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A 20-year update of the emergy ternary diagram: Technical and methodological advancements

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A B S T R A C T

Since its proposal 20 years ago, the emergy ternary diagram has been widely used to assess environmental performance in various production and consumption systems. This Technical Note presents updates and improvements implemented in the tool, both in technical and methodological terms. The modifications include enhancements in the software programming, making it compatible with recent versions of Excel® and different operating systems, as well as a more intuitive and functional layout. Additionally, the software now supports the inclusion of partial renewability for each emergy flow, adjusting the calculations of traditional emergy-based indicators such as renewability, loading ratio, yield ratio, and sustainability index. The inclusion of partial renewabilities can lead to more accurate assessments, as it acknowledges the fraction of the emergy input flow that is renewable. The updated emergy ternary diagram stands out as an effective visual communication tool, enabling the quick interpretation of results and assisting decision-making by researchers and policymakers. A case study with Brazilian agricultural properties demonstrates the model's applicability, highlighting differences in emergy performance across different management practices; more sustainable farms are those that are ecologically managed and have lower dependence on fossil-based resources. With these updates, the emergy ternary diagram is expected to remain a valuable resource in applying the method, contributing to more accurate assessments and advancing sustainability-oriented public policies.

1. Introduction

Among the scientific tools available to quantify, from a biophysical perspective, the pressure that anthropogenic systems exert on the environment, emergy accounting (Odum, 1996) merits attention because it considers the donor side when assigning value while recognizing the quality of energy in a hierarchy that starts with solar radiation. The donor side represents the perspective of ecosystems that provide resources, measuring 'value' based on the embodied solar energy required to generate these inputs and reflecting the environmental work involved – this is an approach opposite to the receiver side as used in business as usual. The advantages of emergy accounting have attracted attention from researchers and decision-makers since the 1990s, as evidenced by the increasing number of scientific publications and government reports. For instance, considering only scientific articles published in peer-reviewed journals available in Web of Science, 114 articles on emergy were published in the 1990s, 399 articles between 2000 and 2010, 1225 articles between 2010 and 2020, and 737 from 2020 to March 2025.

Emergy measures the energy used in producing a good or service, considering all forms of directly and indirectly energy required for its production. For a deeper understanding of the method, the works of Odum (1996) and Brown and Ulgiati (2004) are highly recommended. The synthetic approach to applying this method is called emergy synthesis and follows three main steps: system modeling, emergy accounting table, and the calculation and discussion of performance indicators. Calculating performance indicators is essential for facilitating comparative discussions between evaluated systems and enabling simulations and scenario studies. Furthermore, presenting emergy indicators, along with the aggregated emergy flows used in their calculations, is crucial for ensuring efficient (quick and straightforward) comprehension and supporting subsequent decision-making processes. Here, the role of communication is fundamentally important, as a picture is worth a thousand words.

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Among the various ways to represent numerical results through figures and/or graphs, the Ternary Diagram (also referred to as a ternary graph, triangle plot, simplex plot, or even Gibbs triangle) stands out for its ease of use, its ability to visualize temporal changes, and its effectiveness in communicating information. Its application is commonly found in fields such as Geology, Chemistry, Materials Science, among others. Due to its advantages, Barrella (2004) proposed and applied the ternary diagram for emergy synthesis, since this method involves three main aggregated emergy flows - R (local renewable resources from nature), N (local non-renewable resources from nature), and F (resources imported from the larger economy) - to calculate performance indicators. The author developed the emergy ternary diagram in the Excel® environment using VBA and made the software freely available to interested users upon request via personal email. Further, Giannetti et al. (2006) and Almeida et al. (2007) proposed improvements to the tool, making it even more robust and practical, providing several case studies. Twenty years after its initial proposal, the emergy ternary diagram has been used by numerous researchers in their emergy studies (among many others, Xu et al., 2022; Shah et al., 2022; Zhao et al., 2019; Elsayed and Nishi, 2020), yet advances in the Excel® versions and VBA programming language have highlighted the need for updates. Additionally, the theoretical development of the emergy synthesis method, where some analysts have started considering partial renewability of resources, has also required modifications to the originally proposed emergy ternary diagram to better communicate results. These issues were identified by our own research group, which frequently uses the emergy ternary diagram, as well as through personal emails from software users who encountered problems while using it.

This Technical Note aims to present the improvements and updates to the emergy ternary diagram, twenty years after its initial proposal. Both technical aspects of the software (Excel® versions and VBA programming language) and theoretical aspects of the method (partial renewability approach) are discussed to address the limitations identified in the previous version. The software can be downloaded for free as described in the following sections and used by emergy analysts to enhance the communication of their project results.

2. Theoretical background

2.1. Emergy accounting and its synthesis

Among other applications of environmental accounting in emergy, its most simplified and traditional form, known as emergy synthesis, comprises three main stages: system modeling, the elaboration of the emergy environmental accounting table, and the calculation and discussion of emergy performance indicators. Modeling involves understanding the system under analysis, identifying its functions, internal processes, energy and matter flows crossing its boundaries, products, co-products, and by-products leaving the system, all represented by an energy diagram using symbols proposed by Odum (1996). This stage is considered fundamental as it allows the analyst to understand how the analyzed system functions under a systemic perspective, as well as enabling effective communication with others (Brown, 2004).

Once the energy diagram is completed, the emergy table is elaborated. Initially, data (both primary and/or secondary) on energy, matter, monetary, and labor flows identified in the diagram are obtained, quantifying them based on a pre-selected time unit, usually using an annual period (unit/yr), combined or not with a functional unit. This step is known as data inventory, similar to what is done in well-established and widely applied methods such as Life Cycle Assessment (LCA; ISO 14040, 2006; ISO 14044, 2006). After completing the inventory, each flow is multiplied by its respective solar transformity (sej/unit), defined as "[…] the solar emergy required to make 1 J of a service or product. Its units are solar emjoule per joule (sej/J). A product's solar transformity is its solar emergy divided by its energy" (Odum, 1996; page 10). In the last decade, all conversion factors in emergy synthesis have come to be referred to as Unit Emergy Values (UEVs), a general term that encompasses any denominator considered, whether in terms of energy (J), mass (kg), monetary ($), or otherwise. UEVs are the 'heart' of emergy synthesis because they contain all the memory or effort of nature previously required and incorporated into a unit of a good or service. Generally, UEVs are obtained from some databases - currently scarce and not updated - or even individually from the most current scientific literature, but they all should possess the same global emergy baseline, preferably the current one of 12 E24 sej/yr (Brown et al., 2016).[1] For the LCA method, there are different databases containing a vast amount of emission factors, referring to the emissions caused upstream in the production process. This practicality can be considered one of the main drivers of the widespread use of the LCA method for assessing environmental impacts. Among the available options, the Ecoinvent database (ecoinvent.org/) stands out. As a suggestion for future work by the emergy community, the creation of an "Emergyinvent," similar to "Ecoinvent", is proposed; this is merely an initial idea, a seed that deserves further discussion within the emergy community in order to truly grow, develop, and become effective. As a subsequent step in the application of emergy synthesis, the inventory data is multiplied by the UEVs to calculate the emergy (sej/yr) of each flow listed in the table, where the summation represents the total emergy of the system. Besides quantifying each flow entering the system under study, it is important to classify them into local renewable natural free resources (R), local non-renewable natural free resources (N), and those that feedback from the larger economy (F), which, when summed, result in the total emergy or Yield (Y) of the system.

In the third and final stage, different emergy performance indicators are calculated, the main and most traditionally used of which include renewability (%R), emergy yield ratio (EYR), emergy investment ratio (EIR), environmental loading ratio (ELR), and emergy sustainability index (ESI); please refer to Odum (1996), Brown and Ulgiati (2004), and Viglia and Ulgiati (2023) for the meaning of these traditional emergy indicators. The algebra for calculating the indicators is presented in Table 1 ('Traditional' column), where all are based on the classification R, N, and F - indicators that include partial renewability will be discussed in the following sections. The discussion of the indicators can be done graphically and/or in tables, making a comparison between the performance of the sample of systems being evaluated, or comparing with existing benchmarks of alternative systems, or even comparing with elaborated scenarios. Graphical forms include the traditional ones (bar charts, scatter plots, radar charts, etc.) or the alternative use of the emergy ternary diagram as presented in the following section.

2.2. Emergy ternary diagram

Drawing on prior experience with ternary diagrams across various scientific fields, the idea of proposing the use of the ternary diagram in the emergy synthesis approach emerged during seminars of the Cleaner Production research group at Paulista University, Brazil, resulting in a master's dissertation (Barrella, 2004) and two subsequent papers (Giannetti et al., 2006; Almeida et al., 2007). Since a picture is worth a thousand words, the use of figures to display the results of emergy synthesis - which applies to any other scientific diagnostic tool as well - is recognized as fundamental for quickly and easily understanding the results obtained. This especially applied when comparing many

[1] The global emergy baseline is a key concept in emergy theory, indicating the total annual emergy that the Biosphere requires (from three sources: solar radiation, the Earth's internal heat, and tidal energy) to sustain all activities on Planet Earth. The value estimated by Odum (1996) was 9.44 E24 sej/yr, a value that has been updated over the years to the most recent standardized value of 12 E24 sej/yr, agreed upon by the emergy community due to the variability and uncertainties involved in its calculation - an historical review of the emergy baseline can be found in Campbell (2016).

Table 1
Emergy indicators with and without considering the partial renewabilities.

Emergy indicators	Algebra for emergy indicators	
	Traditional [a]	Including partial renewabilities [b]
Unit Emergy Value	UEV = Y/Output	UEV = Y/Output
Renewability (%R)	%R = 100 x (R/Y)	%R = 100 x (R + Mr + Sr)/Y
Emergy Yield Ratio (EYR)	EYR = Y/F	EYR = Y/(Mn + Sn)
Emergy Investment Ratio (EIR)	EIR = F/(R + N)	EIR = (Mn + Sn)/(R + Mr + Sr + N)
Environmental Loading Ration (ELR)	ELR = (N + F)/R	ELR = (Mn + Sn + N)/(R + Mr + Sr)
Emergy Sustainability Index (ESI)	ESI = EYR/ELR	ESI = EYR/ELR

Legend: R, local renewable natural free resources; N, local non-renewable natural free resources; F, feedback resources from the larger economy; Mr, renewable fraction of material flows; Mn, non-renewable fraction of material flows; Sr, renewable fraction of service flows; Sn, non-renewable fraction of service flows; F = M + S; Yield, Y=R + N + F.
[a] Brown and Ulgiati (2004) and.
[b] Agostinho and Ortega (2012).
Source: Based on

different systems simultaneously.

In general, some characteristics of the emergy ternary diagram are provided in Fig. 1, but it is suggested to refer to the original authors (Giannetti et al., 2006; Almeida et al., 2007) for further details and to explore its potential applications. The fundamental idea is that the classical application of emergy synthesis requires not only the quantification of all energy, material, monetary, and information inputs supporting the development of the analyzed system, but also the classification of all inputs into renewable natural free resources (R), non-renewable natural free resources (N), and those that are feedback from the larger economy (F). When combined, resources R, N, and F indicate the total emergy (or 100 %) demanded by the system, typically classified as Yield (Y). Thus, the system's performance can be represented on a ternary triangle, with vertices R, N, and F.

Some of the properties of using the ternary diagram are observed in Fig. 1. The first property is the resource flow lines (Fig. 1a), which indicate the relative proportions of the emergy flows given by the lengths of the perpendiculars from the given point/system to the side of the triangle opposite the appropriate emergy flow. Another property is the sensitivity lines (Fig. 1b), representing a change in the quantity of the emergy flow associated with the apex. Any point along this sensitivity line represents a condition in which the other two emergy flows maintain the same initial proportion. The syMergy point (Fig. 1c) property represents a composition among other points/systems, in which a minimum of two points is necessary, and there is no limit for the maximum number of points. It represents an average performance when considering the individual performance of all systems analyzed. Finally, the sustainability lines (Fig. 1d) indicate constant values for the emergy sustainability index. They depart from the N apex in the direction of the R-F side, dividing the triangle into sustainability regions useful for diagnosis.

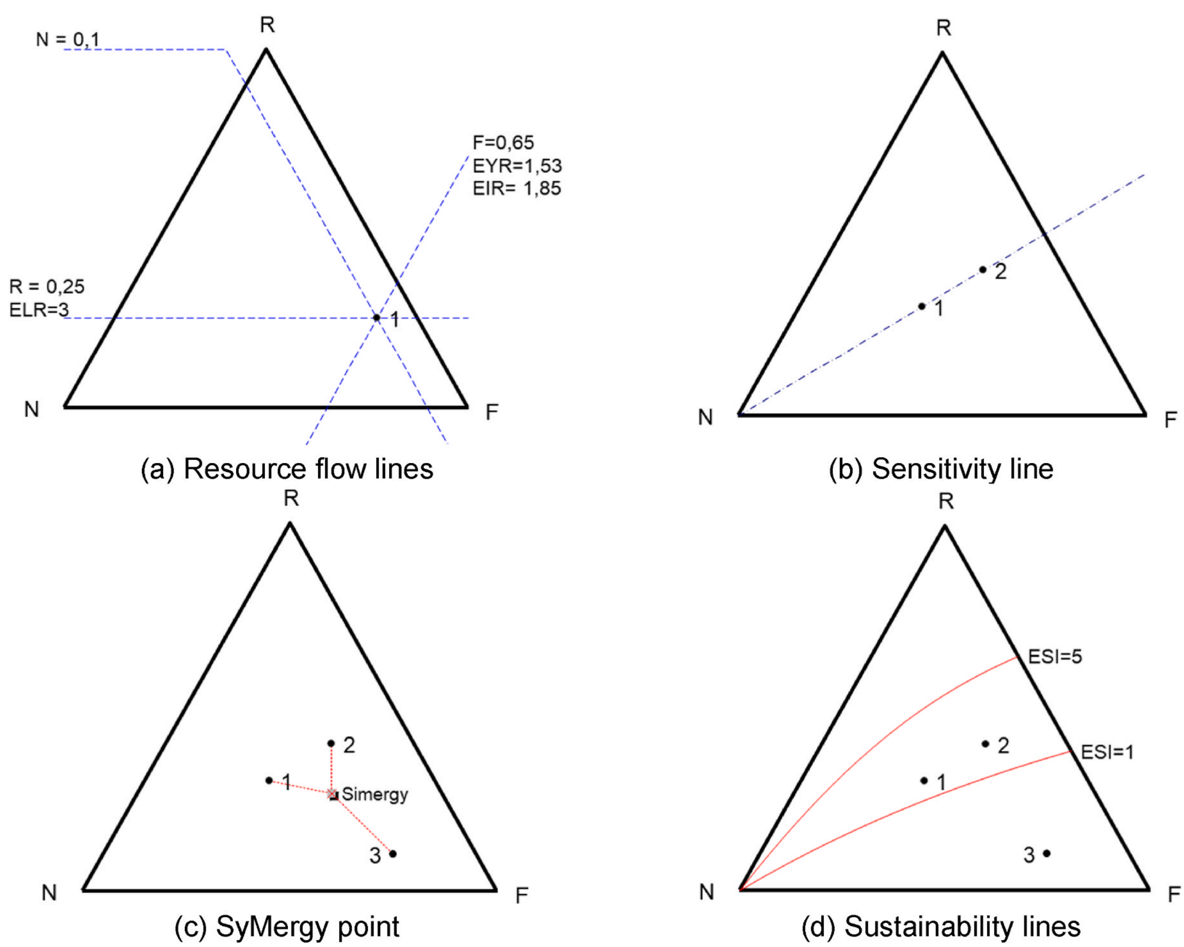

Fig. 1. Structure of the emergy ternary diagram based on traditional algebra of emergy indicators. The plotted systems (points) are hypothetical. (a) Resource flow lines, $R_1 = 25$ %, $N_1 = 10$ %, $F_1 = 65$ %; (b) Sensitivity line, $F_1/R_1=F_2/R_2 = 1$; (c) SyMergy point, average among R, N and F emergy flows of points 1, 2 and 3; (d) Sustainability lines, point 3 with ESI<1 indicating emergy unsustainability, while points 1 and 2 with 1<ESI<5 indicating moderate emergy sustainability.

Since its proposal over 20 years ago, the emergy ternary diagram has been widely utilized by researchers in their studies. While all these research efforts apply emergy synthesis as a diagnostic tool to assess environmental performance, they explore different production and consumption patterns. Among other applications, the emergy ternary diagram has been used for regional analyses (Li et al., 2014), energy systems such as wind power and solar updraft towers (Yang and Chen, 2016; Elsayed and Nishi, 2020), circular economy assessments in eco-industrial parks (Zhao et al., 2019), evaluation of restoration alternatives for coal-mining areas (Sun et al., 2019), the construction sector, to assess green and traditional concrete (Zhao et al., 2020), tourism in a region of China (Xu et al., 2022), agricultural production (Agostinho et al., 2019), and co-treatment systems for urban wastewater (Toledo et al., 2024). In all cases, the emergy ternary diagram is employed to support comparative analyses, scenario evaluations, and/or the study of temporal dynamics in emergy performance.

Although the tool presented here is specifically designed for the emergy practitioners, it is worth noting that the ternary diagram can be readily adapted for studies in various fields that rely on three key components or indicators. Examples include measuring sustainability through energy consumption, carbon emissions, and resource efficiency; analyzing waste distribution into organic, recyclable, and non-recyclable categories; dividing land use into forest cover, agricultural land, and urban development; measuring the distribution of parks, paved pathways, and ecosystem services; evaluating market performance using profitability, market share, and growth rate; allocating household income among expenses, savings, and investments; assessing community well-being based on education levels, health metrics, and income distribution; and evaluating land use in terms of green spaces, residential areas, and commercial zones. The tool's versatility enables it application across diverse studies, shaped by the researcher's creativity and specific objectives.

3. Integrating partial renewabilities into the emergy ternary diagram

This section presents the main methodological update included in the new version of the emergy ternary diagram software: the ability to incorporate partial renewabilities in the calculation and visualization of emergy indicators. It is important to clarify that this Technical Note does not propose the concept of partial renewability itself. That concept has already been discussed in the emergy literature (e.g., Tiezzi and Marchettini, 1999; Ortega et al., 2002; Agostinho and Ortega, 2012). Instead, the innovation here lies in integrating this underutilized concept into the emergy ternary diagram, which, until now, operated solely based on the traditional indicator algebra using the emergy flows R, N and F.

While the integration of partial renewabilities into the emergy ternary diagram represents the central contribution of this Technical Note, it is essential to outline the fundamental concepts that underpin the notion of partial renewability. One key aspect is that emergy indices can also be calculated by incorporating the partial renewability of each input, as illustrated in Table 1. This concept was first discussed by Tiezzi and Marchettini (1999), further developed by Ortega et al. (2002) and Ulgiati and Brown (2014), and subsequently applied by Agostinho and Ortega (2012, 2013). The inclusion of partial renewabilities seeks to account for the renewability of each system input by extending the boundary to include the processes involved in its generation and supply. This approach is particularly suitable when the system relies on inputs from the local or regional economy, which may be renewable or at least partially renewable.

To illustrate the practical relevance of including partial renewabilities, consider the production of animal feed based on corn. Feed made from more ecologically produced corn -grown with fewer petroleum-based resources and sourced near the animal production site -may have a higher degree of renewability than feed derived from conventionally grown corn, which depends heavily on industrial fertilizers, agrochemicals, and long-distance transportation. Another example is irrigation water: small volumes pumped from a high-flow river have a greater degree of renewability compared to large volumes extracted from an underground aquifer. Additional insights into partial renewability and the need to revise traditional emergy indicators are provided by Ortega and Bastianoni (2015), among others.

The emergy analyst should clearly state the criteria considered when selecting partial renewabilities, with the most common approach being to rely on the emergy renewability indicator (%R) of the item in question, as evaluated in previous studies. Estimates can also be made, but they should be based on clear criteria and include the data and calculations used. As the number of publications on emergy continues to grow, the availability of data in the scientific literature has also increased substantially. Consequently, finding the renewability value of a given item previously studied by another author is becoming an easier task. For example, Agostinho and Siche (2014) evaluated sugarcane ethanol production in Brazil and found a renewability of 80 %. This value could be considered by other authors applying emergy accounting in a system where Brazilian ethanol is regarded as an input resource, meaning it would have a partial renewability of 80 %.

The inclusion of partial renewabilities in emergy synthesis influences the algebraic calculations of emergy performance indicators. As presented in Table 1, resources previously classified as Materials are now divided into Renewable Materials (Mr) and Non-Renewable Materials (Mn), similarly to the classification of resources previously referred to as Services. Consequently, the resource Feedback from the Larger Economy (F) is also divided into renewable (Fr) and non-renewable (Fn) components. Specifically, with the exception of the Unit Emergy Value (UEV) indicator, all other emergy performance indicators in Table 1 (Column 'Including Partial Renewabilities') are modified from their original algebra when incorporating partial renewabilities. Therefore, analysts should be cautious when making direct comparisons or interpreting these indicators. It can be observed that, although calculated slightly differently, the %R and ESI indicators retain the same meaning whether or not partial renewabilities are considered. Published studies indicate that when partial renewabilities are accounted for, the values of %R and ESI tend to be higher than when calculated without considering them. On the other hand, the other performance indicators (EYR, EIR, and ELR) have a slightly different interpretation compared to the original ones provided by Brown and Ulgiati (2004) when incorporating partial renewabilities, as they subtract the renewable portion from the total values of F and M, adding it instead to the emergy flow R.

Although still open to discussion, the new interpretations of these three indicators are presented here. The original idea of the EYR remains partially valid, as the core concept of assessing the process's ability to generate more emergy than it consumes from the economy is preserved. The updated interpretation could be: "It measures the process's ability to generate net emergy relative to its dependence on external non-renewable inputs". Regarding the EIR, the original idea of assessing the process's dependence on external economic inputs is maintained, but now restricted to non-renewable inputs. The updated interpretation could be: "It assesses the process's dependence on external non-renewable inputs, compared to the support provided by local and renewable resources". Finally, the original concept of environmental pressure associated with the ELR remains valid, but now incorporates a more realistic distinction between the resources that generate pressure and those that are sustainable. The updated interpretation could be: "It measures the environmental stress caused by the use of non-renewable resources in relation to the support provided by renewable resources, including the renewable fractions of materials and services". Analysts must exercise caution when comparing and discussing these indicators to ensure they accurately convey their intended meaning.

According to Table 1, modifying the algebraic formulation of emergy-based performance indicators to incorporate partial renewabilities also changes the underlying logic of the ternary diagram, including its programming and graphical layout. This integration has led to the development of a new version of the emergy ternary diagram. Importantly, this is where the core novelty of this Technical Note lies: the incorporation of partial renewabilities into the ternary diagram, which until now relied exclusively on the classical formulation based on the emergy flows R, N, and F. This conceptual and algebraic refinement also required changes to the visual representation of the diagram itself. In its classical form (as shown in Fig. 1), the ternary diagram is based on vertices representing R, N, and F, following the traditional algebra of emergy indicators. However, the inclusion of partial renewabilities demanded an update in this structure: the vertices are now defined as R + Mr + Sr, N (which remains unchanged), and Mn + Sn.

The central idea of the ternary diagram remains intact: the total emergy demand of the evaluated system is normalized to 100 %, allowing each system to be represented as a point within the diagram. The updated version thus preserves the communicative function of the original tool, while incorporating greater methodological sensitivity to differences in resource quality and renewability.

4. Discussion and contributions of the updated emergy ternary diagram

This section discusses and contextualizes the main contributions of the updated version of the emergy ternary diagram software. These contributions can be grouped into three areas: (i) technical aspects, (ii) layout aspects, and (iii) methodological aspects. While the first two improvements apply to both versions of the software - regardless of whether partial renewabilities are used - the third applies specifically to the version that incorporates partial renewabilities into the calculation of emergy indicators.

Again, it is important to clarify that this Technical Note does not propose the concept of partial renewability itself, which has already been discussed and applied in the emergy literature (e.g., Ortega et al., 2002; Agostinho and Ortega, 2012). Rather, this work contributes by operationalizing the concept through its integration into the emergy ternary diagram, which until now had been limited to the classical algebra of emergy synthesis. In this sense, the innovation is both practical and technical, supporting more accurate and differentiated assessments of sustainability in diverse systems.

4.1. Technical and layout improvements

A primary contribution of the new programs for creating emergy ternary diagrams - regardless of whether partial renewabilities are included - is the resolution of certain existing technical issues that previously limited their functionality. These issues were primarily related to circular references and other aspects associated with the Excel® VBA macro, which has evolved since the first version of the software released in 2006. With the updates, the software now runs on Microsoft Excel® versions later than 2013 and is compatible with Microsoft Windows, Linux, and macOS operating systems.

A second contribution relates to the new layout. In the 2006 version, the software provided a range of information on emergy synthesis, including definitions and explanations, while also allowing users to create their own emergy calculation table within the software. This often led to methodological errors, especially when users lacked prior experience in emergy synthesis and needed to pay close attention to quantitative inventory data and the Unit Emergy Values (UEVs) used, including consistency of units. In the current version, the software's role has been simplified and clearly defined: it serves exclusively to generate the emergy ternary diagram and produce a summary report. Users must enter emergy flow data that has been previously calculated and validated by themselves.

The number of input points has also been increased: the software now allows for the insertion of up to 30 evaluated systems, compared to only 10 in the previous version. The layout has been redesigned to be more intuitive and user-friendly, including buttons for task execution, and now offers options to export the ternary diagram as a.jpeg image or print it directly. Additionally, users can print or save a.pdf summary table of the emergy synthesis results, including aggregated flows and performance indicators.

It is important to emphasize that all functionalities from the previous version of the ternary diagram have been retained, including the ability to: Show or hide selected data points (i.e. evaluated systems), Graph points based on their emergy quantity relative to the total sample, Display emergy sources, Visualize sustainability lines, sensitivity lines, and syMergy points, Customize line colors and types, and Apply zoom and scaling as needed.

4.2. Methodological improvement: incorporating partial renewabilities

The main methodological advancement concerns the graphical representation of emergy-based system performance using the ternary diagram when partial renewabilities are taken into account. This innovation reflects the evolution of the emergy method in recent years and is increasingly considered important by emergy practitioners, as discussed in Section 3. While the idea itself is not new, this is the first time it is being formally and systematically incorporated into the structure and logic of the emergy ternary diagram.

To illustrate the application of the updated diagram with partial renewabilities, the study by Cordoba Correoso et al. (2022) that discussed about the use of homeopathy in agricultural production was used, which evaluated six different rural properties in Brazil with varying products and management practices. Table 2 presented the emergy flows calculated for these six farms using partial renewability data. One key observation is that all properties had the same R value (because they are all in the same region), but differed in N, M, and S components, especially in their renewable and non-renewable fractions. For example, P5 showed higher N, P3, P5, and P6 had greater M inputs, while P6 had the highest emergy yield (Y). These variations affect the emergy-based indicators, which are better visualized and interpreted through the emergy ternary diagram.

While presenting emergy flow data in a table format helps to understand magnitudes and enables the calculation of performance indicators, graphical representation through the emergy ternary diagram can be considered a more effective approach. It allows for quicker and clearer visualization of the differences among evaluated systems while

Table 2
Emergy flows (in E+14 se/ha yr) calculated based on the concept of partial renewabilities for six family farms located in Santa Catarina State, Brazil. Source: Cordoba Correoso et al. (2022).

Aggregated emergy flows	Family managed farms					
	P1	P2	P3	P4	P5	P6
Renewable natural resources (R)	17.33	17.33	17.33	17.33	17.33	17.33
Nonrenewable natural resources (N)	0.73	1.93	1.70	1.14	8.02	3.23
Materials (M = Mr + Mn)	9.97	15.44	26.24	22.42	8.33	20.66
Renewable materials (Mr)	5.11	0.38	0.14	1.24	0.21	12.29
Nonrenewable materials (Mn)	4.85	15.06	26.09	21.17	8.12	8.36
Services (S=Sr + Sn)	25.72	24.68	35.02	43.37	20.35	77.08
Renewable services (Sr)	18.40	7.50	9.50	15.25	9.30	58.58
Nonrenewable services (Sn)	7.29	17.17	25.52	28.12	11.04	18.49
Indigenous resources (I=R + N)	18.06	19.26	19.03	18.47	25.35	20.56
Feedback from economy (F = M + S)	35.69	40.12	61.27	65.80	28.68	97.74
Emergy yield (Y=I + F)	53.75	59.38	80.30	84.27	54.03	118.30

Legend: P1 agroecological, P2 grains & cattle, P3 milk & grains, P4 grains, P5 diversified, P6 organic. Emergy baseline of 1.20 E+25 sej/yr.

also automatically calculating the key indicators. The emergy ternary diagram shown in Fig. 2 was generated using the proposed software, incorporating partial renewabilities as presented in the example in Table 2. Fig. 2 shows that, among the six evaluated systems, P1 (agroecological), P4 (grains), and P6 (organic) have an Emergy Sustainability Index (ESI) above 5 (highlighted by dashed green lines), indicating long-term sustainability. In contrast, P3 (milk & grains) presents the lowest ESI, below 1, indicating a condition of unsustainability. The remaining two systems exhibit ESI values between 1 and 5, which suggests moderate sustainability. According to Cordoba Correoso et al. (2022), the better performance of farms P1, P4, and P6 is related to their more ecological management, applying homeopathy throughout the production system, which reduces the need to acquire external resources based on fossil fuels.

Although any other point could have been selected, the red dashed lines in Fig. 2 illustrate the position of P5 as an example. In this case, P5 shows 15 % of N, 35 % of Mn + Sn, and 50 % of R + Mr + Sr as a percentage of the total Yield (Y), which aligns with the data presented in Table 2, resulting in an ESI of 2.8. Another interesting aspect observable in this diagram is that all six evaluated systems present a maximum emergy contribution from N of 15 % or less. This suggests that the primary factors influencing the emergy sustainability performance of these systems are their respective dependencies on R + Mr + Sr and Mn + Sn resources.

Additionally, the software allows users to generate a detailed individual report for each evaluated system (referred to as a "point" in the software), as illustrated for point 5 in Fig. 2. This report displays emergy flow data in both absolute terms (sej/unit) and percentages, along with automatically calculated performance indicators.

Other useful features of the emergy ternary diagram include the option to weight the representation of each point (system) based on its total emergy demand, display sensitivity lines that indicate proportional changes among flows, and identify the syMergy point, which represents the average performance of the group of evaluated systems. All of these functionalities were already available in the previous version of the software, as documented by Giannetti et al. (2006) and Almeida et al. (2007). Finally, the updated software allows for the generation of a final table-format report that includes the results exemplified in Fig. 2 for all evaluated systems, enhancing transparency and facilitating comparison.

4.3. Limitations and final remarks

Despite its advantages, the main limitation of the updated emergy ternary diagram lies in the scientific challenge of determining partial renewability values for each emergy input. This limitation is expected to be progressively overcome as more emergy studies report the %R indicator, expanding the available database for analysts. In the future, further technical improvements could include migrating the platform to a web-based environment with cloud storage and collaborative features, which could assist in estimating renewability fractions when data are missing or incomplete.

We expect that emergy analysts will increasingly adopt the updated ternary diagram in their studies. The tool's potential for clear visual communication, combined with its ability to represent both classical and partial-renewability-based indicators, makes it a powerful asset for emergy synthesis. In particular, it helps bridge the gap between scientific diagnosis and decision-making, especially in policy contexts where non-specialists need robust yet accessible information. By formalizing the use of partial renewabilities in the emergy ternary diagram, this work contributes to enhancing the accuracy, transparency, and strategic utility of emergy-based sustainability assessments.

4.3.1. Technical information

Both software programs, with or without partial renewabilities, are available as Excel® files for free download at < advancesincleanerproduction.net > or by directly contacting the first author. They have been registered with the Brazilian National Institute of Industrial Property (INPI) to ensure legal protection in accordance with Brazilian federal regulations.

CRediT authorship contribution statement

Feni Agostinho: Writing – original draft, Supervision, Methodology, Conceptualization. **André Gomes de Lira Muniz:** Software, Data curation. **Cecília M.V.B. Almeida:** Writing – review & editing, Validation. **Biagio F. Giannetti:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

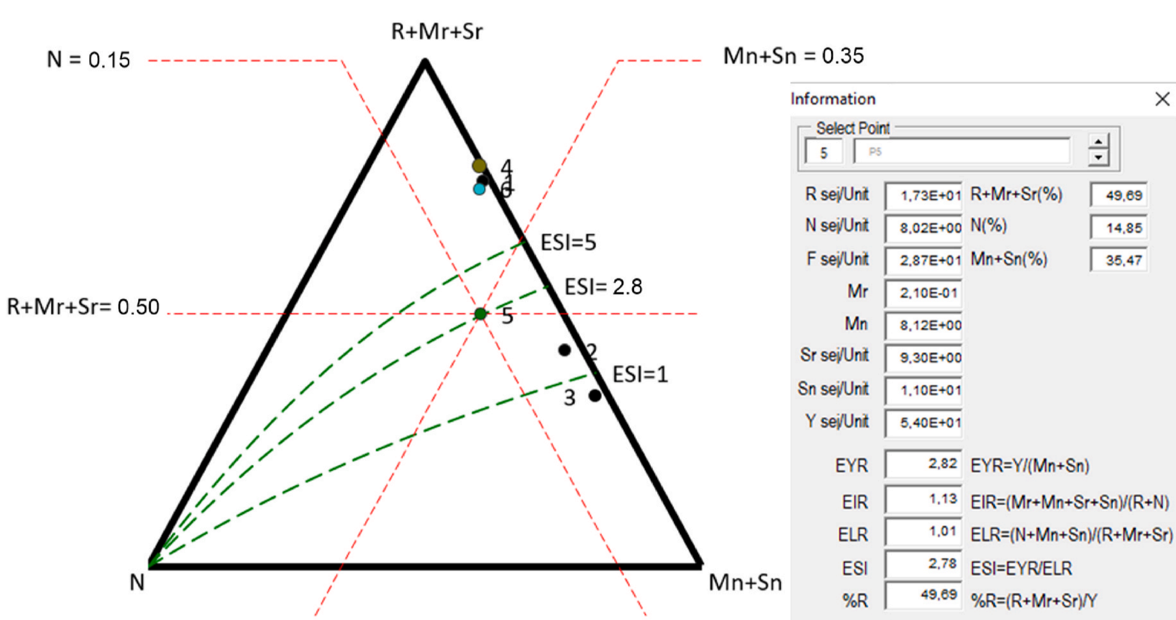

Fig. 2. Emergy ternary diagram considering the partial renewability for the six family farms evaluated by Cordoba Correoso et al. (2022). Data from Table 2.

the work reported in this paper.

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Data availability

All the data used in this technical note are available within the text of the paper itself.

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