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# The world economy in a cube: A more rational structural representation of sustainability

Federico M. Pulselli [a,*], Luca Coscieme [b], Laura Neri [c], Andrea Regoli [d], Paul C. Sutton [e,f], Achille Lemmi [c], Simone Bastianoni [a]

[a] Ecodynamics Group, Department of Earth, Environmental and Physical Sciences, University of Siena, Pian dei Mantellini 44, 53100 Siena, Italy
[b] Department of Zoology, School of Natural Sciences, Trinity College, University of Dublin, College Green, Dublin 2, Ireland
[c] Department of Economics & Statistics, University of Siena, Piazza San Francesco 7, 53100 Siena, Italy
[d] Department of Business and Quantitative Studies, University of Naples "Parthenope", Via Generale Parisi 13, 80132 Naples, Italy
[e] Department of Geography and the Environment, University of Denver, 2199 S. University Blvd, Denver, CO 80208, United States
[f] School of Natural and Built Environments, University of South Australia, Mawson Lakes Campus, Adelaide, SA 5095, Australia

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ABSTRACT

National economic systems are investigated in a 3-axis diagram where three different indicators are used to account for resource use, societal organization, and goods and services produced, respectively. This framework is consistent with an input-state-output (environment–society–economy) scheme based on a logical, physical and thermodynamic order between the three dimensions of sustainability. This approach highlights which input-state-output relations are realized and which relations are less common in the behavior of these systems. It assesses and overcomes major drawbacks of common representations of sustainability. Within a cube diagram, 99 national economies are ranked and grouped into 8 categories, which are labeled to reflect the main characteristics of their behavior according to the three environmental, social and economic parameters. A cluster analysis is also performed in order to statistically support the classification and strengthen the interpretation of results. Results show that no countries exhibit a dematerialization of economic activity and that non-sustainable economic activity can take place over a wide range of income distributions (Gini coefficients).



## 1. Introduction

Sustainable development can be viewed as a process of "interaction among three elements: the biological and resource system, the economic system, and the social system" (Barbier, 1987). A common representation of sustainability is that of three intersecting circles defined using these three dimensions (e.g. environmental, social, and economic). The intersection of the three circles is where sustainable development is realized. This representation supports the idea that sustainability must consider the goals of economic and social activity, together with environmental conservation. However this representation has two main weaknesses: (1) it does not include the temporal dimension of sustainability as intended by the Brundtland Commission "*Our Common Future*" Report (UN-WCED, 1987); (2) this framework, except in the very central area where all the sustainability requirements are satisfied, leads to consider the ecological, social and economic elements of sustainability as interchangeable or substitutable. The three circles representation consequently allows trade-offs between sustainability dimensions and allows reductions in the contribution of one dimension in order to improve the contribution of another. This substitutability between the environmental, social, and economic dimensions is often regarded as "weak" sustainability.

This classical viewpoint on sustainability inspired approaches based on a large number of juxtaposed indicators to monitor the development of countries, or systems in general (e.g. the Millennium Development Goals indicators – UN, 2000; the System of Integrated Environmental and Economic Accounting (SEEA) – UN, EC, IMF, and World Bank, 2003; the EU Strategy for Sustainable Development indicators – Eurostat, 2013, 2014). In a set of tens or hundreds of ecological, social and economic indicators, bad or low values of some can be compensated by very good or high values of others. Furthermore, the interactions between different indicators are not accounted for. For example, Costanza et al. (2014) highlight the interconnection "between built, social, human and natural

* Corresponding author.
*E-mail address:* fpulselli@unisi.it (F.M. Pulselli).

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capital required to produce human well-being", with a particular emphasis on the role of ecosystem services (MA, 2005). The supposed substitutability among these forms of capital is a problem that may create legitimate confusion which undermines the effectiveness of Sustainability Agendas (UN-SDSN, 2014) and Development Goals (French, 2005), as well as other tools for policy makers (Dessai et al., 2013; Glaser, 2012; Payne and Raiborn, 2001).

The use of a multidimensional representation is thus necessary, but the information embodied in a large number of different indicators has to be synthesized or represented in an easily readable form to be effective (e.g. in a sustainability index and/or in models). There is a tradeoff between the simplicity of single number indices and the detail in multi-variate metrics that attempt to characterize sustainability. Oversimplified indexes can hide serious issues associated with the fact that sustainability results from a suite of interacting variables. Nevertheless, keeping a large number of indicators completely separated often does not help the understanding of the overall sustainability/unsustainability of the system under study.

We suggest the adoption of a more logical/consequential approach for combining and evaluating different indicators in an environment–society–economy scheme, starting from the dependence of the economy on societal organization and environmental resources. An input-state-output framework will orient the use of a well-defined triad of systems indicators able to represent the interconnection of the three aspects of sustainability. In this way, the information gained by different indicators is not lost in final aggregations, instead it is maintained by keeping non-redundant indicators separated.

We claim that this approach can represent and monitor sustainability with a trade off that aims at maximizing information with the minimum numerosity of indicators: the information should be obtained by using indicators representative of the whole system; the numerosity is kept to the minimum to independently depict the three different dimensions of system sustainability, ensuring that every indicator maintains its identity, and complementary informative capacity. In addition, this approach allows for the relationships between different aspects of sustainability to be investigated by putting the environment, the society, and the economy in the proper relational order. We conducted a statistical analysis of a very rich nationally aggregated dataset which inspired a categorization of national economies worldwide. We believe this work will facilitate a basic representation of the nations of the world in a three-axis diagram that is proposed as a tool for static and dynamic investigations of sustainability, also usable for policy making.

## 2. The input-state-output (environment–society–economy) framework

A growing proportion of the scientific community recognizes that ecologic, social and economic elements of sustainability cannot be considered as interchangeable (Ostrom, 2009), and should be evaluated and represented in a holistic picture (Pulselli et al., 2008). This work strives for this holistic perspective that avoids the pitfalls of the 'Three Circles of Sustainability' approach. We have structured our representation of sustainability to consider the logical, physical, relational and thermodynamic order (i.e. environment–society–economy) that has been recognized by sustainability scholars (e.g. Costanza et al., 2014) and economists (e.g. Daly and Farley, 2003): "The linear flow of money and stuff is only a fragment of the larger real economy, embedded in human society. The economy and society are both embedded in the rest of nature. Without intact ecosystems and the services they provide us, neither can long survive" (Lovins et al., 2014).

Consider a three-storey pyramid to represent the mutual relationships among the three dimensions of sustainability (Fig. 1a). The base of the pyramid represents the natural assets, which form the crucial inputs to the system; the intermediate level

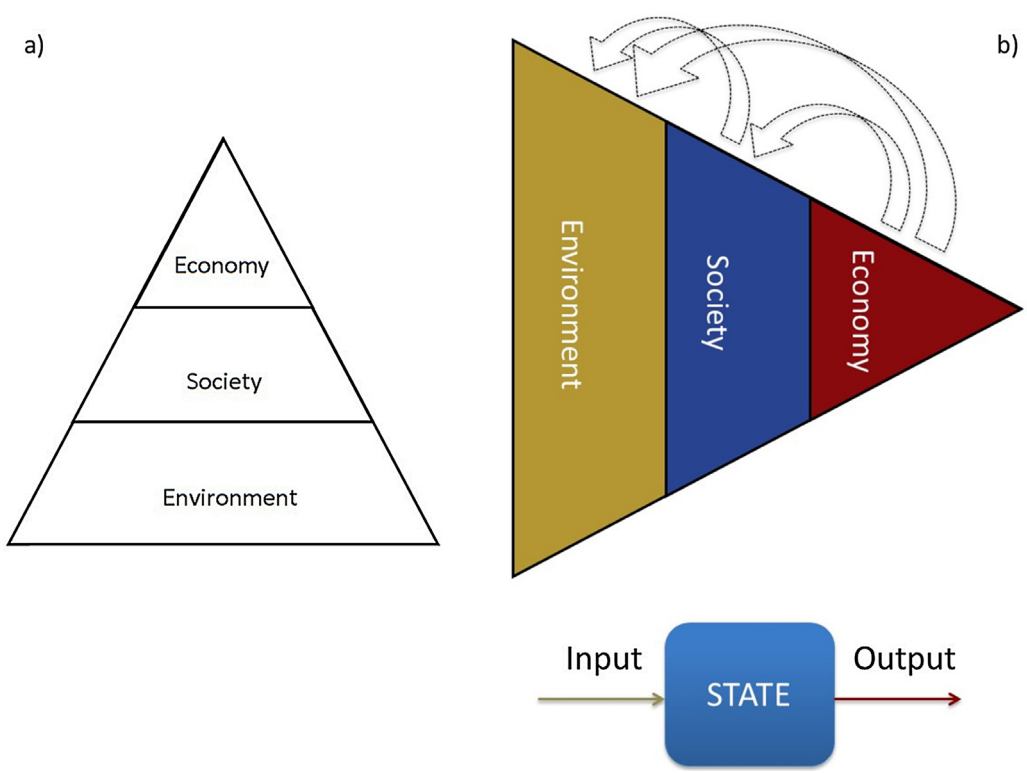



**Fig. 1.** A three-storey pyramid representation of sustainable development recognizes a relational and physical order of environment, society and economy. It resembles an input-state-output diagram to investigate economic systems. Feedbacks between compartments are also shown.

can be viewed as the state of the system, specifically the society and its organization and structure; the top level of the pyramid, is the real economy of the system, that should produce the "useful" output of the system. This picture can be considered an evolution of the three concentric circles representation, also used to integrate the environmental, social and economic components (for an overview, see Lozano, 2008).

Let us now rotate the pyramid clockwise and orient the succession of the stages (Fig. 1b): a flow of material and energy inputs, generated by the available stock of Natural Capital, feeds (is captured by) the system. These resources are necessary for the elements of the system (namely, the society and its organizational units) to operate (act, live, survive); the level of organization of the society influences the degree of utility/satisfaction derived from processing/using/consuming resources. An organized society is supposed to be able to achieve better economic results providing outputs from its productive processes. The pyramid can be actually and immediately translated into an input-state-output scheme (Fig. 1b). Here different combinations of indicators can be used to account for the energy and matter inputs to a system, describe the state organization, and quantify the outputs of the system.

This input-state-output framework, introduced by Coscieme et al. (2013) to characterize ecosystems, can be successfully applied to investigate economic systems (e.g. the national or the regional economies) regarding their level of sustainability (see also Pulselli et al., 2011; Coscieme et al., 2014). Several combinations of indicators can be adapted to this structure that supports the integration of different disciplinary approaches. In this case, the three dimensions are not simply juxtaposed, but the logical structure of the pyramid shows how the three compartments work together through relations, interactions, feedbacks, etc.

## 3. Methods

### 3.1. The indicators

The dominant interpretation of sustainability inspires approaches based on "single discipline" tools, long lists of indicators (e.g. Sustainable Development Goals), aggregated indexes (e.g. the Environmental Performance Index, the Human Development Index, among others) or systemic "umbrella" indicators (e.g. the Ecological Footprint). These approaches are useful to rank national systems, build charts, highlight best examples, and design and monitor possible policies toward sustainability. However, the choice of one of these approaches can be questioned because of different ability in representing the multidimensional aspects of sustainability.

As we believe that sustainability is a problem of relationships among compartments, we need an information framework that is able to identify and describe human activity and the physical, the social, and the economic contexts in which it develops. The use of analytical indicators makes sense for a closer look at critical points or single aspects of a system: in such cases, 'microscopic' monitoring of problems is essential. On the contrary, in our case, to encompass the characteristics of the whole system, synthetic indicators are needed: for instance, GDP is a proper measure to express the economic performance of a country using money as a common unit. We maintain that this logic should be followed also to choose the other indicators representative of the environmental and social dimensions. We have thus selected three indicators from systems approaches applied to three dimensions: the emergy flow per capita is used as an input-based indicator (Odum, 1988, 1996); the Gini index of income distribution is used as a descriptor of the organization of the state of the economic system; the Gross Domestic Product per capita (GDP) is used as a measure of the total economic output.

#### 3.1.1. Emergy flow per capita

The use of energy and matter resources by a national system can be accounted for by using the emergy methodology. Emergy accounts for the quantity of solar energy that has been directly or indirectly used to produce a flow or a product. Emergy (and the emergy flow, i.e. emergy per unit time), is defined as the equivalent amount of solar energy "memorized" in different types of energy and matter forms. It is expressed in solar emjoules (seJ) by using specific factors, the Unit Emergy Values (UEVs), to convert all kinds of energy and matter into the common basis of solar energy. The total emergy flow of the inputs to a given economic system expresses the convergence of different forms of resources times the quantity of equivalent solar energy that has been necessary to make available one unit of each of them (Odum, 2000). The use of this indicator in the input-state-output framework has two important qualities: (1) it allows for the combination/aggregation of inputs of very different quality, work capacity, and flexibility of use; and (2) it weights the environmental processes, and the time and space required to make available the resources used and transformed by the economic system. Emergy data are available for different countries from the National Environmental Accounting Database, the NEAD, compiled by the Center for Environmental Policy at the University of Florida (http://www.cep.ees.ufl.edu/nead/; Sweeney et al., 2007; Brown et al., 2009). In the NEAD, the most recent data are referred to the year 2008.

#### 3.1.2. Gini index of income distribution

Evaluating the inequality degree in the income distribution is crucial to assess the state of a society. In fact, greater income inequality has proven to be related with declining social capital, worsening health status of the population and decreasing chances of moving up the social ladder (Wilkinson and Pickett, 2009). However, it is not easy to decide how to measure inequality. The Gini coefficient is the most frequently used measure of inequality. It ranges from a value of 0 in the situation of perfect equality, where every unit has the same income, to 1 (or 100% when expressed as a percentage), in the situation of greatest inequality, where only one unit receives the whole income. The popularity of the Gini index can be explained by the high understandability (what the coefficient indicates and how it is computed), making explanation, communication and dissemination relatively easy.

Gini values for different countries over time are available among the World Development Indicators (WDI) developed by The World Bank (2014). A more complete list that covers more countries can be found by using the "All the Ginis" database (Summer 2013 version; http://econ.worldbank.org/projects/inequality). This latter database represents a compilation and adaptation of the Gini coefficients retrieved from eight sources (Luxembourg Income Study-LIS, Socio-Economic Database for Latin America-SEDLAC, Survey of Living Conditions-SILC by Eurostat, World Income Distribution-WYD, World Bank Europe and Central Asia dataset, World Institute for Development Research-WIDER, World Bank Povcal, and Ginis from individual long-term inequality studies) in order to create a single "standardized" Gini variable.

Whenever the Gini value for the year 2008 was found neither in the WDI database nor in the All the Ginis database, it has been imputed from the average values of the available Gini indexes of the adjacent years from WDI dataset. The Gini indexes for Australia, New Zealand and USA were collected from the OECD database.

#### 3.1.3. Gross domestic product

GDP is the sum of the market value of the overall set of goods and services produced by an economic system in a given period of time (generally 1 year). It can thus be intended as an indicator of

the economic output. In particular, GDP per capita, converted into international dollars using purchasing power parity rates (GDP, PPP), should be used to make rightful comparisons among the GDP of different national economies. GDP, PPP data are available from The World Bank, International Comparison Program database, as part of the WDI database (The World Bank, 2014). From now on, the simpler notation GDP will be used to indicate GDP, PPP.

### 3.2. An input-state-output 3-axis diagram: the cube

The input-state-output scheme (Fig. 1b) can be developed as a three axis diagram, where the axes represent, respectively, the emergy flow utilized by the economy on a per capita basis, the distribution of income as measured by the Gini index, and the GDP per capita. This structure is able to summarize the relationships among indicators and provides the guidelines for a classification of economic systems in a sustainability perspective.

On the three axes, three equal segments are identified, measuring the distance from the origin to the maximum value of the corresponding indicator, in such a way that the 3D space under study is totally included in a cube. More in particular, in the case of per capita emergy and GDP, the direction of the axis is from zero to the highest value, indicating progressive increase in the use of resources or in the economic performances, respectively; in the case of the Gini Index, the direction of the axis is from 100% (at the axis origin) to zero (the limit of the segment), indicating progressive increase in equality in income distribution. In addition, each segment is split into high and low domain of values, so that the three indicators will assume two possible states. In a preliminary application, high and low domains can be distinguished using simple statistical objects such as the median value calculated for the entire set of data. This threshold is artificially forced in the middle of each segment in order to have the three axes/segments (the dimensions of the cube) divided into two equal domains (high and low), so that 8 sub-cubes characterized by different combinations of the indicators are visible (Fig. 2).

The distribution of data in preferential regions of the scheme allows a categorization of economies. The volumes of the cube that are populated by a very low number of data provide insights about anomalous relationships among indicators. The areas that are populated by a large majority of data can be intended as the probable configurations that the economic systems can achieve.

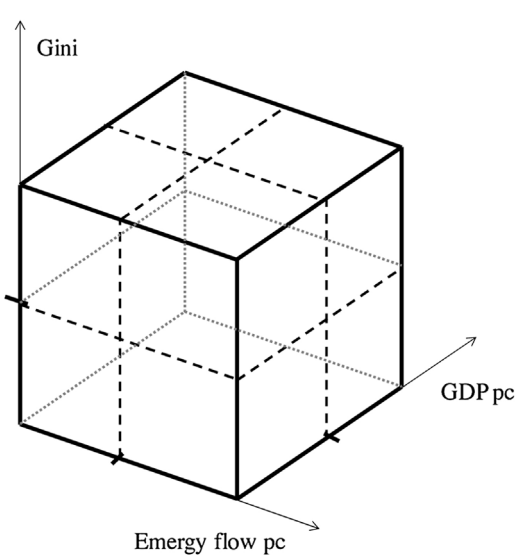



**Fig. 2.** A cube can derive from a three-axis diagram. Median values are forced in the middle of the segments. In this way, 8 sub-cubes can be used to characterize different combinations of the indicator values.

Every point in the cube does not represent a single number, but it maintains the contribution of every single indicator, without losing information. Moreover, it is not the result of a basic juxtaposition but it may emphasize the relationships among indicators. The cube can be regarded as "holistic" because it represents multiple relations with a single "point" or "region" of a diagram.

Further developments are implemented by using more accurate statistical methods that are able to discriminate different clusters of values for the indicators used.

### 3.3. Cluster analysis

Cluster analysis is a numerical technique for classifying a sample of heterogeneous objects (the countries in this analysis) in a limited number of groups, with the property that the objects included in the same group are homogeneous and the different groups are well separated (Everitt et al., 2011).

Our goal is to produce a classification that is reasonably "objective" and "stable". To this end the cluster analysis is suitable to give consistent statistical support to the 3-axis diagram previously introduced.

By using the available information on the set of indicators covering the proposed scheme, that is the per capita emergy, Gini index and per capita GDP, the clustering algorithm starts from an initial partition of the countries into a fixed number of groups, where each group is represented by a typical observation ("reference object"). The grouping is then updated: based on the distance between every single observation and the reference objects of each group, every observation is reallocated to the closest group. Subsequently the reference objects of each group are recalculated and new iterations are made until a convergence is reached, namely when no further move can increase the overall homogeneity within the groups.

Instead of the most widely known *k-means* method, a *k-median* algorithm has been used, where the "reference object" of each group is calculated through the median values of the variables. This choice has a twofold motivation. On one side it allows to align this analysis with the one illustrated in the previous section, where the median is used as a threshold to discriminate between high and low values of the three indicators. On the other side, the *k-median* algorithm is more robust than the *k-means* algorithm to the presence of outliers. In this study some extreme values are observed for every indicator, which can influence the calculation of the groups' means when these are used as reference objects.

The quality of the cluster final solution can then be evaluated through useful diagnostic tools like the silhouette plot (Kaufman and Rousseeuw, 1990).

For each observation $i$, an index $s_i$ is calculated based on the comparison between a dissimilarity measure within its group and a dissimilarity measure to the observations in every other group. Value of $s_i$ close to 1 indicates that the $i$th observation is well classified whereas value close to $-1$ suggests a misclassification. When the index is near zero, the observation lies between two clusters.

Single silhouette indexes are then averaged across each cluster and finally an overall index (average silhouette width) is calculated for the resulting partition. The average silhouette of the data is a useful criterion for assessing the natural number of clusters: the higher the overall index the better the quality of the solution.

## 4. Results

### 4.1. National economies in a cube

The joint use of emergy flow per capita, Gini index, and GDP per capita is represented in the input-state-output cube. The 3D space

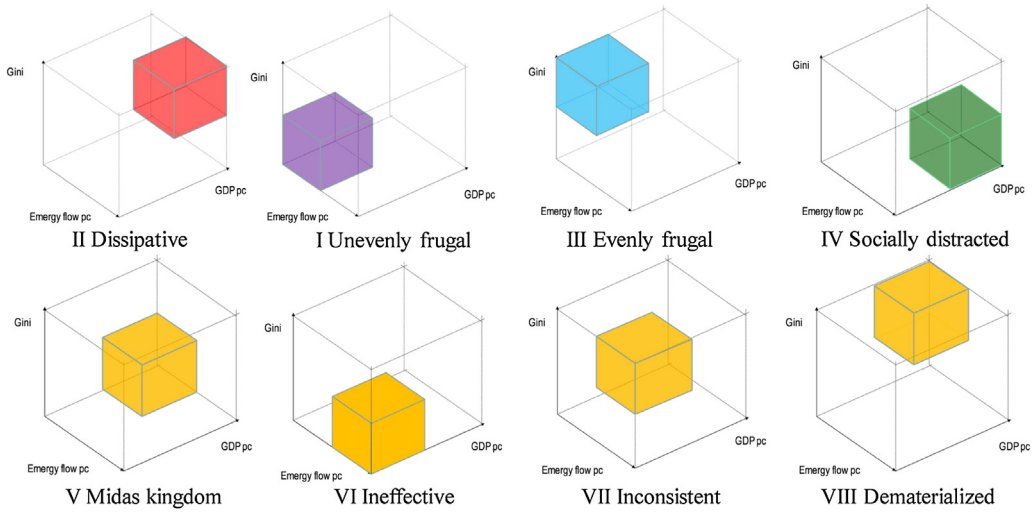



**Fig. 3.** The economic systems investigated are mainly distributed in the 4 categories in the upper section of the figure. The 4 categories in the lower part of the figure can be intended as areas of the diagram where only few data are observed.

within the cube is populated by points, representing the world countries, which are identified by the values of the three selected indicators. The discrimination between low and high domain along the axes enables the categorization of every single point. A total of 99 national systems have been investigated in the 3-axis diagram. Most of them (85) fall in 4 of the 8 possible configurations (sub-cubes) (Fig. 3). These configurations characterize economies that are the result of a somehow "usual" set of relations between the environmental, social and economic elements. The other 14 points fall in portions of the cube that are less populated, thus constituting more exceptional, unusual, input-state-output relations.

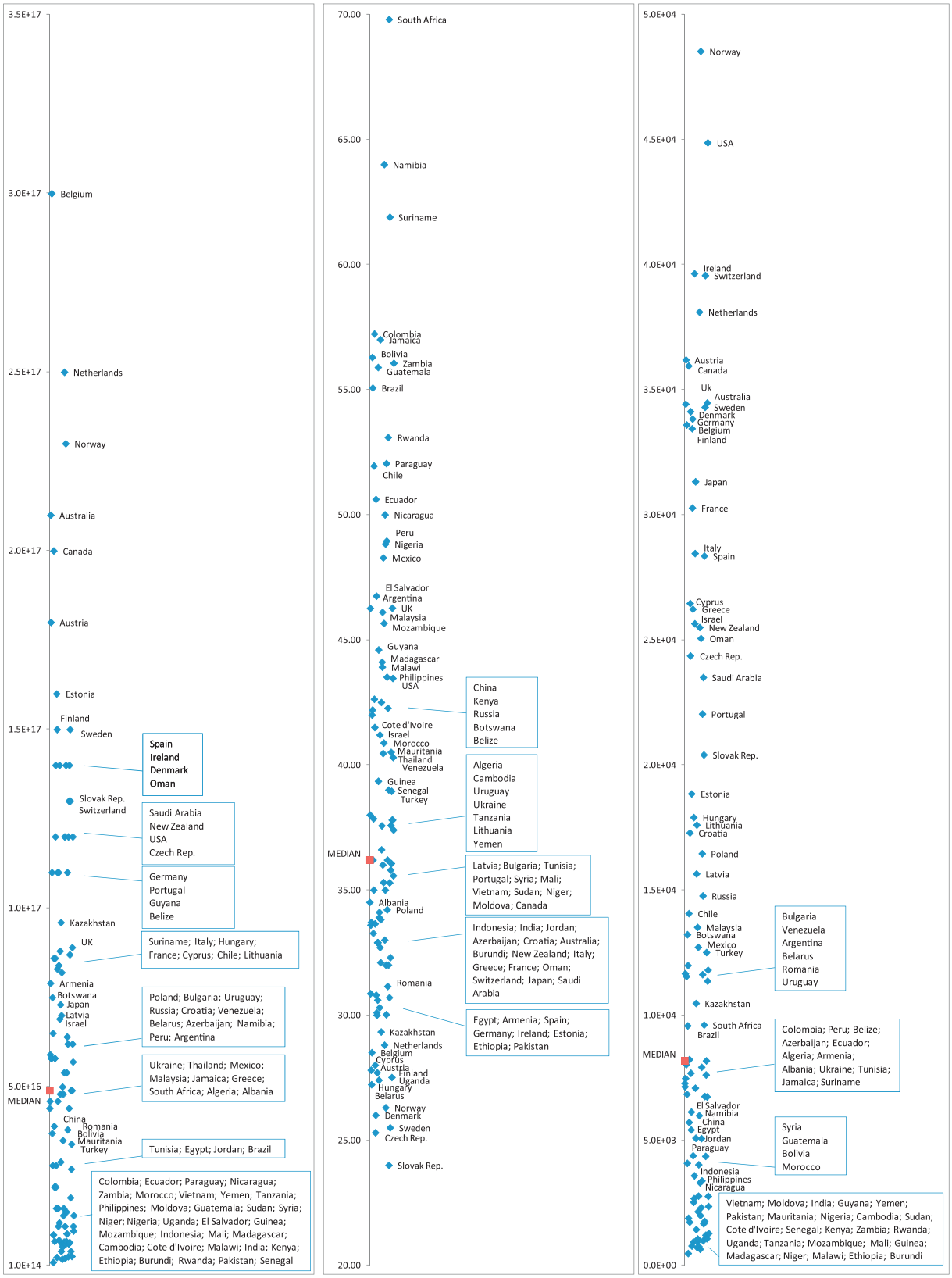
The characteristics of the 8 categories (usual and unusual economies) are summarized in Table 1, while the distribution of data for each indicator is represented in Fig. 4. Median values, that discriminate between high and low domains for each axis of the diagram, are respectively equal to 4.90E + 16 seJ year$^{-1}$ for the emergy flow per capita, 36.2% for the Gini index of income distribution, and 8.170 \$ year$^{-1}$ for the GDP per capita.

The 8 sub-cubes depicted in Fig. 3 have been labeled using categories to represent high and low values for the indicators and summarize the general behavior of the economic systems included in each category. Most of the European countries, but also Australia and New Zealand, Canada, Japan, Oman and Saudi Arabia, have a high level of per capita resource consumption, an equal distribution of income and a high GDP per capita. These economic systems are able to "dissipate" conspicuous resource flows, by generating high GDP and equitably sharing income. However, "to dissipate" also means to use large amounts of energy and matter resources and to generate wastes as an effect of the economic production. This category is the most represented in our dataset, including 30 "dissipative" countries. "Unevenly frugal" economic systems have a low level of per capita resource use, an unequal distribution of income and a low per capita GDP. 27 countries have been identified in this category. In these countries, most of people have a frugal lifestyle. This can be due to (1) a low availability of resources, as is the case of African countries here included (i.e. Algeria, Morocco, Zambia among others) or (2) a very big population, as is the case of China (please remind that our data are referred to 2008. More recent data would show a totally different position of this and other countries in the sub-cubes). In the "Evenly frugal" economies we observed a generalized low income and difficulty to access to energy and matter resources. In this category, 16 countries are included. These are countries with the lowest emergy flow per capita and GDP per capita in the overall dataset, such as Burundi, Ethiopia, Sudan, Mali, Jordan, Moldova, Vietnam and India. The last "usual" input-state-output configuration, characterized by high emergy flow per capita, unequal distribution of income and high GDP per capita, includes "socially distracted" economies. In our dataset, 12 countries can be classified as "socially distracted", the most representative of them being Israel, USA, United Kingdom, Russia, and Argentina. These economic systems are actually distracted by the paradigm that strictly links welfare to the earning power: the high level of economic wealth, obtained by consuming resources in large quantity, do not spread over the whole society. This questions the idea that economic growth increasingly contributes to the wellbeing of people in a somehow automatic way.

Regarding the 4 "unusual" configurations of inputs, state and outputs, we observed a dissonance between resource use per capita and GDP per capita in all of them. "Ineffective" and "inconsistent" economies are not able to produce economic

**Table 1**
Categorization of National Economies through the input-state-output scheme. "low" indicates below-median values; "high" indicates above-median values.

| Category | Input<br>Emergy flow per capita | State<br>Gini index of income distribution | Output<br>GDP per capita | Number of countries |
|---|---|---|---|---|
| Dissipative | High | Low (equal) | High | 30 |
| Unevenly frugal | Low | High (unequal) | Low | 27 |
| Evenly frugal | Low | Low (equal) | Low | 16 |
| Socially distracted | High | High (unequal) | High | 12 |
| Midas' kingdom | Low | High (unequal) | High | 5 |
| Ineffective | High | High (unequal) | Low | 5 |
| Inconsistent | High | Low (equal) | Low | 2 |
| Dematerialized | Low | Low (equal) | High | 2 |




(a) Emergy flow per capita (seJ * $yr^{-1}$) (b) Gini index of income distribution (c) GDP per capita (2005 int. $ * $yr^{-1}$)

**Fig. 4.** Distribution of data relative to (a) emergy flow per capita; (b) Gini index of income distribution; (c) GDP per capita; considering 99 national economies.

welfare, despite the high availability of resources. "Ineffective" economies are also characterized by high inequality in income distribution. This can be related to a strong dependency on other national economies. In fact, most of the countries labeled as "ineffective" are postcolonial countries (i.e. Suriname, Belize, Guyana) highly dependent on foreign capitals. On the other hand, "inconsistent" economies have an equal distribution of income. These are some post-communist countries (i.e. Armenia, Azerbaijan) that experienced democratization accompanied by economic collapse (Inglehart et al., 2008). The names "Midas' kingdom" and "dematerialized" reflect the fact that an economy cannot provide market goods and services without consuming resources, and this is independent from societal organization. Furthermore, the 7 countries included in these categories, such as Greece, Romania, South Africa, Mexico and Brazil show values of emergy per capita and GDP per capita that are not significantly different from the median values, as can be noted in Fig. 4. This highlights the need of a more statistically relevant approach based on the concept of dissimilarity among different countries instead of using a threshold in order to discriminate between high and low domains.

### 4.2. Categorization of national economies through cluster analysis

The *k-median* optimization algorithm has been implemented on the three standardized indicators (rescaled to have zero mean and unit variance). The average silhouette index assesses that the partition in four groups can be considered as the best classification since it shows both the highest silhouette index and the greatest homogeneity in the group size. The classification in more than four groups is not optimal, which means that any partition in more than four clusters suffers for both a poor homogeneity among the countries in the same group and a lacking separation between the groups.

This choice is consistent with the four "usual" configurations in the cube representation.

In the silhouette plot (Fig. 5) the cluster silhouette widths are displayed in descending order within each group. For the first group the silhouette index shows the lowest average value and the greatest number of objects misclassified or whose allocation is anyway unclear. The second and third groups exhibit slightly higher average values of the silhouette width than the first group with just one misclassified country (those with negative average silhouette width). Finally, the fourth group appears as the clearest-cut cluster, with the highest average value of the silhouette index. The objects allocated in this group indeed set up a well separated cluster of homogeneous countries on both the emergy and GDP dimensions.

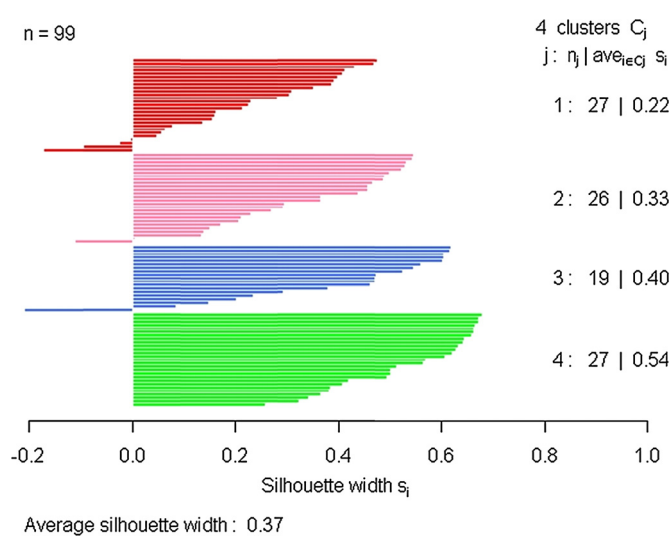



**Fig. 5.** Silhouette plots for the cluster solution. For each group $c_j$ ($j$ = 1, 2, 3, 4), the size $n_j$ and the average width of the silhouette $ave_{i \in c_j}$ $s_i$ are listed.

Fig. 6 presents a descriptive picture of the four clusters, respectively composed of 27, 26, 19 and 27 countries.

For cluster 1 the distributions of the three variables summarized by the corresponding boxplots are all concentrated around the null values. Taking into account that the null value is the average value of the three standardized indicators, we can label this cluster as the "environmentally, socially and economically medium group of economies". Indeed, its distribution, more than the others, looks like the distribution of the whole set of countries. Countries included in this group are geographically heterogeneous, most of them are countries of the former Soviet Union, Eastern Europe countries plus China, Turkey, Greece, Argentina, Uruguay and Venezuela.

It is worth noting that this "environmentally, socially and economically medium group of economies" cannot be captured by the classification in cubes, presented in the previous section, because, using the median value as the only classification threshold for each indicator, each country can be characterized by low (below-median value) or high (above-median value) level of each indicator. Indeed the countries belonging to this cluster were scattered in the 8 cubes.

For cluster 2 the distribution of both emergy per capita and GDP per capita is sharply above the average values. Actually this cluster is composed of nearly all high income countries according to the World Bank classification (all Western EU Countries, USA, Australia, New Zealand, Japan, Oman and Saudi Arabia). This group includes strong natural resource dependent countries with high economic development. The figures for Gini index are lower than the average for all but two countries (USA and United Kingdom). Nearly all the countries of this group were included in the cube of the "dissipative" countries. Because of their high inequality indexes, USA and UK were found in the cube of the "socially distracted" countries.

Cluster 3 presents the highest levels of inequality (highest Gini). This group includes countries with lower than average emergy per capita, strong disparities and poor economic performance (Namibia, Nigeria, Rwanda, South Africa, Suriname and Zambia among the others). Most of the countries belonging to this cluster were classified as members of the "unevenly frugal" cube.

Cluster 4 is a very peculiar cluster. The thin boxplots for both emergy per capita and GDP per capita stress a very strong homogeneity of their elements. It includes developing African and Asian countries with lack of resources and the lowest economic output, in combination with an average level of inequality. Most of the countries belonging to this cluster were classified as member of the "evenly frugal" cube (they include India, Egypt, Indonesia, Pakistan, Vietnam, Jordan, Burundi, Cote d'Ivoire, Ethiopia, Morocco, Niger, Senegal, Sudan, Tanzania, Tunisia and Uganda).

## 5. Discussion

### 5.1. Methodological issues

In our 3-axis diagram, a country is represented as a point in the 3D space, where the environmental, social and economic aspects are included but not aggregated in a single number. The relationships between different indicators can thus be graphically and numerically investigated as well as the overall input-state-output characteristics of different systems, in a sustainability perspective.

The 3-axis diagram is flexible and can be used by combining various input-state-output indicator sets. In this case, the emergy flow per capita, the Gini index of income distribution and GDP per

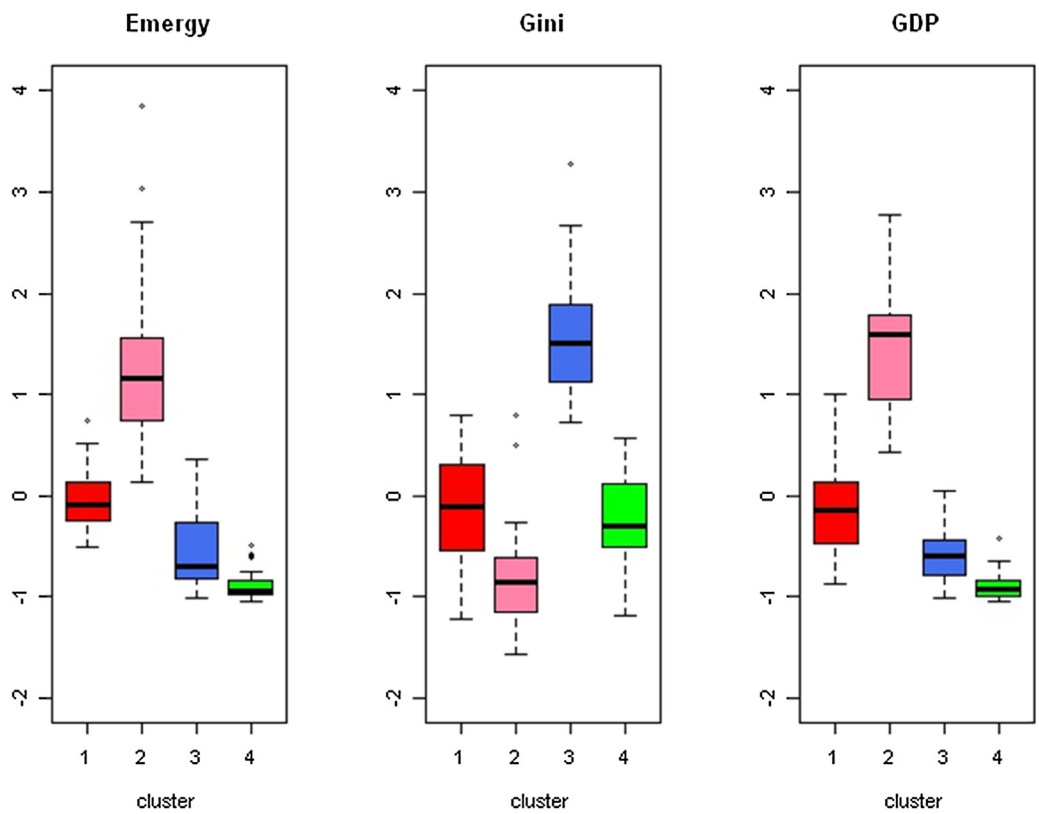



**Fig. 6.** Boxplots of the cluster solution: in each panel the distributions of every variable are presented on the vertical axes for the four clusters. The thick line in each box represents the median value of the cluster.

capita were used. However, other input-based indicators, state descriptors and output-based measures can be applied to this framework, helping to further characterize particular behaviors and highlight differences among countries. For example, the Ecological Footprint, or the Material Flow Accounting, can be used to represent the overall inputs required by a national economy. Different information may derive from the application of different input-based methods. For example, Ecological Footprint explicitly identifies a threshold, i.e. biocapacity; the Material Flow Accounting represents the material weight of each country within a global mass balance. In our case, we use emergy to depict the energetics behind the dynamics of human systems, providing a representation of sustainability in absolute rather than relative (to a threshold) terms. Nevertheless, the emergy accounting can help understand the distance from a hypothetical share of the global emergy that renewably flows through the Earth system (about $2 \times 10^{15}$ seJ per capita per year). Looking at Fig. 4a, we can observe that only the nations belonging to the group close to the bottom-line fall around this limit.

The employed force over total/active population, measures of poverty, or alternative inequality measures can be used to describe the state of the system. For example, it should be interesting to adopt as an inequality measure the Palma ratio (Palma, 2011) which measures only changes to the distribution of income if it either affects the lowest earners or the highest earners and therefore relates better to the common understanding of inequality. Adjusted measures of welfare with respect to GDP can be used as indicators of the outputs produced by the economy: for example the Index of Sustainable Economic Welfare (ISEW), the Genuine Progress Indicator (GPI), or the Happy Planet Index (HPI).

Our approach produced a categorization of nations that goes beyond the classical categorization of countries regarding their development level. Distinctions between different development patterns cannot be based on a generic "developed" versus "developing" countries, nor exclusively on a "high-income"/"low income" criteria (The World Bank, 2014). However, other grouping criteria can be used to refine our approach. For example, the Ecological Footprint creditors and debtors can be distinguished in our framework, supporting a deeper understanding on the global and local effects of different countries' behavior from a sustainability viewpoint.

Finally, sustainability assessment of countries needs to be based on up-to-date data, and be referred to no longer than one year old information. Otherwise, final considerations are not suitable to be implemented into effective policies.

### 5.2. Outcomes from cube and cluster analyses

From the cross-country analysis that we have proposed, a series of observations can be made.

Looking at the whole picture (Table 1 and Fig. 3), a strong relationship between resource use per capita and GDP per capita can be noted, pointing out how economic growth drives, and depends on, an increasing requirement of energy and matter to be transformed by the economic system. This is consistent with existing findings regarding the causal relationship between the quantity and quality of energy consumption and economic growth (Warr and Ayres, 2010). Within the cube, we may observe a tendency of the nations of distributing along the diagonal of the plan defined by input (emergy) and output (GDP), from low to high values, as demonstrated by the presence of the "usual" categories of nations. Actually, it is a diagonal plan, because, independently of the values of per capita emergy and GDP, we may have very different levels of income distribution within the societies. In particular, the fact that "dissipative" and "unevenly frugal" economies are the most represented categories in our analysis,

also highlights that a major division exists regarding the access to, or availability of resources, between equal and unequal societies, and rich and poor economic systems. In other words, the three indicators fall in different domains for these two categories. Our framework and the indications coming from the three-axis diagram make "dissipative" economies aware that, despite the high levels of GDP per capita and a relatively fair distribution of income, upcoming environmental challenges and planetary boundaries (Rockström et al., 2009) can become limiting factors for the durability of this level of development. In "frugal" economies, low levels of resource availability per capita generally correspond to low level of per capita GDP. The cube shows that there is not just one way for the poorer systems to emancipate, i.e. by becoming "dissipative". Once the access to resources up to a subsistence level is guaranteed, more economic opportunities can emerge from better environmental conditions. To reach this goal, it is fundamental to safeguard land and resource sovereignty, and improve social mobility through more widespread and efficient cultural and educational systems.

The role of society is the most difficult to be monitored and measured. It is however fundamental to take into account social dynamics because they contribute to the general well-being of a population. In particular, a "societal bypass" effect can be revealed as a spontaneous characteristic of some national economies. For instance, the "socially distracted" nations risk to behave like machines designed to transform inputs into outputs without taking care of the members of their communities. Overall, to successfully manage societal parameters, in our case equity, a large amount of energy and matter from the environment or the growth in GDP are not sufficient; what is needed is a punctual political intervention agenda in this sense.

Few nations populate the "unusual" sub-cubes. Some of them ("ineffective" and "inconsistent") are inefficient users of resources; the others ("Midas' kingdom" and "dematerialized") seem able to obtain economic wealth without resources. Indeed no cluster with these unusual input–output configurations has been found. Looking at the boxplots in Fig. 6 it can be observed that there are no clusters presenting the characteristics of high emergy level–low level of GDP or low emergy level–high level of GDP.

The main contribution of the cluster analysis can be found in the fact that it sharpens the classification by overcoming the drawback of using a crisp threshold for the categorization. Indeed a group of countries with values around the average for every indicator, the "environmentally, socially and economically medium group of economies" (cluster 1) is identified and isolated. Some countries included in this cluster like Belize, Guyana, Armenia, Malaysia, Azerbaijan, Turkey, Greece and Romania were included in the over-mentioned "unusual" sub-cubes.

Like the 3-axis diagram, the cluster technique identifies two groups of "frugal" countries that appear to be polarized with respect to the income inequality. The so called "dissipative" countries find their place in a distinct group in the cluster results too. Even if they can be given the same label, the groups identified through the cluster analysis differ from the ones resulting from the previous method both in the number of countries and in some specific countries included.

Nevertheless some misclassification problems arise for a limited number of countries. To address these issues in future studies, a fuzzy clustering approach could be envisaged where for every unit a membership function is estimated, indicating the membership degree to each cluster.

Finally it is worth noting the set of the "dematerialized" countries: the category is almost empty in the cube representation whereas it does not emerge at all in the cluster analysis. This is in contrast with many neo-liberal prescriptions of a path to sustainability. Dematerialization can be defined as the progressive reduction of the material base of the economic process, through various means (reduction of material intensity, decoupling, transition toward service economy, etc.). It is seen as a way to reduce the environmental impact (but also the costs) of the production process. However, it is hard to accept this as a solution for perpetual economic growth. For example, Kander (2005) is "skeptical about the idea that the transition to a service economy will bring about dematerialization of production and consequent environmental improvement [...] because the shift to a service economy is an illusion in terms of real production". In our proposal we use this term to label a sub-space characterized by high economic wealth and low resource consumption (with a low Gini index); however dematerialization is a transformation process and not a static evidence, as in the case here presented. Anyhow, our cross-country results suggest that there may be physical limits for the dematerialization process, which, at least, has not yet happened, and represents a non-spontaneous and uncommon characteristic of a national economic system. This outcome might seem in contrast with the findings of some other studies presenting the profiles of energy and carbon intensities (see, for example, Sun and Meristo, 1999; Ayres and van den Bergh, 2005); on the other side, the results of the correlation between the Ecological Footprint and other global resource use with GDP (Weinzettel et al., 2013; Seppelt et al., 2014) confirm our conclusions. This can be explained by the fact that, while the former consider energy use and carbon emissions linked to a geographically defined system, both emergy and Ecological Footprint assume a final-user responsibility that considers a complete supply chain vision. The studies on dematerialization should be thus verified considering a consumer responsibility approach (see for example, Davis and Caldeira, 2010; Caro et al., 2014, for carbon emission accounting), in order to avoid the possibility of improving carbon and energy intensities by virtue of delocalization rather than reduction of emissions or energy use.

### 5.3. Toward a complete picture of sustainability

The input-state-output framework is characterized by an ordered series of processes that describes the system behavior. Flows of raw materials and energy must be organized and processed to obtain final products. This highlights the dependence of an economic system on a level of societal organization and, especially, on environmental resources. All these aspects must be carefully monitored because the relationships among the three components may result in sustainable or unsustainable behaviors.

Regarding the strict link between the economy and the environment, some feedbacks can be identified. Some examples include: the fast exploitation of non-renewable resources beyond the limits of regeneration or waste absorption capacity of the environment is a characteristic of the development model of western economies, but it must not be taken for granted that the ecosystems will be able to support this trend in the future; the phenomenon known as "land grabbing" (see, for example Rulli et al., 2013) is a consequence of the growing need of natural resources and land to feed the economic growth processes, but it will also be the cause of problems in environmental and social equilibria both locally and globally. On the other hand, massive investments in natural capital that enable increased use of renewable environmental goods and services without compromising ecosystem functions may have positive effects in the future perspectives and the sustainability of entire national economies.

Another aspect that becomes crucial in the study is thus the temporal dimension. The evolution of a single point (i.e. a country) in the diagram can be monitored when it moves from one to another region of the space within the cube, characterized by different input-state-output values. One can wonder whether an optimal trend for a single country exists and must be followed, or

how exogenous factors, like the economic crisis or the progressive exhaustion of a non-renewable resource, influence the position of a nation in the 3D space. Moreover, this tool can be useful to evaluate the effects of national policies in economic but also in social and environmental terms.

Furthermore, when monitoring a single country in time, extensive indicators must be used. The intensive indicators used here (i.e. normalized on a per capita basis) are suitable to make comparisons between nations, but may lead to misleading considerations if they are used to assess the effects of policies on sustainable development. Sustainability is in fact an extensive problem, because it depends on the total, limited availability of resources and on a finite system's capacity to accept wastes and contaminants. Improvements of intensive parameters is not sufficient to reduce unsustainability. For example, the emergy flow per capita can diminish in the case of an increasing total emergy in input that is compensated by a faster increase in the population of the country. The improvement in intensive indicators has to be accompanied by a parallel decrease in total consumption in order to direct development toward sustainability.

## 6. Conclusion

We have proposed an input-state-output framework to describe the multidimensional aspects of system behavior with appropriate indicators. The framework encompasses the three sectors that traditionally compose the concept of sustainability, namely the environmental, the social and the economic ones. The three spheres are represented in a three axis diagram (cube) in which several representative national economies have been included and categorized into 8 macro-categories (sub-cubes), according to the values of the indicators chosen for every axis: emergy per capita (environmental), the Gini index of income distribution (social), and the GDP per capita (economic). Every nation is therefore identified by three numbers and, from its position within the cube, it is possible to acknowledge the main characteristics of the system. We have found that the economic result is always strictly correlated with the use of natural resources (without which nothing is possible), and that the society and its organization are often bypassed. Some important elements are also apparent, such as the presence of huge inequality worldwide, and the non-existence of a dematerialized economy at any national scale.

In this paper we have demonstrated that this application is a rational solution for the study of system sustainability, because it incorporates consistency with traditional sectors proposed in sustainability research and is feasible because it is limited to small number of (already available) data.

The rationality of the framework also relies upon the logic with which system behavior is represented: the environment is the physical basis upon which human society develops and produces goods and services that are valuable in economic terms.

The language and metrics we use are also important. The pure economic representation (based on GDP, profit, cost-benefit logic, convenience, etc.) is the most common to identify the systems, but it is often an over-simplification that is limited to only one aspect of the reality. On the other hand, juxtaposing hundreds of single indicators, or concentrating many figures into a single number representative of the entire system does not seem the most appropriate way to represent the multidimensionality of the system. Our proposal maintains the informative capacity of every aspect of system behavior, but it also provides a synthetic picture of the reality. Moreover, the ability of this framework to evaluate sustainability can be maximized in the case of dynamic analyses (see Bastianoni et al., 2014) at both the macro- and micro-system level: policy makers can use this "beside-GDP" monitoring system as an orientor to pursue sustainability programs.

This new way of considering these fundamental aspects of our life can be the basis for assessment of long term system sustainability and help us identify the contradictions, hypocrisies, and non-sustainable nature of many of our current behaviors.

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