The rationale behind our selection of a set of emergy indicators to assess sustainability included such factors as increased efficiency, setting a priority for local resource use and minimization of the use of non-renewable resources. Two actual examples from the literature that resulted in contradictory evidence of system sustainability were compared within the framework of PL3v. Emergy indicators that correspond to positive evidence of sustainability (i.e., those that show increased efficiency and greater local resource use) were assigned as two favorable logic measures of sustainability. The PL3v analysis is completed with the identification of evidence that is unfavorable to sustainability, which is given by a third indicator negatively correlated with sustainability (i.e., non-renewable resource use). Operationally, the methodology proposed the normalization of the indicator values between [0,1] to fit to the PL3v annotation framework. Comparison of the systems examined is presented through the Paraconsistent Logic approach with the aid of a graphical representation and the calculation of the degree of certainty related to the truthfulness of the sustainability proposition.

1. Introduction

Environmental accounting using emergy (Odum, 1996) is an evaluation method suitable for the appraisal of the long-term sustainability of various systems (Brown and Ulgiati, 1999). Emergy evaluation takes into account the behavior of whole systems and their dynamics in exploiting resources (Pulselli et al., 2004). It has been used to assess the environmental sustainability of a diversity of systems such as crop production (Brandt-Williams, 2002) biomass production (Bonilla et al., 2010), pulp and paper production (Corcelli et al., 2018), livestock (Castellini et al., 2006), energy production systems (Ulgiati and Brown, 2002), biofuels (Bastianoni and Marchettini, 1996), cities (Ascione et al., 2009), basins (Chen and Chen, 2009; Campbell and Garmestani, 2012), states (Campbell, 1998) and countries (Ulgiati et al., 1994).

Emergy accounts for all the natural and economic resources of a system expressing them on an equal basis and using a common unit, the "solar emjoule" (sej). In short, emergy is defined as the sum of all inputs of available energy directly or indirectly used by a process to provide a given product, when the inputs are expressed in the same form (or type) of energy, usually solar energy (Ulgiati et al., 1995). Every input of a system is not only quantified but also classified as renewable, non-renewable or purchased (R, N and F, respectively) according to its renewability and origin.

Traditionally, Odum (1996) defined a set of emergy indicators in order to evaluate environmental performance. The Emergy Yield Ratio, EYR, is the ratio of the flow of emergy exported in the form of goods and services to the outside market (Y), divided by the emergy of the purchased inputs (F). The Emergy Investment Ratio, EIR, is the ratio of purchased inputs (F) to the emergy fluxes derived from the total local free resources (R + N). The Environmental Loading Ratio, ELR, is the

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https://doi.org/10.1016/j.ecolmodel.2018.12.015
Received 10 July 2017; Received in revised form 29 November 2018; Accepted 16 December 2018
0304-3800/

ratio of the total non-renewable inputs, local and purchased (N + F) to renewable emergy flows. Brown and Ulgiati (1997) extend the previous emergy indices and introduce the Emergy Sustainability Index, ESI that aggregates the measure of yield and environmental loading indices (ESI = EYR/ELR) and most of the emergy literature published afterwards refers to the latter when assessing sustainability.

Several approaches have been used to assess sustainability within the emergy framework. Among them, the "renewable support area", which is calculated based on the renewable empower density of the region. It can be considered as a predictor of long term sustainability, assuming that all the environmental requirements for an enterprise are derived from renewable resources (Brown and Ulgiati, 2001). On the other hand, the support area required to balance the effects of a development as measured with the ELR of the region can be considered as a predictor of short term sustainability (Brown and Ulgiati, 2001). Bastianoni et al. (2009) explore unsustainability by means of accounting for the use of N and F resources, thereby emphasizing the necessity of considering extensive parameters to assess the distance of a system from what is considered to be a sustainable state. Lei et al. (2012) borrow the Genuine Savings Indicator from the World Bank, and recalculates it in emergy terms to address the real capital storage of a system, namely the sustainability of that system. In addition, they complement the longterm sustainability assessment by addressing how the change of real wealth impacts the inhabitants' emergy consumption. A modification of the ESI, the Emergy Sustainable Use Index (ESUI) considers the benefits gained by the larger system compared to the potential for local environmental damage. It was proposed by Campbell and Garmestani (2012) in order to preserve the real meaning of the index when examining regional systems. Since according to Winfrey and Tilley (2016), existing emergy indices don't capture the sustainability of waste treatments, they propose the TSI (treatment sustainability index) which accounts for the free renewable inputs relative to purchased inputs and downstream requirement for further treatment. For sustainability evaluation of technical systems, Hay et al. (2017) considered a matrix that includes among other indicators of diverse origin, an emergy set composed of the sum of renewable resources, the ELR and the sum of local non-renewable resources.

Nevertheless, the use of the ESI is the most general approach used as a criterion for evaluating sustainability in emergy terms.

The ternary diagram (Giannetti et al., 2006) is a graphical tool that allows the categorization of systems (Almeida et al., 2007; Giannetti et al., 2007; Agostinho et al., 2008; Li et al., 2014) within sustainability regions as a function of the ESI criteria of sustainability, in the short and long term, as proposed by Brown and Ulgiati (1997).

The main characteristic of the ESI is that it assesses the emergy yield per unit of environmental stress, and in this sense, the concept of sustainability it reflects is not directly concerned with the efficiency of the convergence of global resources to support the system.

The emergy necessary to produce a joule of a certain product or a process, the "solar" transformity, expressed in sej/J, is an indicator of the reciprocal of the efficiency when comparing processes with the same output: The lower its value, the higher the efficiency of production. The same can be said when other physical units are used for expressing the efficiency of product generation.

Thus, an attempt to take a more integrated approach to the assessment of sustainability was carried out by plotting the inverse of transformity and the ESI on the x-axis and y-axis, respectively. The points define geometrical areas in the Cartesian plane, which represent a measure of the relative-sustainability of the systems under study (Bonilla et al., 2010). Except for the option giving the best performance where the greatest ESI and efficiency values are a direct determination of the best solution, the other situations all lead to contradiction or inconsistency, hindering decision-making.

Thus, we believe that the use of paraconsistent logic (PL), a non classical logic, capable of dealing with uncertainty, contradictory data or inconsistencies (Abe, 1992) would be beneficial in clarifying situations where the emergy indicators lead to contradictory conclusions. This type of logic can deal with reasoning that resembles human commonsense reasoning, since it is based on information that is incomplete or inconsistent (Abe et al., 2015).

Paraconsistent annotated logic with annotation of two values (PAL2v) allows decision making through assigning favorable and unfavorable independent evidence (i.e., quantifying the degree of belief and disbelief, respectively) to any proposition, thus generating a logical state located within the four extreme logical states: true, false, inconsistent, and indeterminate (Abe, 1992). The degree of belief (on the x-axis) and the degree of disbelief (on the y-axis) are placed in a Cartesian plane thus generating a point that can lie in any of four possible logical states.

Paraconsistent Tri-Annotated logic (PAL3v) presented by Papalardo (2016) extended the attribution of two pieces of evidence (one favorable and other unfavorable) to a set of three independent pieces of evidence (two favorable plus one unfavorable). This will generate a tridimensional graphic where each system is represented by a point within a unitary cube (Papalardo, 2016).

Since a system may be better in some respects and worse in others, PAL3v is proposed to aid in decision-making when the three emergy indicators used are not simultaneously better in terms of assigning sustainability. This necessary background to justify the selection and understand the applicability of PAL3v will be described in Section 3.

The objective of the present study is to demonstrate the use of Paraconsistent Tri-Annotated Logic by indicating which system, when quantified by the most appropriate set of three emergy indicators, presents the best performance from the view point of sustainability.

An example from the literature, (Tassinari et al., 2016), which showed contradictory emergy indicators in terms of sustainability (according to the analysis of sustainability adopted in the present work) was explored using the PAL3v tool.

The paper is organized as follows: first, we start by justifying the need for a tool to handle contradictory information, when it is provided by the emergy indicators. Second, we discuss the selection of a set of emergy indicators that are consistent with the sustainability approach taken here (i.e., higher sustainability corresponds to more efficient use of inputs, relatively less use of nonrenewable inputs N, and less dependence on external resources). Then, we focus on explaining the usefulness of PAL3v as a decision tool for handling contradictory information. The Materials and Methods section first introduces the system under study and then presents the operational tools needed to carry out data analysis, finally we discuss the integration of the emergy methods with the paraconsistent logic framework to improve decision-making. In the Results and Discussion Section, we analyze the two systems through integrating the analysis of the emergy indicators and the evaluation of sustainability premises using paraconsistent logic for decision-making. The last section summarizes the results of our analyses. A theoretical background on paraconsistent logic is presented in Appendix A.

2. About the sustainability approach adopted

2.1. Emergy and environmental accounting

The Emergy accounting methodology (Odum, 1996) has been developed over the last five decades to evaluate the role of the quality of resources in the dynamics of complex systems and to provide guidance in implementing environmental policies. A complete assessment of the methodology cannot be provided here, but the reader may refer to other publications (Odum, 1996; Brown and Ulgiati, 1997; Odum et al., 2000; Sciubba and Ulgiati, 2005)

Briefly, solar emergy is defined as the sum of all inputs of available energy directly or indirectly required by a process to produce a given product when inputs are expressed in the form of solar energy (Odum, 1996)

The emergy flows represent three categories of resources: R defined as renewable resources, N defined as non-renewable resources and the purchased inputs provided by the economy, F. All three categories are fundamental for emergy accounting and for the understanding of a system's interactions with the environment. The R and N flows are locally supplied by the environment and are economically free.

While 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 to recuperate. The economic inputs, F, are provided by the market and are related to flows supplied by the economy. All the emergy that converged into a system is assigned to an output flow (namely the intentional product or service), and it is expressed as Y or the yield of the process.

Operationally, each input that enters the system has to be quantified and the raw data expressed in compatible units (mass, energy or monetary units) with the transformation factors that will convert, via multiplication, the raw data flows into emergy flows. The transformation factors include solar transformity (solar emergy required to make one joule of a service or product, in solar emjoule per joule, sej/*J*), solar emergy per mass unit and solar emergy per money unit. Nowadays, the ratio of emergy required to make a product to the energy, mass or units of the respective material or energy flow of the product is called the Unit Emergy Value (UEV) in a attempt to unify methodology's nomenclature.

The identification and calculation of the emergy flows enables the calculation of emergy indices. Only a brief description of the indices is provided here but background information can be found elsewhere (Ulgiati et al., 1995; Odum, 1996; Brown and Ulgiati, 1997).

The Emergy Yield Ratio, EYR, is the ratio of the emergy of the output, Y, divided by the emergy of purchased inputs (F) and shows the importance of local resources with respect to exogenous ones. The investment ratio, EIR, is the ratio of purchased inputs (F) to all emergy fluxes derived from local free resources, R + N. The index measures the level of economic development and the degree of dependence of a system on the environment. The Environmental Loading Ratio, ELR, is the ratio of non-renewable (local N and purchased F) to renewable emergy flows (R) and represents the potential pressure on the natural environment. The Emergy Sustainability Index, ESI aggregates the measure of yield and environmental loading (ESI = EYR/ELR).

2.2. Outlining the sustainability approach and selection of the indicators to be analyzed by PAL3v

According to Bastianoni et al. (2009), sustainability is an ideal state, and it is only possible to quantify the distance from the ideal point of sustainability. Throughout the text we refer to sustainability in the sense of quantifying the contribution towards the sustainable state or the actions to achieve sustainability targets, that is, the contributions to decrease the distance from that ideal state. So, although the term sustainability is used throughout the text, its real meaning even without making it explicit, is related to the concept of degree or levels of proximity from the ideal state.

Additionally, the concept of sustainability is linked with extensive properties, since it depends on the availability of limited resources within the biosphere. In this way, Bastianoni et al. (2009) argued that it is not possible to assess sustainability by using intensive parameters because the problem is strongly correlated with the size of the system. Taking into account that we are not proposing any extensive emergy indicators for assessing sustainability, the indicators here adopted are useful only for comparing processes that generate the same products. Bastianoni et al. (2007) also states that emergy evaluation can only show the relative level of sustainability enabling the choice of the better arrangement according to the characteristics of the viewpoint. Based on the latter considerations, we adopt the concept of "relative sustainability" since it properly evidences the extent and limitations of the approach explored here.

After having explained the sustainability approach used here, it seems necessary to justify the selection of the indicators capable of reflecting the "degree or level of relative sustainability".

Without disregarding the contribution that the ESI index brought to the emergy assessment of sustainability, its contributions are not related to the conversion efficiency of the solar energy that drives a process. Thus, the incorporation of transformity to account for the total resources, directly or indirectly used, even though it is a relative indicator, it can quantify the efficiency of resource convergence needed to deliver a unit of a given product. Transformity is not concerned with the distribution among types of resources, but since it quantifies the total quantity of resources used per unit of product it is related to efficiency. In this way, the higher the transformity the greater the environmental activity required for product processing. In agreement with Brown and Ulgiati (1997), transformity (or another measure of the emergy per unit product) is an indicator of past environmental contributions to a resource and the future load on environmental systems.

The combination of the indicators Transformity and ESI can be used to evaluate the relative "goodness" of systems in terms of their environmental performance and it can be considered a preliminary attempt to measure the "degree of relative sustainability" of the systems, which was explored by Bonilla et al. (2010). With this purpose, the inverse of transformity (or product per unit of emergy), which represents an emergy productivity measure, was plotted in the same graphic with ESI. The areas defined by the points show a way to evaluate the "goodness" of the systems under a sustainability point of view. The points represent the values of ESI and the inverse of Transformity for bamboo production in Brazil and China, respectively (Fig. 1, adapted from Bonilla et al., 2010). This figure combines information about the efficiency of solar emergy supplied in the production of a unit of product and the performance of that process in terms of the emergy yield obtained per unit of environmental loading.

The best performance will correspond to the system that defines the larger area in the figure with the simultaneous maximization of ESI and the inverse of Transformity. In this way, points located at the high right extreme of the graphic (indicated by the ascendant arrow) correspond to those privileged positions where both the indicators are maximized. On the other hand, the worst situation corresponds to points located on the left-bottom side of the graphic (shown by the descendant arrow). When the points lie in positions other than the extreme ones (as shown in Fig. 1), a direct conclusion about the selection of the system with the best performance is not possible without prioritizing one indicator (or goal) over the other. Even though the areas delimited by the points are graphically equal, the values of ESI and the inverse of Transformity are extreme for both situations. In this case, the two indicators selected to compare systems performance generate contradictory information and

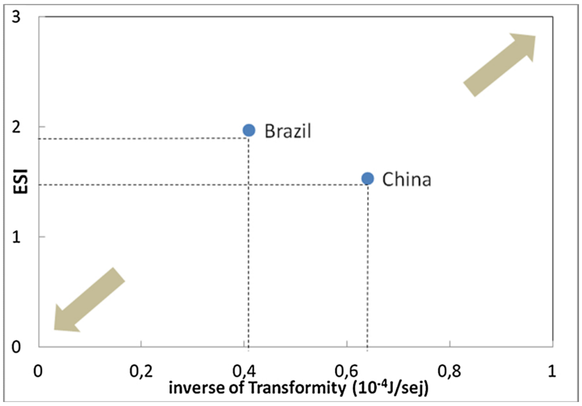


Fig. 1. Graphical representation of ESI vs. the inverse of Transformity (energy of product/unit of emergy input) for bamboo production systems in Brazil and China.
Figure adapted from Bonilla et al. (2010).

decision-making is not straightforward. This means that when comparing two different events by using the two indicators, it is only possible to affirm that A is more sustainable than B if all indicators show better performance in A than in B. To conclude that one is more sustainable than the other in other situations will be possible, if one indicator is prioritized over the other. Although when these combinations occur, decision-making will imply the need to select an indicator weighting procedure or prioritize the desired outcomes.

According to the definition of ESI (Brown and Ulgiati, 1997), sustainability is shown to be a function of the net yield and the load on the environment. Even so, it was shown that ESI is maximized by combinations of inequalities involving R, N and F that are not related to maximizing renewable use or minimizing the use of N (Giannetti et al., 2012). In this way, the EYR and ELR generated by those R, N and F combinations do not individually contribute to improve sustainability even though they result in large values of the index. As argued by Lei et al. (2012), the advantage of integrating metrics offered by ESI conceals the impact of the individual indices, thereby providing unclear indications of a system's true sustainability.

To address this, we prioritized the adoption of the individual components of the index to assess sustainability instead of the index as a whole.

The Transformity (or UEV) corresponds to the consumption of solar emergy required to create a unit of a product or service, thus it represents the environmental value based on the effective resource consumption that occurs during the production process and therefore it can provide significant information on the environmental basis of an item from a comparison of the reciprocals of the UEVs (Pulselli et al., 2004).

The inverse of the Transformity represents the efficiency of total resources use in a production process, and we will adopt the term "Emergy Productivity" (EP) for this ratio. The term productivity reflects the concept of the ratio of an output to inputs, in this case, the units of products (in energy or mass units) generated by a unit of resources invested (in sej).

The measures chosen to assess sustainability are EYR, which captures the productivity of local resources with respect to exogenous ones, the ELR, which represents the potential pressure on the environment caused by non-renewable and purchased resource use and the transformity, which assesses the efficiency in the use of solar energy and is also the inverse of the EP.

3. Paraconsistent Tri-Annotated Logic as a decision tool for contradictory information

Classical logic is restricted to handle binary information, that is, situations when the favorable evidence is total or the inverse condition, when the unfavorable evidence is total. The first case allows concluding that the proposition is true and the second that the proposition is false. However, Classical logic due to its premise of binary conditions is unable to deal with real-world situations where indetermination, uncertainty, ambiguity and contradiction frequently occur (Da Silva Filho, 2006).

When a proposition is simultaneously described by favorable and unfavorable pieces of evidence, paraconsistent logic allows reaching conclusions without trivialization and thus it enables decision-making without the necessity of disregarding or discarding data (Da Silva Filho et al., 2010).

Only the background necessary to justify the selection of the PAL3v to handle contradictory information will be addressed in this section. The theoretical basis for PL and PAL that enables the understanding of the framework within which PAL3v is comprised, is presented in Appendix A.

The proposition to be analyzed in the present work is concerned with the sustainability of two hydropower plants that have been evaluated through the emergy indicators described in detail in the previous section. The indicators correspond to three attributes that can be associated with the proposition of sustainability as pieces of favorable or unfavorable evidence. The analysis can be accomplished within the framework of Paraconsistent Tri-Annotated logic, presented by Papalardo (2016). Within this framework, the proposition "Porto Primavera Hydropower plant is environmentally sustainable" is annotated by using the expression p(μ; λ; ω) and can be graphically represented as a point within a unitary cube (Papalardo, 2016). The point is determined by the values μ; ω; λ and will belong to the orthogonal plane α depicted in Fig. 2 as a green shadow. The geometrical distance from the vertex C (which corresponds to the True logical state) to the plane α which contains the point (μ; ω; λ) is related to the logical "distance" between the proposition and the True State. Thus, our proposal is to associate the PAL3v in such a way to assign to each indicator a degree of evidence projected into the real interval [0, 1], The evidence could be favorable or unfavorable to the proposition under analysis.

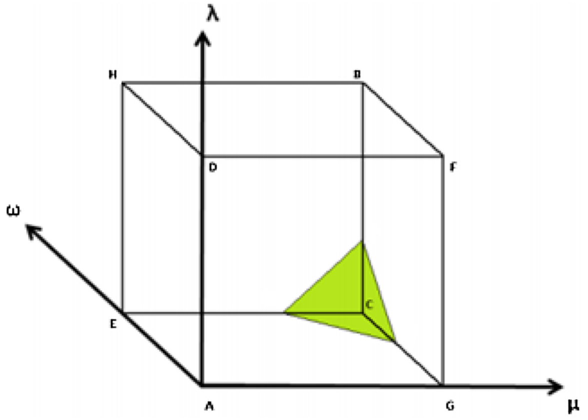


Fig. 2. Unitary cube showing the orthogonal plane α (shading) that contains the point that represents the proposition p(μ; ω; λ). Point C expresses the True logical state.
Adapted from Papalardo (2016).

Since the geometrical distance from C is an indicator of proposition consistency, it will be introduced as the Degree of Certainty (defined as H), which mathematically expresses this distance. The calculation of H assessed through the PAL3v perspective is beyond the scope of this work and can be found in Papalardo (2016).

The Degree of Certainty (H) is defined by the expression (Papalardo, 2016):

$$H(\mu;\omega;\lambda) = \mu + \omega - \lambda - 1$$

The Degree of Certainty is used when it is necessary to know the proximity to the True State. H will vary between 1 and -2 ($-2 \leq H \leq 1$); the closer to the value of 1, the greater the degree of certainty of the proposition. The closer the point is to the True state, the closer to 1 the H value will be.

In addition, a criterion should be established to consider if the situation represented by the point (μ; ω; λ) is acceptable or not acceptable. A requirement value or confidence level K (see Table B1) in the interval [-2, 1] can be established for H, above which the proposition can be considered true.

In fact, the plane through points X, Y, and Z represents the limit considered acceptable and therefore divides the unit cube into two volumes (see Fig. 3).

As the plane through points X, Y, and Z approaches the extreme C (the true state) the volume delimited between the points decreases and the probability of the proposition being 100% true increases. Therefore, the requirement level or confidence level K can also be expressed as the probability that a proposition belonging to the True State. The probability represents the ratio of the volume limited by the points C, X, Y, Z (shaded in beige in Fig. 3) to the volume of the unitary cube. The values of K and the correspondent probability are shown in Table B1.

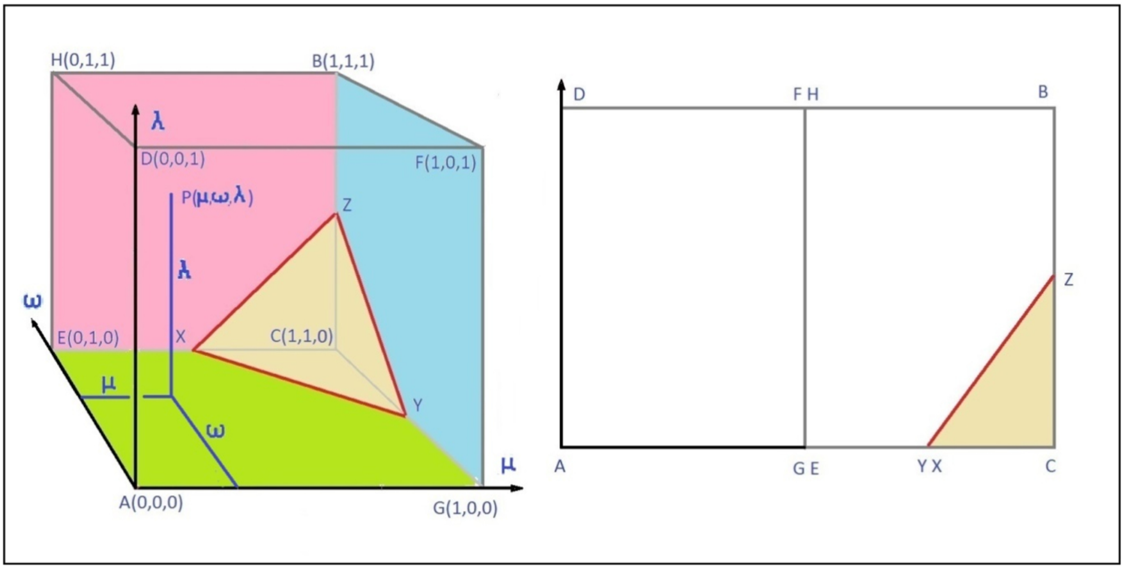


Fig. 3. Perspective of the Unitary Plane; in beige the plane that limits the region of premise acceptance for a requirement level of K = 0.5. Diagonal viewpoint where the polyhedron shaded in beige corresponds to the region of acceptance of the proposition's truth.

4. Materials and methods

4.1. Systems selected for evaluation of the premise that they are sustainable

The results from two hydropower plants from Tassinari et al. (2016) are applicable, since the indicators set proposed in this work as a sustainability criterion, resulted in contradictory information.

The two hydropower plants are located along the Paraná River, within Brazil. The Eng. Souza Dias plant, known as the Jupiá plant, can supply 1550.2 MW with a reservoir of 330 km^2. The Eng. Sergio Motta plant, known as Porto Primavera (PP), a typical impoundment plant, has a reservoir of 2250 km^2 and can provide 1540 MW.

Table 1 displays the values of the emergy indicators and the evidence that EYR suggests a better performance in sustainability terms for the PP plant, whereas ELR and EP indicators show the opposite trend.

4.2. The integration between emergy accounting and Paraconsistent Tri-Annotated Logic

Section 2.2 explained the rationale behind the selection of the set of emergy indicators used to assess sustainability. This set of indicators characterizes sustainability from the viewpoint of increasing efficiency in the use of resources, prioritizing the use of local resources with respect to exogenous ones, and the minimization of non-renewable resources with respect to renewable ones.

Therefore, the PAL3v assigns three degrees of evidence to the indicators within the real interval [0,1]. The degrees of evidence can be favorable or unfavorable (contrary) to the proposition under analysis. For the present case, the proposition that is being analyzed is related to the sustainability of the systems, considering the results provided by the indicators. Within the frame of PL3v the attribution of two favorable pieces of evidence corresponds to EYR and the emergy productivity indicators, whereas the unfavorable evidence corresponds to the ELR. In this way, the degree of belief provided by EYR and EP will be indicated by μ and ω, respectively, while the degree of disbelief provided by ELR will generate the λ value.

Table 1
- Set of the Emergy indicators adopted to assess sustainability for the hydroelectricity generation plants of Jupiá and PP. Data is extracted from Tassinari et al. (2016). The emergy baseline of 12.0×10^{24} sej/yr is adopted throughout this paper (Brown et al., 2016).

	Jupiá plant	Porto Primavera plant
EYR	11.8	15.3
ELR	0.19	0.59
EP(J/sej)	2.61×10^{-5}	1.61×10^{-5}

Since the PL3v methodology establishes that μ, ω and λ values belong to the real unitary interval [0, 1], it is necessary to normalize the indicator values to integrate both methodologies.

Consequently, each system studied through the emergy approach and which delivers a set of contradictory indicators (EYR, ELR vs. EP) can be converted to a PL3v premise and handled in a way to promote better decision-making.

Each premise will determine a point within the Cartesian volume and the Degree of Certainty H can be calculated to compare the systems and to allow better informed decision-making.

The reason for normalizing indicators was to allow each of them to vary between zero and one, thus allowing them to be analyzed through the PL3v approach.

The indicators were normalized by assigning upper and lower bounds. Thus:

$$EYR_n = (EYR - EYR_{min})/(EYR_{max} - EYR_{min}), \quad (1)$$

EYR_n being the normalized value, EYR the value for the system under study, and EYR_{min} and EYR_{max} the upper and lower bounds. Normalization is carried out in an analogous way for ELR and EP.

The upper and lower values are set from the maxima and minima, respectively, extracted from systems with comparable characteristics found in the literature. In this way, upper and lower values are restricted to an interval of observed values found for similar systems. As real systems can improve their performance over time for any of the criteria adopted here, the normalization intervals may be modified in the future.

Literature research on hydropower plants with comparable characteristics provided the threshold values depicted in Table 2. Since the value of these indicators strongly depends on the hydropower installed capacity, this is the characteristic used to restrict the search for threshold values. That restriction is taken from Zhang et al. (2014) who show differences in the emergy indicators according to the installed capacity interval considered. Based on this evidence the indicators corresponding to small hydropower plants were disregarded.

Having normalized the indicator values it is possible to set values for μ, ω, λ and to place the point generated for each system under study (i.e., the Jupiá and PP plants) within the unitary cube. The Degree of Certainty H is calculated to know the proximity with the True State of the premise defined

Table 2
Observed maximum and minimum indicator values extracted from literature research corresponding to hydropower plants with similar installed capacity.

Indicator	Observed Maximum	Observed Minimum
EYR	22.45(1)	0.73(4)
ELR	3.2(2)	0.19(1)
EP	2.61×10^{-5} (3)	2.24×10^{-6} (4)

All the values are expressed relative to the emergy baseline of 12.0×10^{24} sej/yr. 1- Fang and Chen, 2014; 2- Brown and McClanahan, 1996; 3- Tassinari et al., 2016; 4- Yang et al., 2012.

Table 3
Calculated normalized values of the emergy indicators selected for sustainability assessment, using the expression (μ; ω; λ) where μ and λ represent the favorable evidence and ω the contrary evidence given by the normalized indicators, and values of the degree of Certainty H.

	Jupiá plant	Porto Primavera plant
EYR_n	0.51	0.67
EP_n	1.0	0.58
ELR_n	0	0.13
(μ; ω; λ)	(0.51; 1; 0)	(0.67; 0.58; 0.13)
H	0.51	0.12

by each set of values (μ, ω, λ). The "degree of relative sustainability" will be greater the closer the point gets to the True state represented by C. The True State corresponds to (1; 1; 0) and represents here a hypothetical state that combines the best three values for EYR, EP and ELR extracted from the literature, and these values will be assigned to the better "degree of relative sustainability" (as defined in Section 2.2).

For a fixed K, that is, the minimum value, the degree of certainty H should allow us to accept the proposition, it is possible to affirm that if H > K, the point p(μ; ω; λ) belongs to the region of the unitary cube where the premise is considered true.

5. Results and discussion

As shown in Table 1, the set of Emergy indicators adopted to assess sustainability for two hydroelectricity generation plants (Tassinari et al., 2016) provides contradictory information about which system has better performance in terms of sustainability. The best performance will correspond to the system that combines the greater EYR and EP with the smaller ELR values. None of the systems under study show these characteristics, since the PP plant has the best performance in terms of EYR but it is worse than Jupiá when ELR and EP are considered.

The interpretation of the contradictory information through the point of view of PAL3v allows the attribution of the degree of belief and disbelief related to each emergy indicator. The attribution of the degree of belief and disbelief is accomplished through the normalization of the emergy indicators and results in the values shown in Table 3 for the Jupiá and PP plants. In this way, the contradictory information provided by the emergy indicators can be treated without the necessity of adopting any type of weighting procedure in order to prioritize one indicator over the others. Normalization allows the translation of the emergy indicators into a unified decision variable within the PAL3v framework.

The proposition on sustainability evaluated is related to the favorable and contrary evidence assumed for the hydropower plants performance. Each state has the form (μ; ω; λ) where μ and λ represent the favorable evidence and ω the contrary evidence.

Comparison of the two plants can be accomplished through the states (0.51; 1; 0) and (0.67; 0.58; 0.13), for the Jupiá and PP plants respectively, which result from translations of the emergy indicators into PAL3v as already explained. The graphical representation of the states within the unitary cube is depicted in Fig. 4.

We can calculate the degree of certainty (as determined by Papalardo (2016)) for the two plants as follows:

$$H_{Jupiá} = 0.51 + 1.0 - 0 - 1 = 0.51 \text{ and } H_{PP} = 0.67 + 0.58 - 0.13 - 1 = 0.12,$$

which represents the proximity to the true logical state. The right side of Fig. 4 shows the localization of both points within the unitary cube through a diagonal viewpoint.

If K = 0.1 is adopted as the level of requirement, it is possible to say that both plants are located into the region of acceptable sustainability, that is, both are viable, with 87.85% probability or confidence (according to Table B1).

However, if a level of requirement equal to 0.5 is adopted, the Jupiá sustainability is acceptable whereas the PP sustainability is not acceptable, with 97.92% confidence.

When translating the PAL3v results into the emergy framework, it is possible to state that the Jupiá plant has better performance in

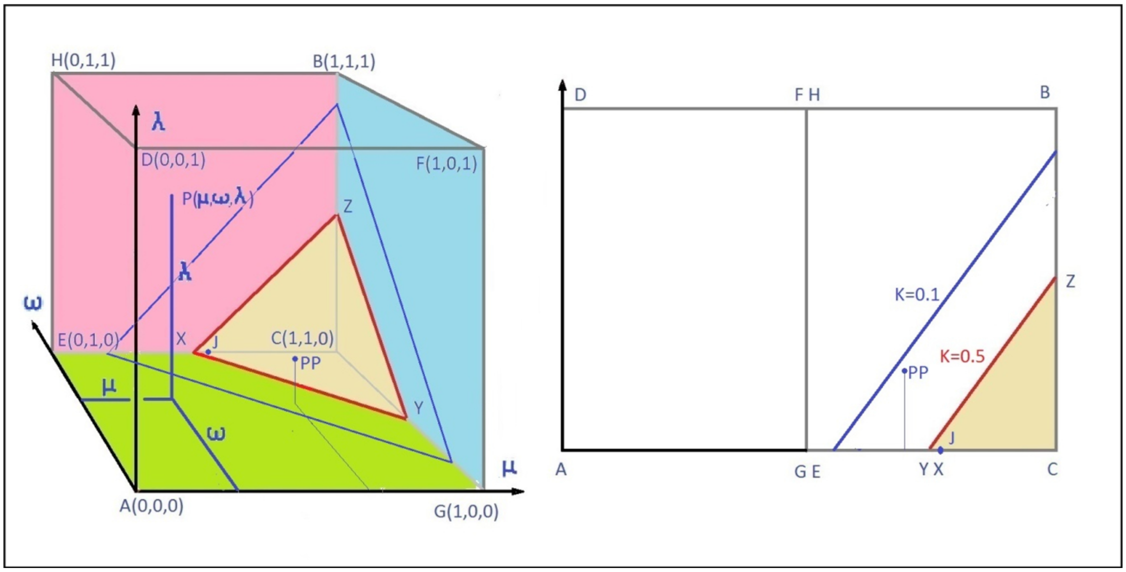


Fig. 4. Perspective of the Unitary Plane showing with the points corresponding to the Jupiá (as J in the cube) and PP states. For the Jupiá plant the state is (0.51; 1; 0); for the PP plant the state is (0.67; 0.58; 0.13). Two requirement levels are shown, K = 0.1 and K = 0.5. Diagonal viewpoint where the polyhedron shaded in beige corresponds to K = 0.5 and the transparent one corresponds to K = 0.1.

sustainability terms. The integrating tool proposed in this work allows the selection of the best system, that is, one that balances the efficient use of resources, with a relatively low ELR and a relatively high EYR.

The degree of certainty H can be proposed as a sustainability indicator, since it quantifies the degree of adherence of a system to the chosen sustainability criteria of maximizing efficiency of global resource use and EYR while minimizing ELR.

6. Final commentaries

When the information extracted from the emergy indicators selected to assess sustainability is contradictory, the need to handle decision-making using a tool that can deal with contradictory results arises. The PAL3v proposed by Papalardo (2016) offered the possibility of handling three emergy indicators, thus allowing comparison of systems and the selection of the one with the best performance based on sustainability or another point of view. The degree of certainty, H, may be seen as a logically-supported sustainability composite indicator, since it can show which choice is better through evaluating the integration of the efficiency of global resource use, the use of relatively less non-renewable inputs and less dependence on external resources.

The usefulness of the proposed procedure can be extended to propositions involving other systems when environmental sustainability is addressed with the same set of emergy indicators discussed here.

Accurate decision-making is needed to evaluate future management plans as well as to direct strategic choices for development. Comparing alternatives or analyzing policy scenarios can be a complex task that gets harder if the information provided by indicators is contradictory or uncertain. The integration of PAL3v logic as a decision tool with the already successful environmental emergy accounting methods adds transparency, ease of reporting and will result in a comprehensive tool that can support decision-making when dealing with assessments that contain contradictory results.

Acknowledgments

The Vice-Reitoria de Pós-Graduação e Pesquisa of Paulista University (UNIP) is fully acknowledged. The authors want to thank Prof Dr. J.M. Abe for the revision of the text concerning Paraconsistent Logic. We are deeply grateful to the anonymous reviewers for the helpful comments and suggestions that have served to improve the work.

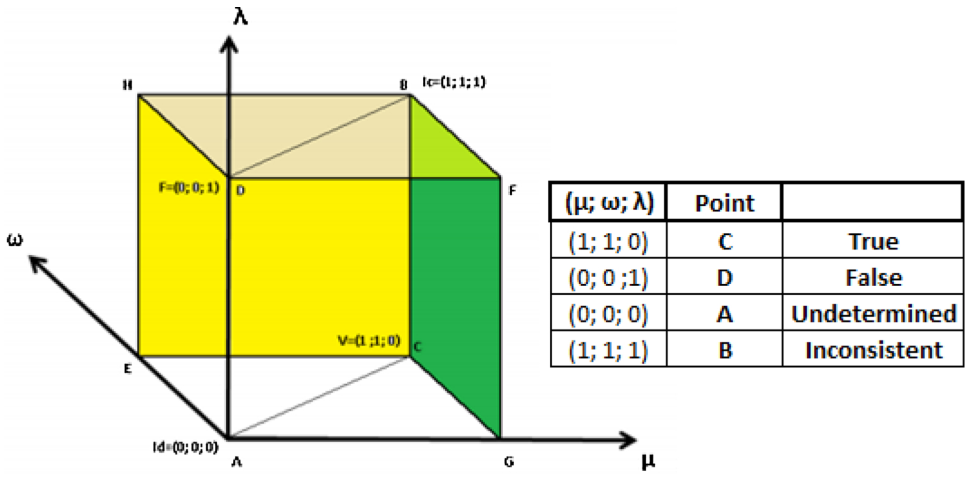
Appendix A

Paraconsistent logic is a non-classical logic, whose main feature is the revocation of the non-contradiction principle of classical logic. It emerged from the necessity of handling, logically, contradictory situations without trivialization of the result (Da Silva Filho et al., 2010). An introduction to paraconsistent logic is given here to permit the reader to understand the usefulness of this logic and the framework within which the PAL3v is composed. More information can be obtained elsewhere (Da Costa et al., 1991; Abe, 1992; Da Silva Filho et al., 2010; De Carvalho and Abe, 2011).

Within the PL family, Paraconsistent Annotated Logic (PAL) offers the language and structure to properly express the concepts involved in this study. PAL provides a language to capture the nuances of reality in a more complete way than is possible in classical logic (Da Silva Filho et al., 2010). It is comprised of atomic propositions, each of which is accompanied by an annotation composed of the degree of belief or favorable evidence (De Carvalho and Abe, 2011).

PAL can be represented through a lattice of four vertices that correspond to the extreme logical states (true, false, inconsistent, and indeterminate) referring to the proposition that will be analyzed (Da Silva Filho et al., 2010). The annotation can also be composed by a pair, being the first element of the pair the favorable evidence and the second element the contrary evidence which negates the proposition (De Carvalho and Abe, 2011). So, it is possible to achieve a better representation of how much the evidence can express the knowledge about a proposition through Paraconsistent Annotated Logic with two values (PAL2v), if a pair $(\mu; \lambda)$ is used with Favorable Degree of evidence μ and Unfavorable Degree of evidence λ (De Carvalho and Abe, 2011). The atomic formulas of the language of the logic are of the type $p(\mu; \lambda)$, where p denotes a propositional variable and μ, favorable evidence and, λ, unfavorable or contrary evidence, with (μ, λ) belonging to the real Cartesian product $[0, 1] \times [0, 1]$ (Abe, 2014). The proposition $p(\mu; \lambda)$ can be intuitively read: “It is assumed that p’s favorable evidence is μ and contrary evidence is λ.” Depending on the applications, other terms can be considered instead of ‘evidence’, such as ‘probability’, ‘belief’, etc. (Abe, 2014). The values of μ and λ that vary in the interval [0,1] can be plotted in a Unitary Square on the Cartesian plane. The four vertices are the points (0;0), (0;1), (1;0), and (1;1) which correspond to the paracomplete (or indeterminate), false, true and inconsistent (or contradictory) logical states, respectively.

Similarly, if there are three attributes each associated to pieces of favorable or unfavorable evidence, the analysis will be able to work within the framework of Paraconsistent Tri-Annotated logic (PAL3v) presented by Papalardo (2016). In this way, any proposition p will be expressed as $p(\mu; \lambda; \omega)$ representing a point within the unitary cube (Papalardo, 2016). Four of the Eight vertexes of the unitary cube, correspond to the priority logical states, A, B, C, and D as depicted in Fig. A1.



(μ; ω; λ)	Point	
(1; 1; 0)	C	True
(0; 0 ;1)	D	False
(0; 0; 0)	A	Undetermined
(1; 1; 1)	B	Inconsistent

Fig. A1. Unitary cube representing the eight extreme logical states, four of them being primary states (A, B, C, D) and four secondary states (E, F, G, H). Point C, (1;1;0) corresponds to the True state; Point D, (0;0;1) corresponds to the False state; Point A, (0;0;0) corresponds to Undetermined or paracomplete state; Point B, (1;1;1) corresponds to Inconsistent or contradictory state. The secondary logical states will not be analyzed here.

Point C expressed by (1; 1; 0) is defined as the true state. On the contrary, point D, expressed by (0; 0; 1) is defined as the false logical state. Point A, expressed by (0, 0, 0), corresponds to the extreme state of indeterminancy (or paracompleteness), and point B, (1, 1, 1), represents the extreme state of inconsistency (contradiction). Since the points E, F, G and H don't represent relevant logic states, they will not be analyzed here.

In this way, any proposition p will be expressed with a triple annotation, p(μ; λ; ω).

Appendix B

Table B1

Requirement value, K, and the probability (as a percentage) that a proposition belongs to the True logical state calculated for Paraconsistent Tri-Annotated logic.

K	Probability %	K	Probability %	K	Probability %
1.00	100.00	0.00	83.33	−1.00	16.67
0.95	99.99	−0.05	80.00	−1.05	14.29
0.90	99.98	−0.10	76.67	−1.10	12.15
0.85	99.94	−0.15	73.34	−1.15	10.24
0.80	99.87	−0.20	70.01	−1.20	8.53
0.75	99.74	−0.25	66.68	−1.25	7.03
0.70	99.55	−0.30	63.35	−1.30	5.71
0.65	99.29	−0.35	60.02	−1.35	4.58
0.60	98.93	−0.40	56.69	−1.40	3.60
0.55	98.48	−0.45	53.36	−1.45	2.77
0.50	97.92	−0.50	50.00	−1.50	2.08
0.45	97.23	−0.55	46.67	−1.55	1.52
0.40	96.40	−0.60	43.34	−1.60	1.07
0.35	95.42	−0.65	40.01	−1.65	0.71
0.30	94.28	−0.70	36.68	−1.70	0.45
0.25	92.97	−0.75	33.35	−1.75	0.26
0.20	91.47	−0.80	30.02	−1.80	0.13
0.15	89.77	−0.85	26.69	−1.85	0.06
0.10	87.85	−0.90	23.36	−1.90	0.02
0.05	85.71	−0.95	20.03	−1.95	0.01
0.00	83.33	−1.00	16.67	−2.00	0.00

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