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Sustainability assessment procedure for operations and production processes (SUAPRO)

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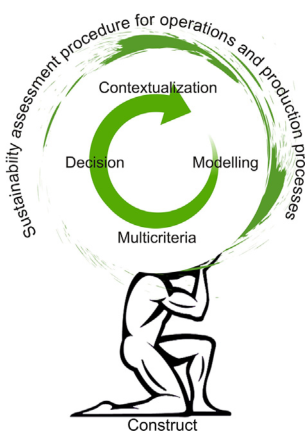
HIGHLIGHTS

- A new framework for assessing sustainability is presented and discussed.
- SUAPRO is suggested to overcome existing inconsistencies in sustainability assessments.
- The 5SEnSU model, goal programming, uncertainty and sensitivity analysis support SUAPRO.
- Road and railroad soybean transportation options in Brazil are used as case study.

GRAPHICAL ABSTRACT



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ABSTRACT

Sustainability assessment is a fundamental step to support decisions towards sustainable development, and several procedures to assess the sustainability of antrophic production systems have been suggested. However, most of them lack a scientific-based construct supporting their conceptual model of sustainability, which usually results in a choice of indicator(s) without criterion that can best represent a fraction of the larger and deeper concept of sustainability. This work proposes a novel framework, named Sustainability Assessment Procedure for Operations and Production Processes (SUAPRO), supported by the PDCA four-step management method (plan, do, check, and act) and the five sectors sustainability (5SEnSU) model. Grounded on scientific bases, SUAPRO provides the steps for a sustainability assessment, including its contextualization (objectives, functional unit, boundaries, energy diagram), the choice of indicators based on the 5SEnSU model, the quantification step including goal programming as a multicriteria tool, and conclude the first cycle with a sensitivity analysis. To illustrate an application of SUAPRO, the road and railroad transportation options for soybean in Brazil are considered as a case study. Results show that the railroad mode has better performance as for the Sustainability Synthetic Indicator (SSIS of 3.6 ± 0.4) than the road mode (SSIS of 4.0 ± 0.3). Towards a SSIS improvement, the sensitivity analysis highlights that public policies or even private actions should be mainly focused on reducing the emergy invested in the railroad system, while the road transportation option claims effort in reducing its global warming and

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acidification potentials. SUAPRO is the main contribution in this work, as it tries to overcome shortcomings as usually found in scientific papers aiming to assess the sustainability of antrophic systems. The subjectivity inherent in any multicriteria method is present as the main limitation, thus all criteria used in choosing weights must be clearly presented.

1. Introduction

The traditional and perhaps most accepted definition of sustainability is based on the development that should be planned in order to meet the needs of the present generation without compromising the capacity of future generations to provide for their own needs. This definition became popular as from the end of the decade of 1980, through the Brundtland Report (un-documents.net/our-common-future.pdf), and remains an operational challenge for environmental policymakers and the general scientific community (Ramcilovic and Pulzl, 2018). Operationalizing the existing resolutions of the Brundtland Report supporting decisions towards higher degrees of sustainability is still a puzzle, as well as the work of the scientific community in classifying, measuring and proposing models to represent sustainability. An important advance in this direction was the new proposal for a sustainability model provided by the United Nations in September 2015, which established the 17 sustainable development goals (SDGs; sustainabledevelopment.un.org) quantified over 169 indicators when evaluating economies. Although considered as an important proposal, some authors have pointed out some weaknesses in UN's sustainability model and in its implementation. For instance, Persson et al. (2016) state that it will be difficult to define a way to implement SDGs and allocate eventual responsibility during this process due to a needed broad and extensive agenda, while Wackernagel et al. (2017) highlight that SDGs are mostly short-term development goals that claim efforts to more robustly embrace the reality of resource constraints and climate change.

The UN's SDGs are the most recent effort in modelling sustainability, however, other important efforts have been carried out during the last few decades and, most likely, they also supported the creation of the SDGs. Daly (1990), among others, described the development of the human economy as a subsystem of a finite global ecosystem, emphasizing that economy cannot grow and be sustainable for long periods of time when the natural resource utilization ratio is uncontrolled; in other words, the biocapacity supporting such economic development must be understood and respected (this is the main criticism raised by Wackernagel et al. (2017) on the SDGs). Three different dimensions or capitals (natural, social and economic) should be recognized as important when modelling sustainability. Additionally, Daly (1990) proposed classifying sustainability as weak, intermediate and strong, as a way to evaluate sustainability models. While the natural, social and economic capitals are considered as substitutes in the weak sustainability, they can be only partially replaced in the intermediate sustainability, and no substitutability at all is allowed in the strong one. The main idea behind the strong model is that societal and economic development can be achieved only by preserving the natural capital, respecting its biocapacity.

The advancement in classifying and modelling sustainability can be considered as a fundamental step, allowing for assessments that would support better based and operational public policies. However, it is not difficult to find studies in the scientific literature that have considered a reduced number of indicators and/or methods that, according to their own definitions, are able to embrace only part of the three capitals behind the sustainability concept. For instance, Pellicer-Martínez and Martínez-Paz (2016) considered the water footprint method to assess the environmental sustainability of using water in a watershed; Cai et al. (2019) considered energy savings and emission reduction when discussing about the sustainability of manufacturing industries; Kalghatgi (2019) discussed about the sustainable transport while considering affordability, energy security, impact on greenhouse gas emissions and air quality as indicators; Viglia et al. (2018) considered emergy and cumulative energy demand to develop and validate indicators of urban environmental sustainability; Collins et al. (2018) applied the ecological footprint method to explore the relationship between educational levels with the awareness of the environmental consequences of consumption behavior, and Campbell and Garmestani (2012) examined the sustainability of San Luis Basin, USA, from an emergy accounting perspective. Although these last two studies considered exclusively one indicator or method to discuss about sustainability, both methods (ecological footprint and emergy) consider the strong conceptual model of sustainability based on physical limits to growth. Usually, there are no scientific inconsistencies in the published papers that have chosen one or another indicator/method to discuss about the sustainability of a good or service, however, it is imperative that studies clearly present the conceptual model that supports their criteria in choosing such indicators.

Discussing about the existing challenges to measure development, welfare, and wellbeing, Giannetti et al. (2015) conclude that none of the evaluated methods (including emergy accounting, ecological footprint, gross national happiness, wellbeing index, green GDP) seems to assess the progress towards sustainability, which should address ecosystem functionality and ensuring sustainable societal development; the authors emphasize the need for a multicriteria perspective for such a goal. Trying to overcome the problem in using single criteria in assessing sustainability, Ulgiati et al. (2006) propose the sustainability multicriteria multiscale assessment (SUMMA) model, which clearly presents a conceptual model of sustainability. Authors emphasize that upstream and downstream impacts must be accounted for, when evaluating the sustainability of production systems, and for such a goal, the emergy accounting, life cycle assessment, embodied energy and/or exergy evaluations are the main methods suggested in obtaining indicators. Although an important step towards better described sustainability assessments, SUMMA is based on the strong conceptual model of sustainability without providing indicators for social and economic capitals. Coscieme et al. (2013) advanced in this aspect by proposing the so-called input-state-output (ISO) conceptual model of sustainability, which focuses on the mutual relations among the different indicators feeding it. Authors argue that ISO highlights how ecosystems effectively transform resources, self-organize through processes, and produce goods and services that represent fundamental benefits for societal well-being. Both approaches, SUMMA and ISO, do indicate the need of a multicriteria perspective in assessing sustainability.

The scientific literature is plentiful of studies that have considered the three dimensions or capitals under a multicriteria perspective in assessing sustainability, each one with its own specificities in choosing or weighting indicators. Among several others, Arushanyan et al. (2017) presented the sustainability assessment framework for scenarios (SAFS) to assess environmental and social risks and opportunities of future scenarios; SAFS suggests assessing environmental and social aspects using a consumption perspective under a life cycle approach by focusing on both the production system itself and the system outcome. Escribano et al. (2018) applied a Delphi method to design a set of 24 sustainability indicators adapted to dehesa agroforestry systems in Europe including social, economic and environmental capitals. Stoycheva et al. (2018) proposed a quantitative framework to assess the sustainability of manufacturing applied to the automotive industry;

multi-criteria decision analysis (MCDA) is used to merge the perceived values of executives and decision makers together with materials consumption in the production processes. De Luca et al. (2018) proposed an integrated approach based on life cycle assessment, life cycle costing and social life cycle assessment by means of the analytic hierarchy process; this approach was used to assess the sustainability of olive production in Italy. Millward-Hopkins et al. (2018) proposed a multidimensional model (including social, environmental, technical and economic domains) to assess resource recovery systems under the material flow accounting and life cycle assessment; authors emphasize the advantages of fully integrated models for sustainability assessments rather than applying hybrid approaches that integrate outputs from parallel models. Ekener et al. (2018) proposed and applied, in the case of fuels for transportation, a comparative approach based on life cycle sustainability assessment, environmental life cycle assessment, and life cycle costing, which are further integrated in a MCDA; weighting processes within MCDA are based on different stakeholder profiles including egalitarian, hierarchical, and individualist. Jiang et al. (2018) proposed a three-dimensional model to analyze the corporate sustainable performance based on principal component analysis. Hegab et al. (2018) developed a general sustainability assessment algorithm for machining processes by considering energy consumption, machining costs, waste management, environmental impact, and personal health and safety to express the overall sustainability assessment index. Ibrahim et al. (2018) developed an integrated framework to assess the sustainability of desalination technologies by integrating techno-economic, environmental and social factors under a MCDA; desalination experts determined the relative importance of indicators. Saad et al. (2019) developed a framework for sustainability assessment of manufacturing processes through a multicriteria approach, including indicators of emissions, resource consumption, and natural habitat conservation, economic cost, profit, and investment, number of employees, customers, and community. Nikolaou et al. (2019) proposed a framework to measure corporate sustainability performance by designing a composite sustainability index based on the triple-bottom-line approach and the principles of strong sustainability; in this framework, thresholds can be associated with the concept of carrying capacity, safe minimum standards and critical capital. Rocchi et al. (2019) assessed the sustainability of poultry production under a multicriteria perspective by considering life cycle assessment to evaluate the environmental aspect, simultaneously with economic and social indicators, and animal welfare.

Although the scientific literature is abundant with case studies that propose assessing sustainability under a multicriteria perspective, from our literature review we found a lack of studies that consider and clearly provide the needed constructs in establishing their conceptual model of sustainability. In other words, most studies have chosen methods and indicators to represent sustainability without presenting a construct to support such choice. Why does an author calculate the global warming potential of a good and discuss about its sustainability, while another author considers socio-economic aspects for the same purpose? Why did an author consider the energy demanded in producing a good to discuss about its sustainability, while one other author considered one indicator of each of three dimensions, environmental, social and economic? Is there a right or wrong approach to be considered? We understand that most published papers intending to assess the sustainability of production systems do lack a construct to support their choices of models and indicators to represent sustainability. This is also supported by Brown et al. (2018), who emphasize a lack of maturity on the available multidimensional assessment methods, and by De Luca et al. (2017), who suggest further efforts towards the development of new integrative tools. An important effort trying to overcome this issue was published by Giannetti et al. (2019) that provided a conceptual model of sustainability named five sectors sustainability (5SEnSU), which was elaborated based on the original definition of sustainability as well as on its fundamental axioms. The 5SEnSU model considers the three capitals or dimensions of sustainability, in which the natural and social capitals act as both providers and receivers of energy, materials and/or information. Although the 5SEnSU model could be considered as an advance towards sustainability studies based on solid scientific constructs that support the establishment of a conceptual model, the proposal of Giannetti et al. (2019) still lacks a regulation on standardized procedures that will allow for its application by researchers of different fields assessing diverse case studies and allowing for comparisons. For instance, the regulation provided by the ISO 14,040 (ISO, 2006a) and 14,044 (ISO, 2006b) is related to the application of the life cycle assessment (LCA) method, in which these regulations should be respected to allow for LCA usage under standardized procedures; we understand that a similar regulation should be elaborated for the 5SEnSU model.

Recognizing the importance, in sustainability assessments, of goods and services that are mandatory to support scientific-based decisions towards a societal sustainable development, as well as recognizing the weaknesses on the construct of the existing sustainability procedures, this work aims to propose a novel framework that supports procedures for a sustainability assessment of goods and services. This proposed framework is named sustainability assessment procedure for operation and production processes (SUAPRO). The PDCA four-step management method (plan, do, check and act) is used to sustain our framework, that also includes the main procedures as found in LCA ISO 14,040 (ISO, 2006a). The 5SEnSU model is included in the framework, as well as the philosophy of multicriteria method goal programming, in calculating the sustainability synthetic indicator of a system (SSIS). Uncertainty and sensitivity analyses are also considered to allow for decisions towards improvements on the sustainability of evaluated systems. The application of SUAPRO is illustrated in the soybean transportation from agricultural production centers to port, in Brazil, for exportation, comparing the sustainability of road versus railroad options represented by their SSIS.

2. Proposal of sustainability assessment procedure of operations and production processes (SUAPRO)

Recognizing that the management phase is as important as the diagnosis in sustainability assessments, we have chosen the well-known and used concept of continuous improvement named planning-execution-checking-action (PDCA) as a basis to support the framework of SUAPRO. According to Maruta (2012), the PDCA cycle was initially used as a tool to control the quality of the products, but soon afterwards, it was recognized as a method to develop improvements in organizational processes. The cycle is rooted on the idea of continuous improvement, a philosophy first introduced in the culture of companies, that would lead to gradual improvement changes.

SUAPRO is divided into four stages (Fig. 1), as well as the LCA method according to ISO 14040 (ISO, 2006a) that, comparatively, includes goal definition, inventory analysis, impact assessment, and improvement assessment. First stage contemplates the context of the evaluation, the second stage includes the choice and calculation of indicators, in the third stage the sustainability is quantified, and finally, the fourth stage concerns management through proposal of improvements. Each stage, as represented in Fig. 1, is individually explained in the next subsections.

2.1. Stage 1 ("PLAN"): contextualizing the assessment

During scope definition, some important aspects should be considered and clearly described, including the identification of evaluated operations and production processes (named from here onwards as "system"), the establishment of a representative functional unit, the system boundaries, allocation procedures, data requirements, assumptions and limitations. Defining time and scale of analysis is fundamental. It is desirable that the scope be sufficiently well defined to ensure that some details about the study, such as its extension and depth, are compatible and sufficient to meet the established objective. For comparative studies, the same functional unit and equivalent methodological considerations must be

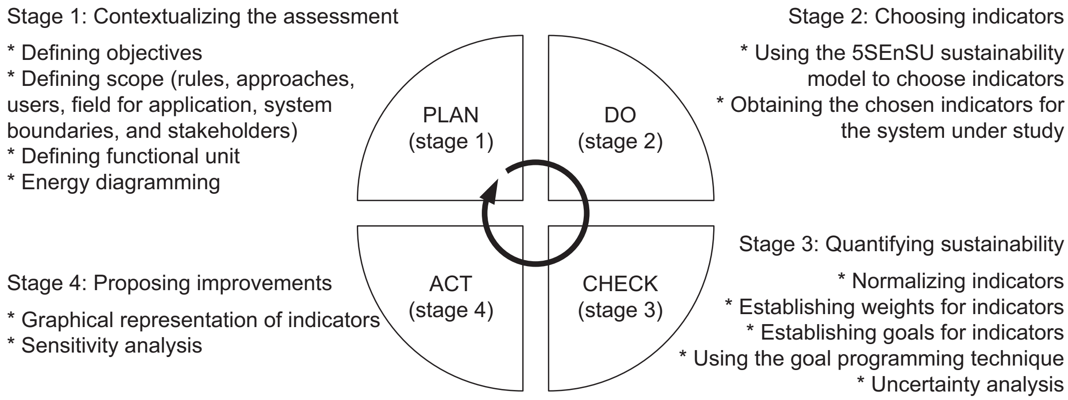

Fig. 1. "PDCA" (plan, do, check, act) concept supporting the proposed approach for the sustainability assessment of operations and productive processes.

considered, including system boundaries, data quality, allocation procedures, and decision rules in the evaluation of inputs and outputs during the inventory phase. Any differences among the evaluated systems with respect to these parameters must be identified and reported.

System boundaries determine which units or processes should be included in the evaluation. Several factors determine the boundaries of the system, including the intended application of the study, the assumptions made, the cutoff criteria, data constraints and cost, and the intended target audience. The selection of inputs and outputs, the level of aggregation in a data category and the system modelling must be consistent with the purpose of the study. The analysist is free to establish the system boundaries, but the criteria used for such a choice must be identified and justified.

Another important parameter for contextualization is the definition of the functional unit, which, in accordance to Goldstein et al. (2013), is the basis of the comparison between two production systems, either for products or for services provided. According to ISO 14040 (ISO, 2006a), the functional unit is a "quantified performance of a production system for use as a reference unit". The primary purpose of a functional unit is to provide a reference to which the inputs and outputs are related. The functional unit allows for the adoption of management strategies towards higher degrees of sustainability including implementation, operation, verification and corrective actions.

Finally, to accomplish all the needed aspects within the contextualization, the elaboration of an energy diagram considering the symbols from the emergy accounting method as proposed by Odum (1996) is recommended. Fig. 2 shows the most used symbols of the energy systems language within emergy accounting; for detailed explanation, please refer to Odum (1996). The diagram is a conceptual model of the evaluated systems and its relation with the natural environment and society. For Brown (2004), the emergy language used in the diagrams represents a concise way to visualize systems, in which simplified models containing enough characteristics of the original system to resemble reality could help the system to understand itself.

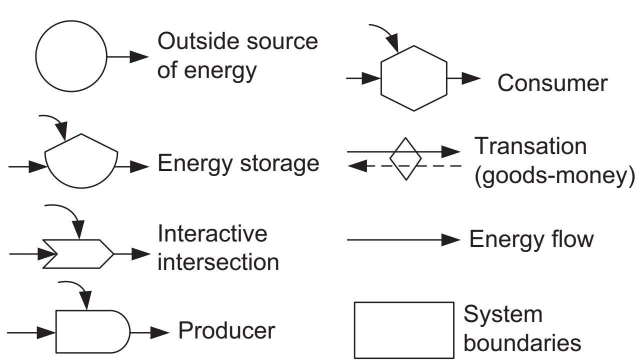

Fig. 2. Symbols of the energy systems language.
Source: Odum (1996).

2.2. Stage 2 ("DO"): choosing indicators

The selection of indicators is based on the five sectors sustainability (5SEnSU) model, represented by Fig. 3. According to Giannetti et al. (2019), the 5SEnSU is based on the three basic axioms proposed by Daly (1990) on the limits of natural resources in relation to the rhythms that are exploited and consumed. To ensure the current pace of sustainable development, the other three axioms were added by the authors: (i) there must be a balance between the environment as a resource provider (sector #1) and as a recipient of waste and pollutants (sector #2); (ii) the production of goods and services should be limited to the restrictions imposed by the sustainable exploitation of natural resources and the responsible consumption of society, which ensures its sustainability; (iii) as a social being, man acts as a supplier of labor (sector #4) and receiver of products and services from the economy (sector #5).

Indicators can be chosen according to the expertise of the analyst, however always taking into account the particularities of the case under evaluation. Further alternatives in choosing indicators are based on participative meetings, in which experts from different fields of knowledge can obtain a common agreement (for instance, using a non-parametric statistical technique as Delphi), as well as governmental plans and reports. Anyhow, indicators must respect the meaning of the sectors as presented by the 5SEnSU model. According to Joung et al. (2012), criteria in choosing indicators could include: (a) measurable: the indicator value can be obtained by experimentation; can be calculated from the values of related indicators; or can be calculated using inventory data; (b) relevant: the indicator is relevant to the system under study; (c) understandable: the indicator can be easily communicated and understood by different stakeholders with varying technical backgrounds; (d) reliable/usable: the indicator definition is not arbitrary and its value can be obtained from a reliable methodology; (e) data accessible: the data should be accessible or can be made available for indicators that need inventory data to derive their values; (f) long-term oriented: the indicator stays relevant for future applications.

2.3. Stage 3 ("CHECK"): quantifying sustainability

Since the SUAPRO is a multimetric-based approach, indicators with different units and magnitude must be normalized to allow for comparisons, reducing redundancy and improving data integrity. Semantically, normalization is the process of bringing something to a normal condition or state. Under a mathematical and operational perspective, normalization (or feature scaling) is used to standardize the range of independent variables so that each variable can contribute or have similar influence on final results. There are several methods of data normalization (for instance, the linear or minimum-maximum normalization, mean

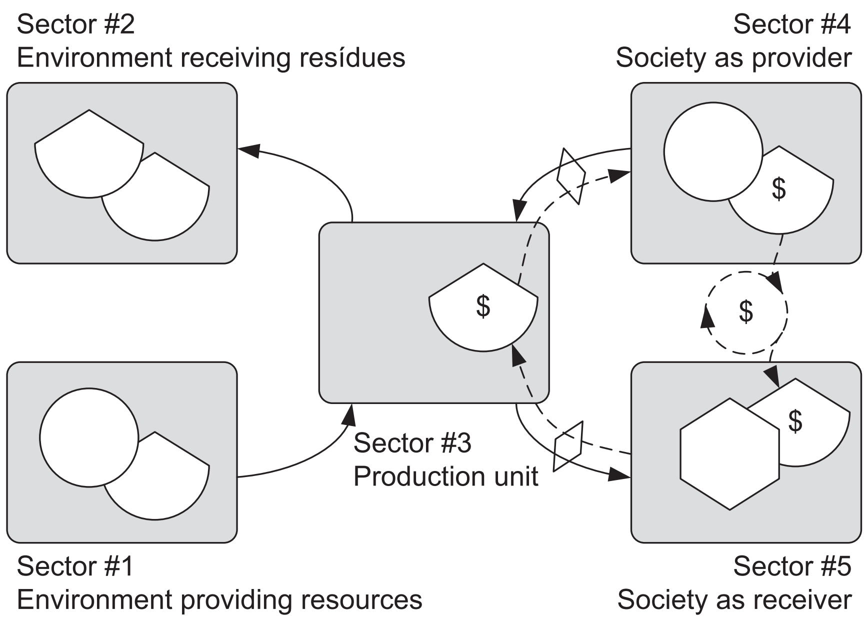

Fig. 3. Five-sector sustainability model (5SEnSU).
Source: Giannetti et al. (2019).

normalization, standardization, scaling to unit length or Euclidean length, and so on). The SUAPRO user can choose the approach he/she deems most appropriate in representing its data, but the choice must be clearly presented. Once normalized, all chosen indicators that feed the 5SEnSU model can be presented in a radar diagram. Indicators that mean to be maximized (i.e. higher is better) can be directly graphed, but for those indicators that mean to be minimized (i.e. lower is better), they must be reversed, which means multiplied by $1/(\text{indicator})^2$. In so doing, when comparing the performance among systems, the highest area presented by the radar diagram indicates higher sustainability performance. Whenever desired, the user can apply weights for indicators and/or sectors, which can be based on the expertise of the analyst, participative meetings, or governmental plans and reports. Appendix A provides an alternative approach in choosing weights for indicators and/or sectors based on the cultural perspective of the analyst, including egalitarian, hierarchical or individualist; the same approach is used in the well known Ecoindicator 99 (Goedkoop and Spriensma, 2000) calculation.

When the radar diagram provides similar areas, or when many systems are being evaluated at the same time, it becomes difficult to identify which one possesses the highest area. Additionally, perhaps the analyst would like to understand what system is closer to or farther from the predefined goals for each indicator, rather than taking a decision based on a simple comparative analysis. These characteristics claim for a multicriteria method to support an integration of indicators with different units, scales, and goals or thresholds. Among several options, the application of goal programming philosophy is recommended within the SUAPRO. The goal programming modelling is that as proposed by Giannetti et al. (2019), in which the main characteristics are here described. Consider:

$$ISG^{+}_{ijk} = \sum_{ijk} \frac{N^{+}_{ijk}}{W^{+}_{jk} \cdot G^{+}_{jk}} + \sum_{ijk} \frac{P^{+}_{ijk}}{W^{-}_{jk} \cdot G^{+}_{jk}} \quad (1)$$
$$\forall i \in \{1, 2, \dots, NE\} \forall j \in \{1, 2, \dots, NS\}, \forall k \in \{1, 2, \dots, NI\}$$

$$ISG^{-}_{ijk} = \sum_{ijk} \frac{N^{-}_{ijk}}{W^{-}_{jk} \cdot G^{-}_{jk}} + \sum_{ijk} \frac{P^{-}_{ijk}}{W^{+}_{jk} \cdot G^{-}_{jk}} \quad (2)$$

where: $\forall i \in \{1, 2, \dots, NE\} \forall j \in \{1, 2, \dots, NS\}, \forall k \in \{1, 2, \dots, NI\}$

ISG = index of sustainability goal of indicator;
N^{+}_{ijk} and N^{-}_{ijk} = positive and negative indicators for the negative deviation variables, respectively;
P^{+}_{ijk} and P^{-}_{ijk} = positive and negative indicators for the positive deviation variables, respectively;
G^{+}_{jk} and G^{-}_{jk} = goals for the positive or negative indicators;
W^{+}_{jk} and W^{-}_{jk} = the weight for each indicator;
NE, NS, and NI are the amount of evaluated systems, sectors, and indicators per sector, respectively;
i, *j*, and *k* represents the system being evaluated, the correspondent sector to the 5SEnSU model, and the indicator(s) for each sector, respectively.

The ISG is a measure of how far the indicator is from its goal, considering the chosen weight (or punishment). When added, the ISGs (Eqs. (1) and (2)) provide the sector sustainability indicator (SSI), representing the sum of the differences between the positive and negative deviations for each sector of 5SEnSU model:

$$SSI_{ij} = WS \sum_{ijk} \left(ISG^{+}_{ijk} - ISG^{-}_{ijk} \right) \quad (3)$$
$$\forall i \in \{1, 2, \dots, NE\}, \forall j \in \{1, 2, \dots, NS\}, \forall k \in \{1, 2, \dots, NI\}$$

where

WS = the weight established for each sector (usually equal to one since according to 5SEnSU model axioms, the idea is to obtain a balance among the five sectors).

Finally, the sustainability synthetic indicator of system (SSIS) can be obtained by adding the SSI (Eq. (3)) of each sector:

$$SSIS_i = \sum_{j}^{5} SSI_{ij} \qquad \forall i \in \{1, 2, \dots, NE\}, \forall j \in \{1, 2, \dots, NS\} \quad (4)$$

The SSIS represents the sustainability performance of the system by considering the relationship among indicators, their nature, objectives, and relative importance. As the SSIS considers the relative deviations to the targets (or goals) and their respective weights (or punishments), the lower the SSIS, the higher the system sustainability will be, which represents the shortest distance to the established target. All these equations were automatized into an Excel® spreadsheet (Supplementary material A) in order to facilitate calculations, simulations and verifications procedures; anyhow, the analyst is free to use any other programing language.

Considering all the uncertainties within any multicriteria method, mainly on the establishment of weights that carry some degree of subjectivity, the use of an uncertainty analysis is suggested; De Luca et al. (2017) and Millward-Hopkins et al. (2018) also recognize uncertainty analysis as an important step in any sustainability assessment. Among those available in the scientific literature, the Monte Carlo stochastic approach method is the one recommended for the SUAPRO users. The Monte Carlo simulation is performed by means of an Excel® add-in (Barreto and Howland, 2006) by randomly varying the weights (or punishments) within a range as previously established (i.e. the minimum e maximum value for weights), assuming a triangular probabilistic distribution function under 10,000 interactions; a similar procedure was previously used by Agostinho et al. (2014). The establishment of a range for weight values follows the same criteria as previously described when choosing indicators and goals. As a result, the mean value of SSIS for each evaluated system and its correlated uncertainties is obtained.

2.4. Stage 4 ("ACT"): proposing improvements

As a final part of PDCA four-step management method, improvements are proposed through the identification of those aspects with lower performance from the diagnosis phase. SUAPRO allows two different approaches in proposing improvements: (a) when the analyst decides not to use goal programming, proposals can be raised by directly reading the radar diagram; (b) when the analyst decides to use goal programming, a sensitivity analysis can be performed. While the former is a fast and simpler approach, it does not allow for quantifying the needed changes for an optimized result, instead, it allows for choosing which indicator should be improved. On the other hand, applying a sensitivity analysis allows to understand not only which indicator should be focused on, but also how much indicators should be improved for an optimized result; De Luca et al. (2017) and Millward-Hopkins et al. (2018) also recognize sensitivity analysis as important in any sustainability assessment. A sensitivity analysis is a statistical method that studies how the variation of inputs influences the value of the output (Duprez et al., 2019). Specifically for the SUAPRO, the sensitivity analysis is used to measure how different values of an independent variable (i.e. indicators feeding the 5SEnSU) affect a particular dependent value (i.e. the SSIS) by decreasing or increasing the indicators' value in percentage units. From this approach, a hierarchy of actions can be provided to support decisions makers, indicating which indicators should be focused on and to which extent.

Fig. 4 shows a schematic flowchart to allow for a faster and better understanding of SUAPRO's practical phases, each one as previously presented by the PDCA of Fig. 1. It can be observed that, while the procedures of stages 1 and 2 are mandatory, stage 3 provides alternatives for the analyst who decides whether goal programming and uncertainty analysis are necessary steps in the study. When the goal programming deemed unnecessary, indicators are normalized, presented in a radar diagram, and used to support decisions. In this case, indicators of sustainability are not calculated, so discussions and interpretations are based exclusively on the radar graph. When goal programming is deemed necessary, a subsequent uncertainty analysis can be applied, and then a sensitivity analysis is performed to provide detailed suggestions to the decision makers towards higher degrees of sustainability for the evaluated systems.

3. Applying SUAPRO in an illustrative case study: comparing road and railroad options for soybean transportation in Brazil

3.1. Evaluation context (stage 1)

According to IBGE (2014), the main soybean producers in Brazil are Mato Grosso, Paraná, and Rio Grande do Sul states, which account for 65% of the national production altogether. Mato Grosso plays an important role because it accounts for 30% of Brazilian production, and this production is concentrated in fourteen municipalities that are focused herein and named as producer regions. The established boundaries for this study include the transportation of soybean from the producer region to the international port located in Santos city, where soybean is exported mainly to China and Europe. All inputs of mass and energy are accounted for in the inventory phase, including construction (or indirect resources) and operation (or direct resources) phases. From the producer region (origin) to Santos port (destination), soybean can be transported by two main options: (a) road and/or (b) railroad (Fig. 5). While for the road option the soybean is transported exclusively by trucks, for the railroad option trucks are considered for the initial part of the total distance (534 km), then soybeans are transshipped to wagons in the Rondonópolis train terminal and proceeds by railroad (1446 km) to the Santos port. Data for soybean transportation logistics come from the Brazilian National Land Transport Agency (ANTT, 2018).

The goal of this case study is to assess which soybean transportation option has higher sustainability, as well as where efforts should be applied by means of private or public policies towards higher degrees of sustainability. The main stakeholders identified as closely related to this case study are private companies and the general society represented by their governors. While the former could use this diagnostic to provide more sustainable service and obtain its resulting advantages (i.e. financial, advertising, etc.), the latter could use the results towards scientifically based policy on sustainable transportation. Considering that soybean transportation is the core of this case study, the most appropriate functional unit that fits in the main objective is mass of soybean transported per a defined distance, precisely, all data will be presented in a ton.km basis.

Fig. 6 presents the energy diagram of road and railroad soybean transportation options, which can be understood as a conceptual model of the evaluated systems. Since both evaluated systems represent soybean transportation and differences are slightly perceived, they were diagramed simultaneously. The main differences are in the quantity of the resources demanded by both, as well as in the addition of an internal process for soybean transshipment in the grains terminal when railroad is the option utilized. Both demand resources from the natural environment (mainly superficial area accounted as a potential loss for agricultural production) and from the larger economy, as well as labor hours. As the output, the service of transportation is made available for both options.

3.2. Choosing indicators to feed the 5SEnSU model (stage 2)

Instead of using a participatory approach in choosing indicators to feed the 5SEnSU model, we have considered our own expertise as well as some suggestions provided by Brazilian governmental reports and related scientific papers on transportation systems; indicators are presented in Table 1 and refereed to the "ton km" functional unit. Two indicators for each sector of 5SEnSU were chosen to keep a balance among them as suggested by model axioms, as well as due to their representativeness in indicating sustainability of transporting systems according to most of the published scientific papers and reports on the theme.

The choice of indicators must respect the meaning of each sector as represented by the 5SEnSU model. Fig. 7 shows the relationship of the chosen indicators with the economic (sector 3), social (sectors 4 and 5) and environmental (sectors 1 and 2) capitals. Emergy represents all

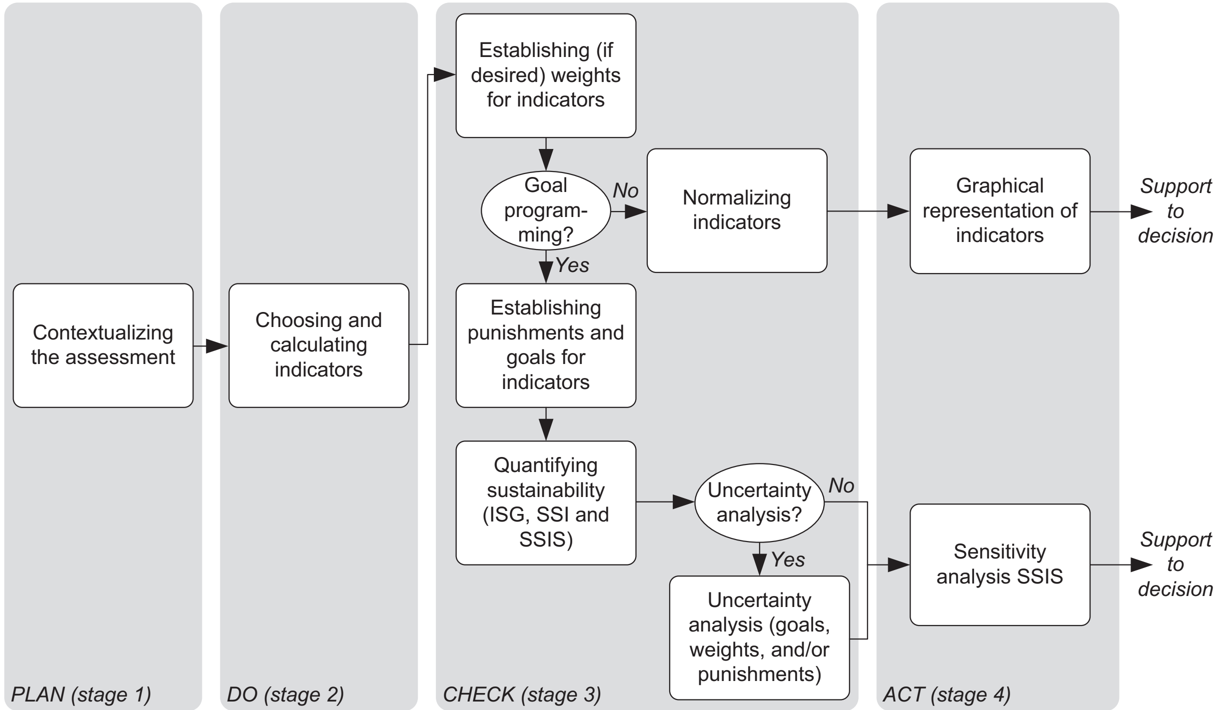

Fig. 4. Schematic flowchart representing the steps of the proposed sustainability assessment procedure.

direct and indirect resources demanded by system from a donor side perspective with the natural environment providing resources; thus, it is located in the output of natural capital storage. Emergy was chosen because it includes the hidden costs (Agostinho and Siche, 2014) usually not considered in other accounting tools, also because it has been labelled as a robust environmental accounting tool (Giannetti et al., 2013). Area of influence negatively affects the generation of natural capital, since the superficial area, mostly occupied with natural vegetation, is replaced by road and rail infrastructure. Besides society, global warming potential and acidification potential affect the environment as a sink to dilute/absorb their related pollutants. Revenue and profit are, as usual, important indicators to represent the financial performance of antrophic productive systems. Formal jobs and salary are both extremely important for society, while the former guarantees all the benefits for an employee (an additional annual salary, health insurance, formal vacations, insurance for retirement, etc.), the latter allows for access to materials and energy for a good life standard of families. Finally, society is affected negatively by carbon oxide emissions that can cause serious respiratory health issues, as well as traffic accidents.

3.3. Quantifying sustainability (stage 3)

For this study, all indicators are considered as equally important in the 5SEnSU to represent sustainability, that is, all indicators were set as weight equal to one. In so doing, all chosen indicators were normalized with reference to the total impact generated, and represented in a radar graph (Fig. 8). As established by the SUAPRO framework, the larger area in the radar diagram represents higher sustainability, which can be observed for the railroad transportation option. While the road option has a better performance, under a comparative basis, for emergy and carrier revenue, the railroad option has a better performance for area of influence, global warming potential, carrier profit per employee and traffic accidents, supporting this option as the most sustainable between them; a similar performance is perceived for the four other indicators.

The analysis can be finished with the use of radar diagram to support decision, according to analyst's goals and as allowed by SUAPRO framework (Fig. 4). However, the use of goal programming is frequently requested, since it allows for the application of punishments on chosen

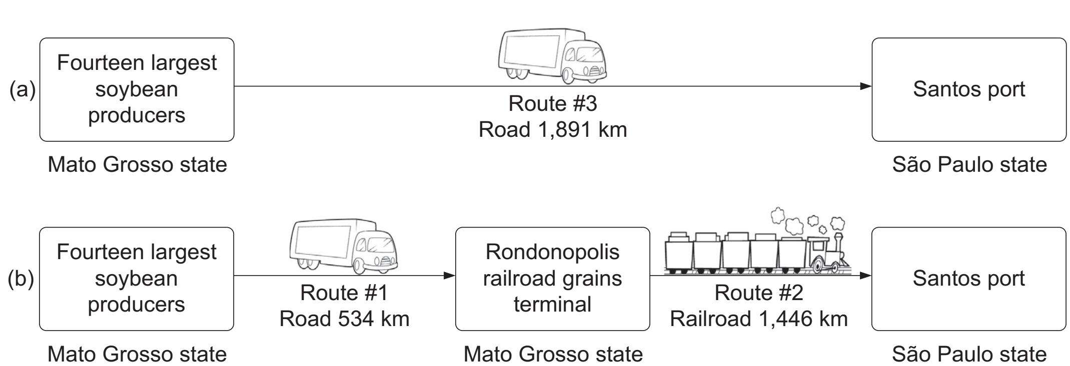

Fig. 5. Road (a) versus railroad (b) options to transport Brazilian soybean from main producers in the Mato Grosso state to Santos port for exportation.

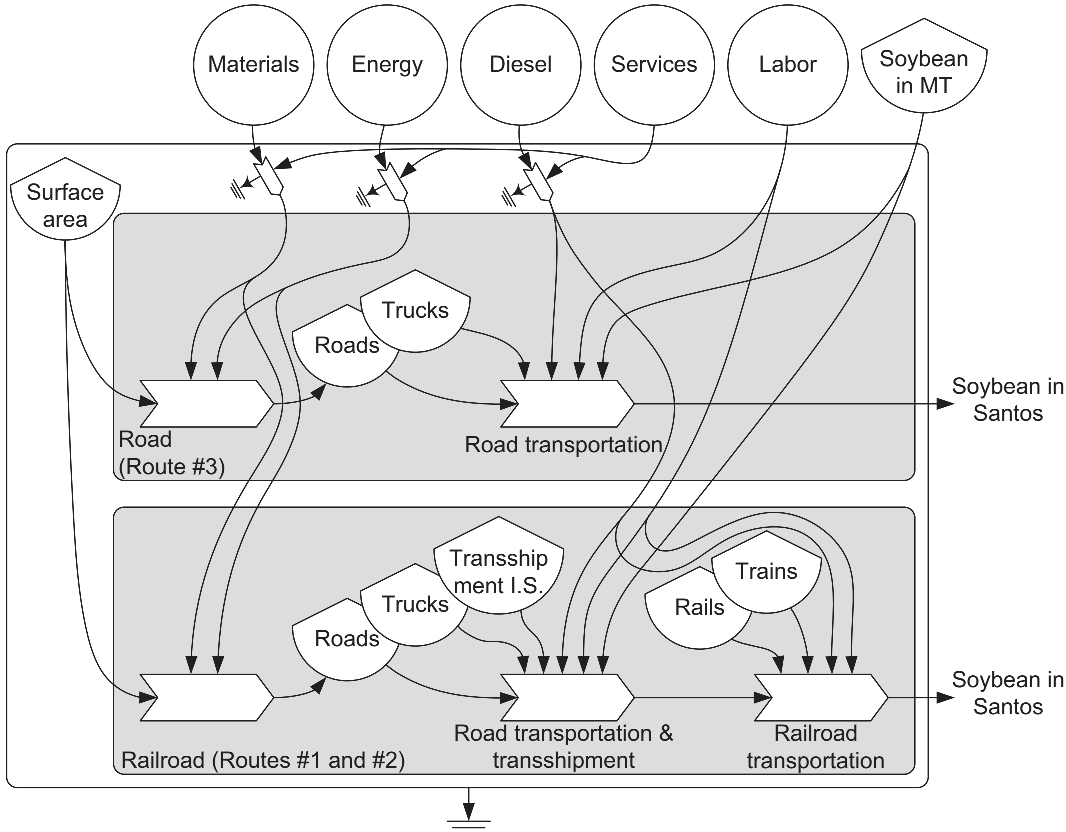

Fig. 6. Energy diagram of road and railroad soybean transportation options in Brazil. Legend: MT = Mato Grosso state; I.S. = Infrastructure.

indicators (according to their distance to goals) as well as for obtaining a final and aggregated numeric indicator expressing the sustainability for the evaluated systems, the SSIS. To apply the philosophy of goal programming within SUAPRO, the first step is defining the goals (or targets) for each chosen indicator (Table 2). For this case study, we have set the goals as the minimum or maximum values of each indicator, according to their ultimate objective of maximization or minimization; at this point, other approaches could be considered in setting goals as participative meetings, scientific or governmental reports, or even the thresholds (when existing) for each indicator.

By feeding the equations that support the goal programming philosophy (Excel® spreadsheet, Supplementary material A) with data from Tables 1 and 2 under an egalitarian cultural perspective of analyst (Appendix A) in setting punishments for indicators, the index of sustainability goal of indicator (ISG), sector sustainability indicator (SSI), and sustainability synthetic indicator of system (SSIS) are obtained (Table 3). Since there are two systems being evaluated (road and railroad) in this case study, and the established goals were settled as the minimum or maximum value of the chosen indicators, the resulting ISG of one system will be always equal to zero, indicating this value as exactly matching the goal. For example, while the K11 indicator shows ISG value of 0.00 for the road system, for the railroad system its value is 9.02, a weighted deviation to the established goal for K11. Table 3 shows that the highest differences among the ISGs are related to emergy (K11), global warming potential (K21), area of influence (K12) and traffic accidents (K52), respectively. This characteristic directly reflects on the differences among sectors (SSI) since sector 1 that contains the emergy indicator has the highest difference between both systems, followed by sectors 5 and 2. Finally, the resulting SSIS of 7.46 for road and 9.74 for railroad indicates road as the most sustainable option for transporting soybean in Brazil.

According to the procedures within SUAPRO, the analyst can, at this point, apply the uncertainty analysis. For this, according to the stochastic method suggested, the establishment of a range of values to assess their uncertainties is mandatory. For this specific case study, the uncertainties are related exclusively to the weights (or punishments) applied to indicators; when more data become available, the uncertainty analysis can also be applied for the established goals. We have based our assumption on the Ecoindicator 99 (Goedkoop and Spriensma, 2000) for an egalitarian cultural perspective of the analyst as presented on Appendix A, and thus the used weights are considered as a source of uncertainty within our Monte Carlo simulation. The weights for the "wanted deviation" (W_{jk}^{+}), were based on Ecoindicator 99, while the weights for the "unwanted deviations" (W_{jk}^{-}) were assumed and are presented in Table 4. It is important to note that, according to Eqs. (1) and (2) of our model, the lower the weights the higher the performance, as weights are in the denominator of both equations. Running the model again, but this time considering the uncertainties on the unwanted deviations, the resulted distribution curve of Fig. 9 indicates an

Table 1
5SEnSU-based indicators chosen to evaluate the sustainability of road and railroad options for soybean transportation in Brazil.

Sector	Indicator	Unit/ton km	Road system	Railroad system
S1	K11, Emergy[a]	sej	4.80 E+05	48.1 E+05
S1	K12, Area of influence	m^2	37.34	12.25
S2	K21, Global warming potential	$kgCO_{2eq}$	1222.91	383.84
S2	K22, Acidification potential	$kgSO_{2eq}$	1.08 E−03	1.27 E−03
S3	K31, Carrier revenue	R$	1270.56	585.68
S3	K32, Carrier profit per employee	R$	1.41	5.84
S4	K41, Formal jobs	jobs	0.09	0.10
S4	K42, Paid salary	R$	1825.58	2146.05
S5	K51, CO emissions	kgCO	7.45 E−01	6.10 E−01
S5	K52, Traffic accidents	accidents	1.26	0.42

R$ means "Reais", the Brazilian currency.
[a] Details on emergy synthesis are available at Supplementary materials B–E.

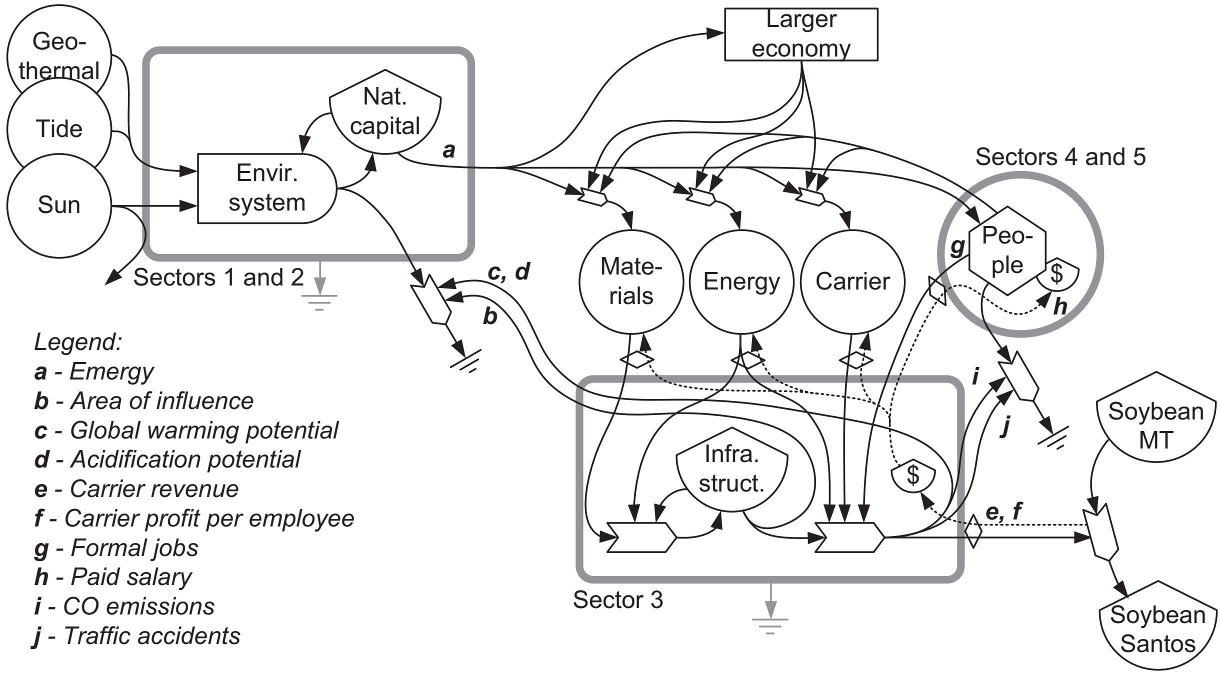

Fig. 7. Energy diagram representing the chosen 5SEnSU-based indicators and their relation with the economic, social and environmental capitals.

average value of 3.6 for the SSIS of railroad transportation option, while the road option obtained an average SSIS of 4.0. This result goes in the opposite direction, when compared to the previous SSIS obtained, since now the railroad possesses a higher degree of sustainability than the road option. This behavior was expected, mainly because the indicator emergy (K11) was the one with the largest difference between systems (reaching an ISG of 9.02 for railroad; Table 3) and, when considering the uncertainties on weights, the punishment for the emergy indicator for railroad renders its ISG closer to road transportation, which has an influence on the SSISs. At this point it is important to bear in mind the subjectivity involved during the establishment of weights inherent in any multicriteria decision analysis (MCDA), as according to Butchart-Kuhlmann et al. (2018), weighting is a perennial issue in MCDA with no correct answer, since the simple process of weight elicitation requires numerous subjective decisions. According to the uncertainties considered in this analysis, Fig. 9 shows the existence of a range of values for SSIS between 3.7 and 4.0 (with 95% of confidence) that indicates similar performance for the sustainability of both systems.

3.4. Improvements proposal (stage 4)

Stage 4 formally finalizes the PDCA cycle of SUAPRO before starting the next one. At this stage, the sensitivity analysis is performed to, after identifying which indicators should be focused on towards improvements on the system's SSIS, obtain the amount of necessary improvement. This stage in fundamental for decision makers, once they must be supplied with simple and easy-to-understand information to make a decision.

Among several alternatives and their accuracies in applying a sensitivity analysis, the scope of this case study allows for working with every five values in percentage for all the ten indicators considered. In other words, each indicator was evaluated individually by considering an increase or reduction (depending on the objective of indicator) with

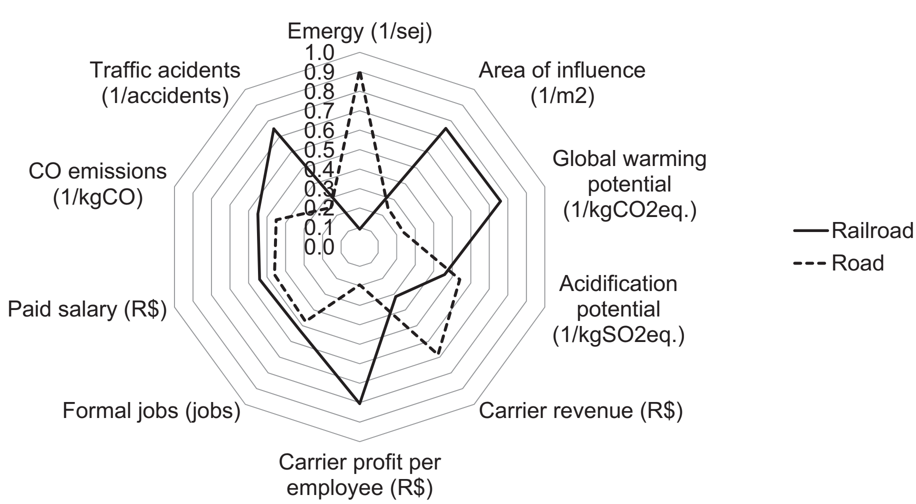

Fig. 8. Radar graph showing the performance of road and railroad options for soybean transportation in Brazil. Indicators presented in Table 1 were normalized with reference to the total impact generated. All numbers are in units per ton km.

Table 2
Goals for indicators feeding the 5SEnSU model applied to rail and railroad options for soybean transportation in Brazil.

Sector	Indicator	Objective	Goal
S1	K11, Emergy	Minimize	4.80 E+5 sej
	K12, Area of influence	Minimize	12.25 m^2
S2	K21, Global warming potential	Minimize	383.84 $kgCO_{2eq.}$
	K22, Acidification potential	Minimize	1.08 E−03 $kgSO_{2eq.}$
S3	K31, Carrier revenue	Maximize	1270.56 R$
	K32, Carrier profit per employee	Maximize	5.84 R$
S4	K41, Formal jobs	Maximize	0.10 jobs
	K42, Paid salary	Maximize	2146.05 R$
S5	K51, CO emissions	Minimize	6.10 E−01 kgCO
	K52, Traffic accidents	Minimize	0.42 accidents

R$ means “Reais”, the Brazilian currency.

every 5%, and then its influence on the final SSIS was verified. Considering the road transportation system, Table 5 shows the hierarchy of actions suggested to decisors, in which global warming potential and traffic accidents stand out and demand a reduction in 30% from their original value to reach an absolute improvement of 0.95 and 0.90 on road's SSIS, respectively. For CO emissions, paid salary, formal jobs and carrier profit per employee, when added, they can achieve a total reduction of 0.54 in the SSIS. Considering the railroad transportation system, Table 5 indicates that a reduction of 30% on the original value of emergy demand will result in a reduction of 3.01 in the railroad's SSIS, meaning higher sustainability. Focusing on the acidification potential (15% reduction) and carrier revenue (30% of increase) would result, together, in a SSIS reduction of 0.32. In short, while efforts should be directed to reduce global warming potential and traffic accidents for the road transportation system, a reduction of emergy demand should be focused for railroad system.

4. Concluding remarks

This work proposed the sustainability assessment procedure for operations and production processes (SUAPRO) with the ultimate goal of overcome the lack of a complete framework to assess sustainability in the scientific literature. A huge amount of research papers that focused on sustainability assessment are available in the literature, however, most of them fail to supply an appropriate construct for the meaning of sustainability when applying metrics and calculating indicators. For example, while some researchers estimate the system's CO_2 emissions and discuss about its sustainability, others calculate economic indicators or even environmental based ones (i.e. ecological footprint, emergy accounting, embodied energy, among others) to also discuss about its sustainability; this raises doubts about the constructs supporting their choices and conclusions. There is no scientific inconsistency at all in choosing metrics and indicators, but at least the semantical meaning of sustainability they are able to embrace must be clearly presented. With this in mind, we proposed the SUAPRO as an alternative in quantifying and discussing about the sustainability of operations and production processes. Its main advantages can be itemized as follows:

(i) SUAPRO framework is based on the standardized, well-known, and worldwide accepted stages of life cycle assessment, which is supported by the PDCA four-step management method (plan, do, check and act), recognized as important in the decision making process. This means that, besides providing a diagnosis of the evaluated operations and production processes, SUAPRO also supports the management or decision step, considered as fundamental for actions in practice.

(ii) The 5SEnSU conceptual model of sustainability is the backbone of SUAPRO and, differently from other sustainability conceptual models, it considers the receiver and provider perspectives of social and environmental capitals. As described by Giannetti et al. (2019), the 5SEnSU model is based on a sustainability construct defined by its supporting axioms, additionally it grants the user a certain freedom in choosing indicators, goals and weights.

Table 3
Index of sustainability goal of indicator (ISG), sector sustainability indicator (SSI) and sustainability synthetic indicator of system (SSIS) for road and railroad options of soybean transportation in Brazil.

Indicator by sector	Road			Railroad		
	ISG	SSI	SSIS	ISG	SSI	SSIS
Sector 1	–	2.05	–	–	9.02	–
K11, Emergy	0.00	–	–	9.02	–	–
K12, Area of influence	2.05	–	–	0.00	–	–
Sector 2	–	2.19	–	–	0.17	–
K21, Global warming potential	2.19	–	–	0.00	–	–
K22, Acidification potential	0.00	–	–	0.17	–	–
Sector 3	–	0.76	–	–	0.54	–
K31, Carrier revenue	0.00	–	–	0.54	–	–
K32, Carrier profit per employee	0.76	–	–	0.00	–	–
Sector 4	–	0.25	–	–	0.00	–
K41, Formal jobs	0.10	–	–	0.00	–	–
K42, Paid salary	0.15	–	–	0.00	–	–
Sector 5	–	2.22	–	–	0.00	–
K51, CO emissions	0.22	–	–	0.00	–	–
K52, Traffic accidents	2.00	–	–	0.00	–	–
Global	–	–	7.46	–	–	9.74

An egalitarian analyst's cultural perspective is used for estimating punishments for indicators: 2.7 for social, 4.5 for environmental and 1.8 for the economic capital (Appendix A).

Table 4
Range of weighting values, under an egalitarian analyst's cultural perspective, considered for the Monte Carlo simulation.

Sector	Indicator	Unwanted deviation		Wanted deviation	
		Direction	Weight interval	Direction	Fixed weight
S1	K11, Emergy	Positive	2.5 to 3.5	Negative	4.5
	K12, Area of influence	Positive	2.5 to 3.5	Negative	4.5
S2	K21, Global warming potential	Positive	2.5 to 3.5	Negative	4.5
	K22, Acidification potential	Positive	2.5 to 3.5	Negative	4.5
S3	K31, Carrier revenue	Negative	1.0	Positive	1.8
	K32, Carrier profit per employee	Negative	1.0	Positive	1.8
S4	K41, Formal jobs	Negative	1.0 to 1.7	Positive	2.7
	K42, Paid salary	Negative	1.0 to 1.7	Positive	2.7
S5	K51, CO emissions	Positive	1.0 to 1.7	Negative	2.7
	K52, Traffic accidents	Positive	1.0 to 1.7	Negative	2.7

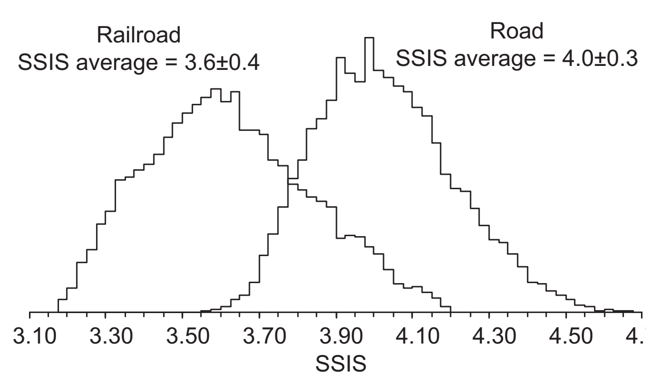

Fig. 9. Uncertainty analysis (95% of confidence) of SSIS calculated to road and railroad transportation systems. Monte Carlo analysis considering 10,000 repetitions under a triangular probabilistic distribution function. Railroad: average 3.62, standard deviation 0.21. Road: average 4.03, standard deviation 0.18. Uncertainty = average ± 1.96 ∗ standard deviation.

Table 5
Proposed action to increase the sustainability synthetic indicator of system (SSIS) for the road and railroad transportation options.

Hierarchy for actions	Indicator	Variation (in %) from the original value of each indicator	Action for improvement	Absolute improvement for the SSIS from its original value
Road transportation system				
1st	Global warming potential	−30	Reduction	0.95
2nd	Traffic accidents	−30	Reduction	0.90
3rd	CO emissions	−20	Reduction	0.22
4th	Paid salary	+20	Increase	0.15
5th	Formal jobs	+15	Increase	0.10
6th	Carrier profit per employee	+30	Increase	0.07
Railroad transportation system				
1st	Emergy	−30	Reduction	3.01
2nd	Acidification potential	−15	Reduction	0.18
3rd	Carrier revenue	+30	Increase	0.14

Complete numbers of sensitivity analysis is available at Supplementary material F. The indicator Area of influence is not considered in this sensitivity analysis because, since it is a fixed and standardized value by the Brazilian governmental offices, the decisor is unable to apply efforts in reducing the area of influence.

(iii) As a multimetric framework due to the use of 5SEnSU model, SUAPRO supports the use of goal programming philosophy as a multicriteria method in integrating the many different existing indicators and units to achieve the sectorial or global aggregated sustainability index. Using the philosophy of goal programing allows for easier procedures and lower time demanding than the regular goal programming approach, and it allows for obtaining a satisfactory result rather than, mandatorily, the optimized one.
(iv) Uncertainty and sensitivity analysis are within the SUAPRO, which allows for obtaining results that are more precise as well as pointing out where the main actions must be directed to, to achieve higher efficacy towards higher sustainability degrees for the evaluated operations and production processes.

The main SUAPRO disadvantage or limitation is related to its existing inherent subjectivity, as found in all multicriteria approaches. This subjectivity is present during the step of choosing goals and weights for indicators to feed the 5SEnSU model. As an alternative in reducing such subjectivity, the use of non-parametric statistical tools (like the Delphi) is recommended, to support the establishment of goals and weights. Additionally, further efforts are still needed towards evaluating the SUAPRO quality in representing sustainability, for instance, by using the same approach as discussed by Sala et al. (2015) in which seven criteria based on the Bellagio Principles are proposed, including boundary-orientedness, comprehensiveness, integratedness, stakeholder's involvement, scalability, strategicness, and transparency.

Focusing on the application of SUAPRO to assess the road and railroad options for soybean transportation in Brazil, both systems can be analyzed under three different approaches (represented in Fig. 4) as allowed by the SUAPRO's framework:

(i) When the use of goal programming is deemed not necessary by the analyst, the chosen indicators feeding the 5SEnSU model can be simply normalized and showed in a radar graph. In this case, Fig. 8 shows that while the railroad option has visibly higher performances for some indicators (area of influence, global warming potential, carrier profit per employee, and traffic accidents), the road option has higher performances for others (emergy, and carrier revenue). For all other indicators, both railroad and road obtained similar performance. The highest area in the radar diagram indicates railroad as the most sustainable one to transport soybean in Brazil for exportation.
(ii) Assuming that the use of goal programming is an important step to support decisions, the obtained results are quite different (Table 3), because the road transportation option obtained a sustainability synthetic indicator (SSIS) of 7.46, a value considered better than the SSIS for railroad (9.74) since it is closer to the previously defined goals; higher SSIS means worse sustainability. When analyzed sector by sector, the railroad obtained low performance for the sector #1 (SSI of 9.02), mainly for the emergy indicator, while it obtained a better performance for all other sectors.
(iii) Considering that goal programming together with an uncertainty analysis is deemed important by the analyst, Fig. 9 indicates that railroad has higher sustainability (SSIS of 3.6 ± 0.4) than road (SSIS of 4.0 ± 0.3), although the existing uncertainties highlight a region (from 3.7 to 4.0, approximately) in which both transportation options have similar SSIS performance.

Another important characteristic of the proposed SUAPRO is the use of sensibility analysis on its stage 4 to support decisions that are more efficient, i.e. it points out where efforts must be focused on to bring larger improvements. For the railroad transportation option, the hierarchical sequence for actions must be reducing the emergy demand by 30% and acidification potential in 15%, as well increasing carrier revenue in 30%. For the road option, the top three actions should be reducing global warming potential in 30%, traffic accidents in 30%, and CO emissions in 20%. After identifying where and by how much indicators must be reduced or increased, the next step is finding ways to achieve such objectives. Perhaps it is not possible to achieve one objective or another due to practical barriers including political, cultural, economic, social, or even environmental ones, in this case, efforts must be applied on the subsequent indicator as identified by the sensibility analysis.

It is important to emphasize that, as established by the usual PDCA four-step management method (plan, do, check and act), the continuous improvement is the main goal that makes necessary a continuous application of SUAPRO in subsequent cycles in the operations and production processes evaluated. During the first cycles, the identified potential improvements can bring faster increase in the SSIS, but after running several cycles, it is expected that SSIS does not change substantially, which is an indicative of the maximum efficiency obtained for the evaluated operations and production processes.

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Appendix A. Alternative approach in choosing weights for indicators, sectors and/or punishments to be used within SUAPRO

This alternative approach is based on both, the judgment scale as proposed by Saaty (2001) when dealing with multicriteria tools, and the analogy (Table A.1) among the categories of Eco-Indicator 99 (Goedkoop and Spriensma, 2000) with the economic, social and environmental capitals of the sustainability conceptual model as proposed by Oliveira et al. (2016).

Table A.1
Percentages by category and criterion.
Source: Oliveira et al. (2016).

Analyst's cultural perspective		Categories		
		Human health	Ecosystem quality	Reserves
Egalitarian	Reserves cannot be controlled, but wishes can (substituting reserves for alternatives).	30%	50%	20%
Hierarchical	Wishes or needs cannot be controlled, but reserves can.	40%	40%	20%
Individualist	The exhaustion of fossil fuels is not perceived as an actual problem, but the decrease in mineral resources is.	55%	25%	20%

Saaty (2001) suggests the use of a judgment scale of weights ranging from 1 to 9, where 1 is set when both elements being compared are of equal importance, 3 when there is moderate importance of one element over another, 5 when there is a strong importance of one element over the other, 7 when there is very strong importance of one element over the other, and 9 when there is extreme importance of one element over the other. Considering that in the concept of strong sustainability the social and economic capitals have limited growth according to the biophysical limits of biosphere, we assumed here the Saaty's (2001) weight of 9, since one element (or capital in this case) has extreme importance over the others. Considering now the percentages of Table A.1, the suggested weights for indicators, sectors and/or punishments to be used within SUAPRO are presented in Table A.2.

Table A.2
Suggested weights to be used within SUAPRO.

Analyst's cultural perspective	Weights		
	Social sector	Environmental sector	Economic sector
Egalitarian	2.7 (=9 * 30%)	4.5 (=9 * 50%)	1.8 (=9 * 20%)
Hierarchical	3.6 (=9 * 40%)	3.6 (=9 * 40%)	1.8 (=9 * 20%)
Individualist	4.9 (=9 * 55%)	2.3 (=9 * 25%)	1.8 (=9 * 20%)

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