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Multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM): Theoretical concepts and basic rationale

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Abstract: The multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM) approach makes it possible to perform a check on the feasibility and desirability of patterns of metabolism of socio- economic systems by providing a characterization at different levels and scales of: (a) the performance of socio-economic activities (for households, enterprises, economic sectors, national economies, world economy) and (b) ecological constraints (micro, meso, macro) by looking at the interference that the metabolism of matter and energy flows controlled by human activity induces on the expected pattern of metabolism of matter and energy flows associated with the self-organization of natural ecosystems. This paper presents three theoretical concepts behind the analytical approach MuSIASEM: (1) how to represent the endosomatic and exosomatic metabolism of societies using Georgescu-Roegen's flow–fund scheme; (2) how to generate a Sudoku effect across representations of different units of production and consumption defined at different levels; and (3) how to perform an impredicative loop analysis when dealing with changes (evolution) of the characteristics of dynamic budgets of metabolized flows, represented across different scales. Since sustainability deals with ''becoming systems''—systems becoming something else in their process of evolution—an analysis of sustainability must adopt analytical tools semantically open in their representation of change. MuSIASEM

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can do that since it is a ''multi-purpose grammar'', which can be used for building a shared perception and representation of this ''becoming'' when studying sustainability. That is, it entails an agreement on an expected set of relations between ''relevant semantic categories'' and ''pertinent formal categories'' across hierarchical levels and across different narratives; for this reason it represents a clear discontinuity from models developed within the paradigm of reductionism to deal with the issue of sustainability.

JEL classification: O11, O13, Q01, Q57, Q58

Keywords: Societal metabolism, Multi-scale integrated analysis, Sudoku effect, Impredicative loop analysis, Exosomatic energy, Multi-purpose grammars, MuSIASEM

1. The endosomatic and exosomatic metabolism of society in the flow–fund scheme

1.1. The epistemological challenge addressed by multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM)

Studying sustainability entails facing a severe epistemological challenge: how to properly perceive and represent a process of becoming which is taking place across different scales, and therefore requires the simultaneous adoption of different dimensions and scales of analysis [1]. For this reason, sustainability analysis requires the use of non-equivalent descriptive domains and non-reducible models that have to be periodically updated and substituted [2–4]. This challenge calls for new conceptual tools of analysis capable of: (i) remaining ''semantically open''—to be adjusted to new meanings and tailored on an evolving issue definition and (ii) integrating quantitative descriptions—i.e. non- equivalent accounting systems—by establishing bridges across different dimensions of analysis and scales.

The methodology multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM)—originally proposed as MSIASM—has been developed to face such a challenge when characterizing the viability and desirability of patterns of production and consumption of socio-economic systems [1,5–7]. The methodology has been developed by integrating various theoretical concepts from different fields: (i) non-equilibrium thermodynamics applied to ecological analysis—Odum [8–10] and Ulanowicz [11,12]; (ii) complex system theory—Kauffmann [13], Morowitz [14], Rosen [15,16], and Zipf [17]; and (iii) bioeconomics (as discussed in the nest section). Empirical analyses based on this approach have been conducted on historic series of countries such as Ecuador [18], Spain [19], Vietnam [20], and China [21].

1.2. Georgescu-Roegen's fund–flow model applied to the representation of endosomatic and exosomatic metabolism of societal systems

The ''metabolism of human society'' is a notion used to characterize the processes of energy and material transformation in a society that are necessary for its continued existence (for an overview, see Martinez-Alier [22] and Fischer-Kowalski [23]). The two terms ‟endosomatic″ and ‟exosomatic″ metabolism, were introduced by Georgescu-Roegen [24]—building on the original idea of Lotka [25]—to indicate flows of energy and material inputs transformed under human control within socio-economic processes both ‟inside″ (endosomatic) and ‟outside″ (exosomatic) the physical body of the members of a given society.

To study the biophysical roots of economic processes, Georgescu- Roegen [24] proposed the adoption of a fund–flow model for representing, in biophysical terms, the socio-economic process of production and consumption of goods and services. This framework proposes a distinction between the different categories used for quantitative representation:

- *Flow categories* refer to elements disappearing over the duration of the representation (that exit without having entered) and/or elements appearing over the duration of the representation (that enter but do not exit)—e.g., fossil energy or a new product. Therefore, flow categories include matter and energy in situ, controlled matter and energy, and dissipated matter and energy. The pace of these flows is controlled by two types of factors: (i) external factors—e.g. the accessibility of an adequate input flow from the environment or availability of a stock and (ii) internal factor—e.g. the capability of processing the available flow during the relative conversion (e.g. Technology and know-how).

- *Fund categories* (capital, people, and Ricardian land) refer to agents remaining ‟the same″ over the duration of the representations (that enter and exit the process); they trans- form input flows into output flows on the time scale of the representation. In relation to the representation of metabolic networks, fund elements should be able to preserve—during the duration of the analysis—their definition as converters. As a consequence of this fact they guarantee the validity of the definition of ‟what is an input″ and ‟an output″. Two key characteristics of fund elements are: (i) they can be used only at a specified rate and (ii) they must be periodically renewed. Therefore, fund coordinates entail an overhead (for their own maintenance and reproduction) and do entail a constraint on the relative rate of their associated flows with them (a range of value for the pace of conversion they control).

This distinction between flows and funds to be made in a quantitative representation has deep epistemological implications. In fact, it deals directly with the choice made by the analyst about ‟how to handle″ the perception and the representation of metabolic systems that are evolving in time. An evolving metabolic system expresses a series of expected patterns of energy transformations simultaneously, but at different scales: (i) inputs become outputs at the level of each node of the network; (ii) the compartments of the network change their original set of internal relations; and (iii) the whole network changes its overall pattern of interaction with its context at a higher level. To make things more difficult the expected characteristics of this complex metabolism evolve across these scales at different paces (Giampietro and Mayumi [26]). Depending on the choices made by the analyst, within a given representation, the definition of ''funds'' remains the same during the duration of the relative analysis.

Therefore we can say that: (A) fund coordinates represent the set of attributes used by the analyst for defining *what the system is* in the chosen representation and (B) flow coordinates represent the set of attributes used by the analyst for defining *what the system does*, when interacting with its context. In fact, the flows disappear in the duration covered by the representation. They have to be either (i) ''consumed'' or ''generated'' by the investigated system and (ii) ''made available by'' or ''absorbed by'' the context of the system.

Put in another way, a given selection of funds and flow coordinates reflects a set of assumptions chosen by the analyst, in a pre-analytical step, for representing her/his perception of the relevant aspects of the pattern of metabolism under investigation. This pre-analytical selection of variables used to define ''what the system is'' and ''what the system does'' becomes the chosen narrative about the metabolism, an obliged step to perform quantitative analysis [2,3]. Obviously, the chosen narrative about ''what the system is'' and ''what the system does'' can be wrong. When checking the representation with empirical data one can, later on, find that one of the chosen funds cannot handle the flow to be metabolized; or one of the chosen funds cannot be maintained and reproduced for the entire duration of the analysis; or the expected flow to be metabolized is not compatible with boundary conditions. Rather than being a weakness of this approach this fact represents its major strength. In fact, as discussed in the next section, given a fund–flow representation, it is possible to check the congruence of the rates of flows in relation to the magnitude of funds organized across hierarchical levels. That is when dealing with a quantitative analysis of the metabolism of a socio-economic system interacting with its environment it becomes possible to verify the quality of the narratives chosen in the pre-analytical step.

2. How to get the ''Sudoku effect'' when representing production and consumption across dimensions and scales

2.1. Multi-level analysis on the consumption side

Let us start the characterization from the ''consumption side''. In this example of application we deal with the characterization across levels of a matrix made of the fund ''human activity'' (HA).

2.1.1. At the level of individuals (level n—3)

The analysis of the fund HA represented at the hierarchical level of the individuals is illustrated in Fig. 1. In this level, we are dealing with endosomatic metabolism (conversion of endosomatic energy into HA).

- ''What the system is'' at this level (definition of the set of metabolic types/parts). In this level we characterize the population as made up of a set of structural types of individuals determining the size (in hours).

The categories we have chosen are six, generated by a 3 x 2 matrix:

- three types for the age: (i) x_1<16; (ii) 16< x_2 <65; and (iii) x_3> 65
- two types for the gender: (i) y_1—males and (ii) y_2—females;

Then, the size of the population—100 people—has to be distributed over these six categories.

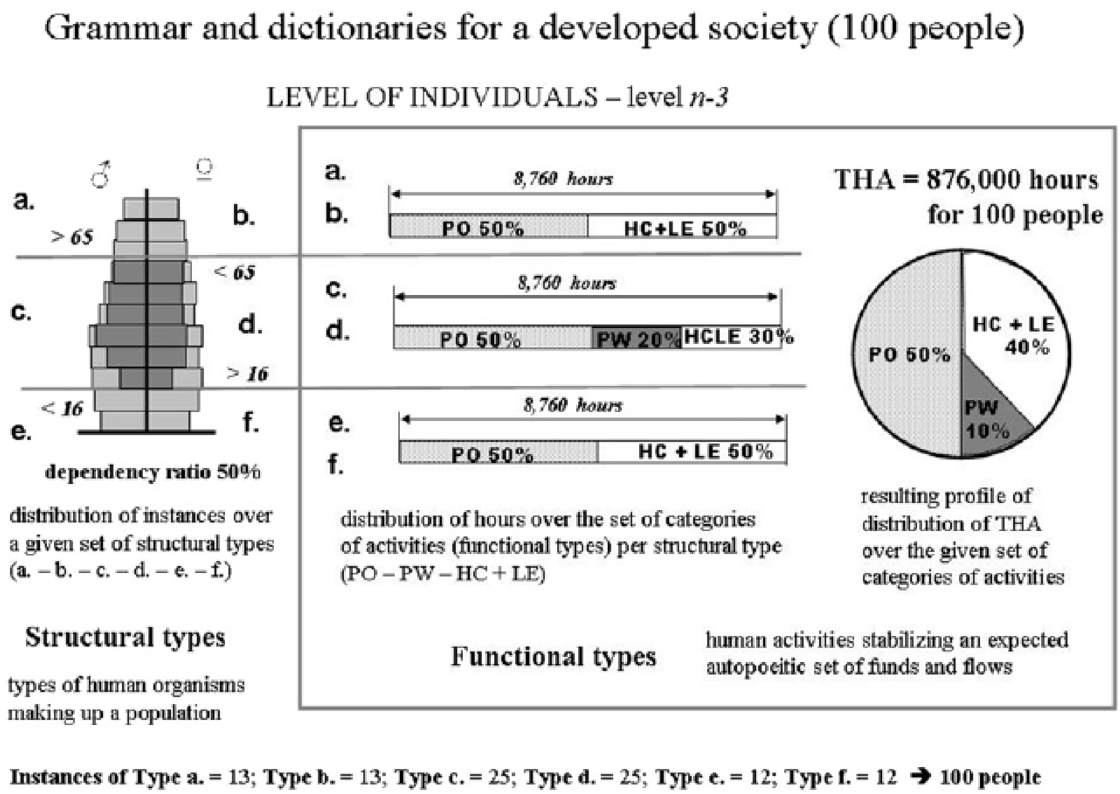

Fig. 1. Representation of endosomatic metabolism (level $n-3$).

- "What the system does" at this level (definition of the categories of HA)—three semantic categories map onto quantitative assessments (hours).

Each individual type allocates entirely its own endowment of HA within the given set of three possible categories of HA:

HA_{PO}= physiological overhead (sleeping, eating, and personal care)

HA_{PW}= paid work (PW) hours in paid economic activities (in this example this category applies only to adults).

HA_{HC+LE}= household (HH) chores+ leisure and education (= disposable HA not invested in PW).

The very simple grammar in which each structural type maps onto a known pattern of allocation of HAs is shown in the middle of Fig. 1. In this way, it becomes possible to map the profile of population (over the given set of structural types) into a profile of distribution of HA (at the level of the whole society) over the given set of semantic categories.

By adopting this representation, the presence of 100 people (instances of types) translates into an overall value for the fund total human activity (THA) of 876,000 h/year ¼ 100 (people) 8760 (hours in a year).

2.1.2. At the level of HHs (level n—2)

The analysis of the fund HA represented at the hierarchical level of HH is illustrated in Fig. 2. At this level, we are dealing with the exosomatic metabolism (conversions of exosomatic energy ''controlled'' or ''associated to'' categories of HA within the socio-economic process).

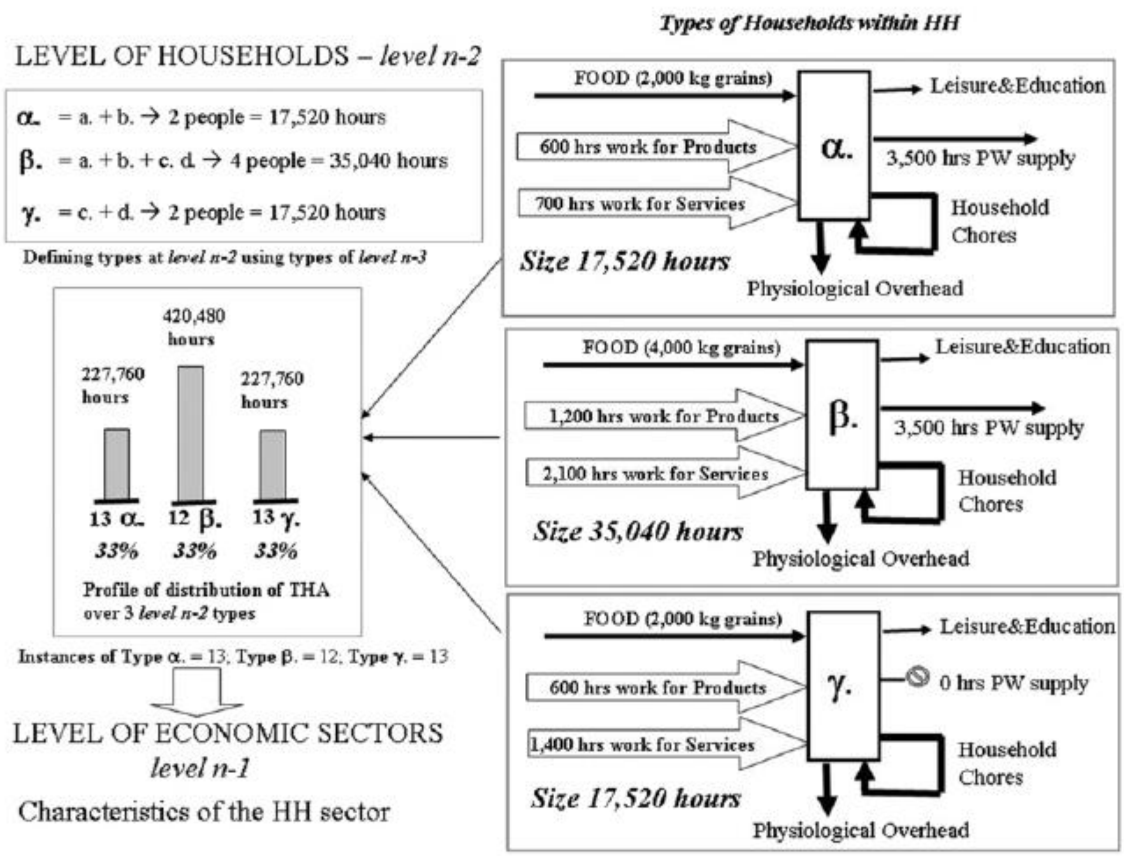

Fig. 2. Representation of exosomatic metabolism for consumption (level $n-2$).

- ''What the system is'' at this level (definition of a set of exosomatic metabolic types/parts). At this level we characterize the population as made up of a set of

HH types mapping into hours of HA. The chosen categories for defining HH types are associated to ''a given size'' expressed in hours of HA:

Type #α—a couple of only adults—size: 17,520 h/year (2 x 8760);

Type #β—a couple of adults + two children—size: 35,040 h/year (4 x 8760);

Type #γ—a couple of only elderly—size: 17,520 h/year (2 x 8760);

The profile of distribution of instances of HH types over this set has to generate an overall size in hours of THA equal to the overall size obtained by summing the size of the 100 individuals. Depending on the different sizes (in terms of hours of HA) and the profile of distribution of actual instances of HHs over the chosen set, we can calculate the profile of distribution of hours of HA over these three types (Fig. 2).

- ''What the system does'' at this level (definition of the categories of HA in relation to flows of services, products, and added value)—the chosen semantic categories map onto quantitative assessments referring to the interaction that HHs have with the rest of society: hours of the fund HA can be related to flows such as exosomatic energy or added value ($).

On the right of Fig. 2 we provide a characterization of each one of these three types, which represent their interaction with the production side.

Within this framework each HH type:

(A) Requires a certain amount of services and products, which entail, for their production, an investment of energy, material, and hours of PW and

(B) Supply hours of PW to the rest of society.

There are HH types—such as HH Type γ —which are net consumers of PW hours: they require more hours in the PW sector (embodied in the services and products that they consume), than the amount of hours of HA they deliver in the PW sector. There are other HH types—such as HH Type α —that are net providers of PW hours to the rest of society.

It should be noted that economics does exactly the same analysis (but using different variables) by focusing on the exchange of monetary flows between the sectors of final consumption (HH sector) and economic sectors generating added value (PW sector). Economic analysis tracks monetary flows (investment, taxes and subsidies, wages, rents, and interests) versus flows of services, products, and the supply of the fund ''labor''. At this point, after having defined a mechanism of ''scaling'' capable of moving from a characterization of the population in terms of individuals to a characterization of the population in terms of HHs, we can look for an additional bridge linking the HH sector to the rest of the economy. To do that, let us imagine that the 100 people were instances of the population of Spain, in 1999, and then check the typology of constraints affecting the HH sector, which can be analyzed using this approach.

2.1.3. At the level of economic sectors (level n—1)

The analysis of the fund HA represented at the hierarchical level of the HH sector (consumption side) is illustrated in Fig. 3. Depending on the characteristics of the chosen set of HH types and the given profile of distribution of the population of HHs over the chosen set of types there, we can calculate the overall flow of products and services required by the HH sector (final consumption), which is associated to an overall supply of hours of HA to the PW sector.

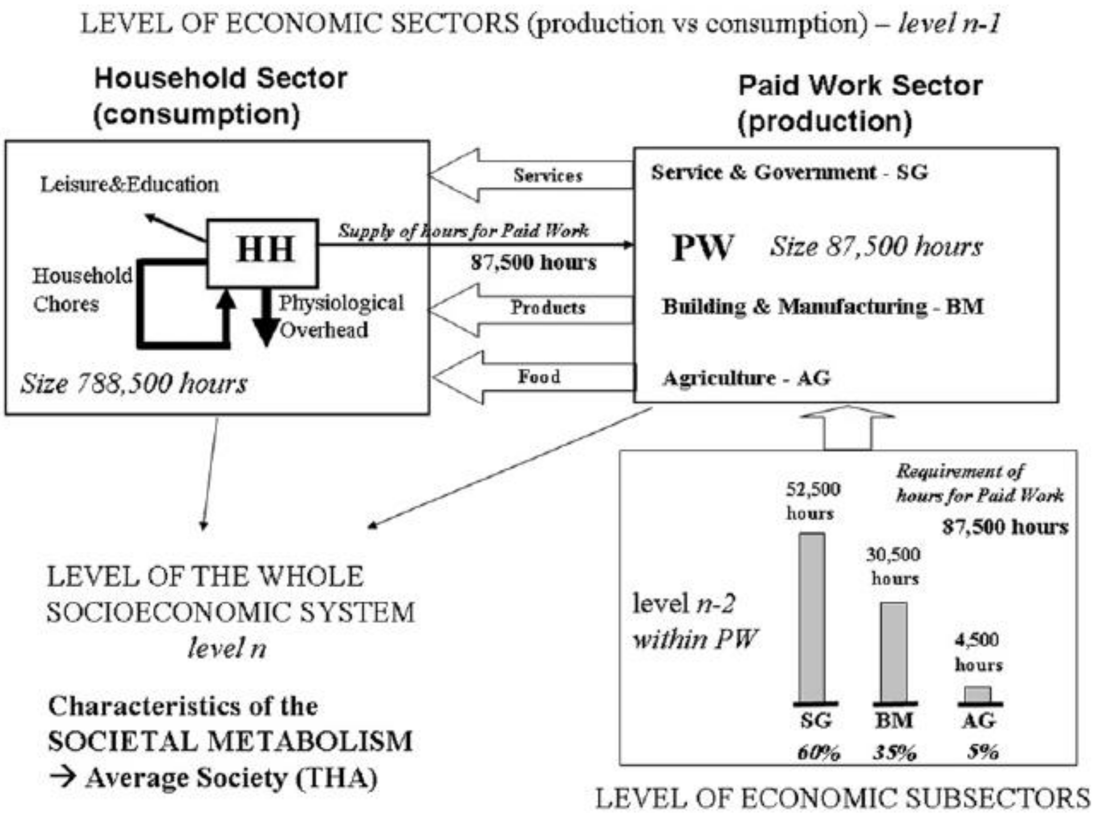

Fig. 3. Representation of exosomatic metabolism of consumption (level $n-1$).

This overall supply of hours of work (in this example, 87,500 h for the 100 people) results from the characteristics of the HH sector—when using the chosen representation of ''what HH is'' and ''what HH does''—and it must result congruent, with the requirement of hours of work of the PW sector, obtained when considering the technical coefficients of the PW sector. That is, there is an alternative representation of ''what PW is'' and ''what PW does'' to deliver the required amount of products and services. In this alternative representation, PW has to require a number of hours of work that is compatible with those supplied by the HH sector in the first representation. To check this congruence one has to look at the technical coefficients of the various technical processes used to generate such a supply in the PW sector of the economy (for instance, the biophysical productivity for products and services and the economic productivity of labor in $ per hour). This operation requires the ability to perform an analysis across different levels while at the same time establishing a bridge between the consumption and the production side of the socio- economic process.

2.2. *Linking the consumption side with the production side*

In this section we extend the characterization of the metabolism of a society also to the "production side" by keeping track of the allocation over different compartments of the fund "human activity". In jargon we can say that the fund HA is the multi-level matrix to be defined across levels when choosing the identity of the various compartments. The metabolism of exosomatic energy can then be mapped against this multi-level matrix. The resulting flow–fund representation, in the MuSIASEM approach, is based on the use of extensive and intensive variables. Variables that are additive (like volume) are called *extensive variables*—they characterize the size of compartments defined in terms of either hours of HA or GJ of exosomatic energy. For example they can be used to characterize the size of HH or PW. Variables that cannot be added, but represent a ratio (such as pressure or potential) are called *intensive variables*—they characterize the pace of metabolism of the exosomatic throughput of a given compartment (ET_i) per hour of HA. The pace of a compartment is called exosomatic metabolic rate (EMR_i) = ET_i/HA_i. The *i* compartment can be the whole society (at the level n) or any one of the lower-level compartments such as HH or PW (at the level n – 1) and other sub-compartments (at the level n—2).

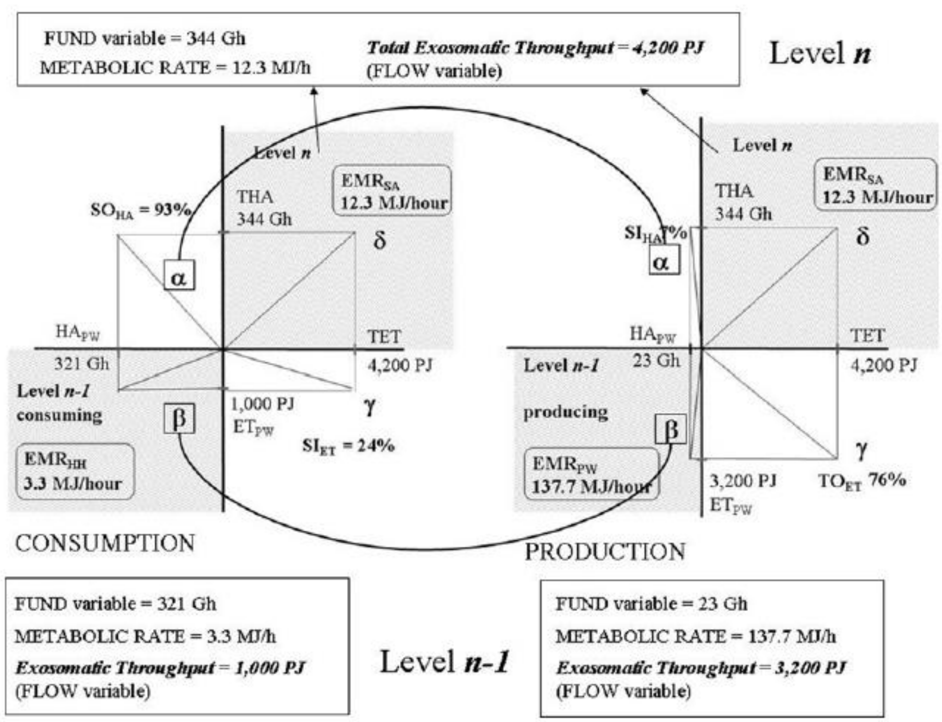

Fig. 4. Establishing a bridge between representations of exosomatic metabolism referring to consumption and production.

The different values of EMR_i can be used as benchmarks to characterize how much both technical capital and exosomatic energy are used to boost, in a given compartment, the efficacy of 1 h of HA allocated there. Obviously, the values taken by EMR_i are different in different compartments and across hierarchical levels. When considering the interface between the level n (the whole society) and the level n-1 (the two economic sectors of production and consumption)—Fig. 4—we can use the following extensive and intensive variables.

The extensive variables for the fund element HA are:

At the level *n*

- THA—the total human time available for the whole economy for 1 year. THA is calculated as: 24 h x 365 days x population. In the example in Fig. 4 for Spain, in 1999, this value is 344 Gh (Gh = 10^9h).

At the level *n − 1*

- HA_{PW}—the hours allocated in the PW sector in a year (23 Gh in Fig. 4).
- HA_{HH}—the rest of THA allocated in HH sector in a year (321 Gh in Fig. 4).

The congruence constraint is: $THA = HA_{PW}+HA_{HH}$.

The extensive variables for the flow element ET are:

At the level *n*

- Total exosomatic throughput (TET)—the total exosomatic energy consumption in terms of joules for the whole economy for 1 year. In the example in Fig. 4 for Spain, in 1999, this value is 4200 PJ (PJ = 10^{15} J).

At the level *n-1*

- ETPW—the exosomatic energy consumption for the PW sector per year (3200 PJ in Fig. 4).
- ETHH—the rest of TET (exosomatic energy consumption) in the HH sector in a year (1000 PJ in Fig. 4).

Again, the congruence constraint is $TET = ET_{PW}+ET_{HH}$

The four intensive variables—either flow/fund ratio or fund/fund ratio—are:

At the level *n*

- EMR_{SA}—the biophysical energy intensity for the whole economy, where EMR_{SA} = TET/THA. EMR_{SA} indicates how much exosomatic energy is consumed per hour of human time at the level of the whole economy. In the example in Fig. 4 for Spain, in 1999, this value is 12.3 MJ/h.

At the level *n-1*

- Fund share n-1/n —the fund ratio between HA_{PW} (measured at *level n-1*) and THA (measured at *level n*). This ratio indicates how much human labor is used in the PW sectors compared to the THA. The combined effect of demographic structure over age classes, social rules and habits, level of education, and workload for paid workers (the information provided in Figs. 1 and 2) all determine the value of fund share n-1/n (0.067 or 6.7% in Fig. 4).

- EMR_{PW}—the biophysical energy intensity in the PW sectors, where $EMR_{PW} = ET_{PW}/HA_{PW}$. EMR_{PW} indicates how much exosomatic energy is used per hour of labor in the PW sectors as a whole (137.7 MJ/h in Fig. 4).

- Flow share n-1/n —the flow ratio between ET_{PW} at *level n-1* and TET at *level n*. This ratio indicates how much energy is used in the PW sectors compared to the total exosomatic energy consumption for the whole economy (0.762 or 76.2% in Fig. 4).

The graphs of Fig. 4 show the possibility of using the fund–flow model adopted by the MuSIASEM approach (in this application, HA is the fund and energy is the flow) to establish a relation between the characteristics of the metabolism of the ''productive side'' and the characteristics of the metabolism of the ''consumption side''. In fact, ''metabolic rate'' of the whole at the level n (determined by the calculation $EMR_{AS} = TET/THA$)—upper-right quadrant—can be related—at the level n-1—to the two EMR_i of the two lower-level compartments. The two paces of ''production'' (EMR_{PW}) and ''consumption'' (EMR_{HH}), having their own distinct paces of metabolism (137.7 MJ/h versus 3.3 MJ/h), are constrained by the relation of congruence of the funds and flows across levels. Put in another way, the total value of the consumed energy (TET) is split between production (ET_{PW}) and consumption (ET_{HH}) exactly like the fund HA (THA), which is split between production (HA_{PW}) and consumption (HA_{HH}).

Therefore, the angle δ in the upper-right quadrant of the graphics of Fig. 4 refers to the ratio between total energy throughput (in PJ) and the THA (in Gh) of a society—in this example, the data refer to Spain 1999. This overall pace of exosomatic energy consumption when considering the whole society coincides with the familiar concept of energy consumption per capita per year (107.7 GJ/year), with the only difference that it is to be expressed in MJ/h (12.3 MJ/h). The angle α in the upper- left quadrants depends on the fraction (α) of THA, which is allocated in the compartment of consumption (HH—figure on the left) and in the compartment of production (PW—figure on the right). The angle γ in lower-right quadrants depends on the fraction of the total energy throughput that goes in the compartment of consumption (figure on the left) and in the compartment of production (figure on the right). Finally, the angle β in the lower-left quadrants indicates the pace of energy metabolism (MJ/h of HA) both in the compartment of consump- tion (figure on the left) and in the compartment of production (figure on the right).

As can be easily deduced by the set of relations indicated in Fig. 4 at the level n-1, one cannot change the characteristics of one sector (e.g. changing the fraction of energy and/or labor used in production) without affecting the characteristics of the other sector (e.g. the energy and/or hours of HA invested in consuming). This approach makes it possible to check the option space of possible integrated changes (scenarios) of the whole and the parts.

2.3. Performing the multi-level analysis of metabolism on the production side

It is possible to generate a multi-level characterization of the exosomatic metabolism of the various compartments of the productive sectors (PSs), as done for the consumption sector. The only difference is that on this side we will not consider endosomatic energy, but only the fund ''HA'' and the flow ''exosomatic energy''. This requires defining a multi-level matrix over the fund HA across different hierarchical levels within the compartment of production. A self-explanatory example (the same approach used in Fig. 4) is shown in Fig. 5.

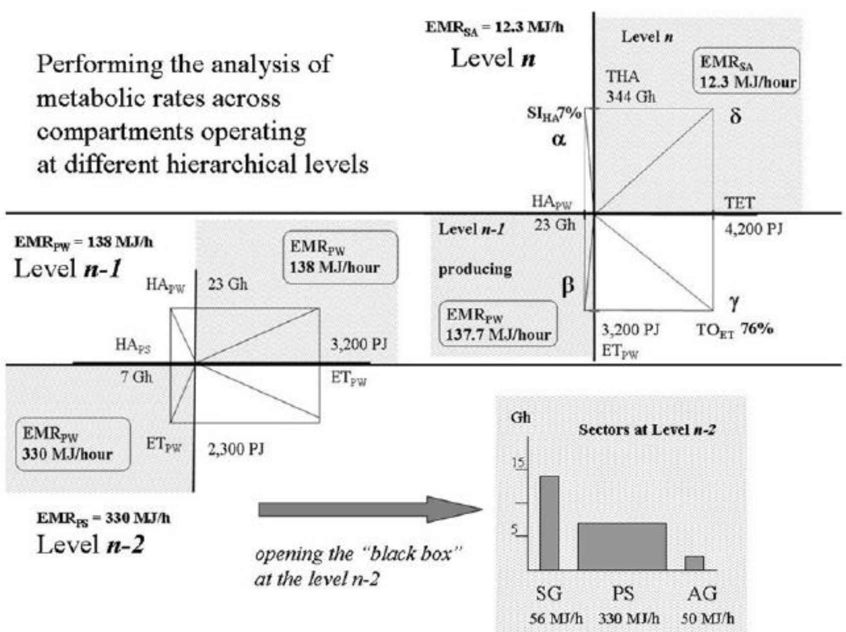

Fig. 5. Establishing a bridge between representations of exosomatic metabolism across levels within the production compartment (PW).

In Fig. 5 there are additional extensive and intensive variables required to build a bridge between the representation of the metabolism of the compartment PW, defined at the level n-1, and the representation of the metabolism of one of the lower-level compartments of PW: the PS defined at the level n-2. In Fig. 5 we have chosen to divide the PW sector —represented at the level n-1 —into three sub-compartments—represented at the level n-2: (i) PS; (ii) service and government (SG); and (iii) AG—agricultural sector.

On the right of the lower part of Fig. 5 we illustrate the ‘‘bridge across levels’’ for only one of the three subsectors considered at the level n-2 —the PS— a chosen sub-compartment of the PW sector. The two extensive variables referring to the PS sector are HA_{PS} and ET_{PS}:

- HA_{PS}—the total labor hours in the PS for 1 year (7 Gh).
- ET_{PS}—the exosomatic energy consumption in PS for 1 year (2300 PJ).

The three intensive variables are:

- Fund share n-2/n-1 —the fund ratio between HA_{PS} at level n-2 and HA_{PW} at level n-1. This ratio indicates the fraction of labor used in the PS compared to HA_{PW} in the PW sector (0.304 or 30.4%).
- EMR_{PS}—the flow–fund ratio and the biophysical energy intensity for the PS, where $EMR_{PS} = ET_{PS}/HA_{PS}$. EMR_{PS} indicates how much exosomatic energy is used per hour of labor in the PS as a whole (330 MJ/h).
- Flow share n-2/n-1 —the flow ratio between ET_{PS} at level n-2 and ET_{PW} at level n-1. This ratio indicates the fraction of the exosomatic energy used in PS in relation to the exosomatic energy in PW as a whole (0.718 or 71.8%).

3. Impredicative loop analysis (ILA)

3.1. The challenge represented by impredicativity

The term, ‘‘impredicative loop’’, might sound esoteric to many. However, without grasping the meaning of this term, any scientific activity in the field of sustainability issues could be muddled. So, let us begin with the definition introduced in mathematical logic:

‘‘When a set M and a particular object m are so defined that on the one hand m is a member of M, and on the other hand the definition of m depends on M, we say that the procedure (or the definition of m, or the definition of M) is impredicative. Similarly when a property P is possessed by an object m whose definition depends on P (here M is the set of objects which possess the property P). An impredicative definition is circular, at least on its face, as what is defined participates in its own definition’’ [27].

Because of this fact, impredicativity is considered as a nuisance in scientific reductionism, since it makes it impossible to establish a linear causation, which is a typical goal of any traditional scientific activity. The usual procedure adopted by scientific analysis to avoid impredicativity is to choose a particular linear causation (a narrative explaining the facts of interest, resulting from a choice of a single scale) and resort to empirical validation to see whether or not this particular causation is acceptable in the relative representation. This requires setting up controlled and repeated experiments reflecting the chosen representation, which must be capable of avoiding the interference of other types of causation. For this reason, in reductionism, causality goes only in one established direction, the direction chosen as relevant in the pre-analytical stage, and focused on in the relative representation and empirical validation [2]. However, when dealing with an evolving metabolic system operating on different hierarchical levels it becomes difficult to obtain a robust identification of just a single linear causal relation. This is especially true when considering simultaneously different representations of events referring to different parts and different scales, leading to a series of bifurcations in the possible direction of causality: Is the system affecting its boundary conditions or vice versa? Is the egg coming before the chicken or vice versa? Is the behavior of the lower-level elements constraining the behavior of upper level elements or vice versa? When considering a set of ''attributes'' referring to different processes occurring simultaneously at different levels the solution developed by reductionism for dealing with this problem no longer works. ILA [1] is an attempt to provide an alternative strategy within MuSIASEM scheme. In order to better explain this type of analysis, it is necessary to introduce another theoretical concept: the concept of grammar, or better the concept of multi-purpose grammar.

3.2. How to bridge semantic and syntax in quantitative analysis of evolving metabolic system through an ILA: multi-purpose grammar

The conceptual tool of ''random grammars'' has been proposed within the field of complex systems theory by Kauffman [13] as a key ingredient for having self-organization in complex adaptive systems. More in general, the concept of ''*multi-purpose grammar*'' can be associated with a meta-system of accounting based on a flexible network of expected relations between semantic categories (e.g. relevant attributes of sustainability) and formal categories (names—indicators) generated by production rules applied to gathered data (tokens)—Giampietro et al. [28]. When using the jargon used in software development we can say that a grammar entails a preliminary definition of:

(A) A lexicon based on a taxonomy—the set of semantic categories and formal categories used in the grammar = the various types that are used in the grammar.

(B) The vocabularies for the various types included in the taxonomy—the attributes used to individuate/characterize the various elements of the different sets. In this step, a shared meaning (perception) has to be assigned to the formalized representation, which is based on ''names'' and ''tokens''.

(C) The distinction between ''tokens'' and ''names'' refers to the use of production rules applied to the chosen formal categories in the grammar. Tokens are associated with a data set that must be assigned to the grammar for its operation (data input). Then, the production rules are associated with a formal system of inference, which determines the values of ''names'' starting from the data input.

In spite of this elaborated formal definition, the concept of grammar, when considered in semantic terms, is very familiar to anybody used to work with a computer. In fact, a spreadsheet of Excel is a classic example of multi-purpose grammar (more in [28]). For example, let us imagine using an Excel spreadsheet for handling the quantification of the economic budget of a research project. To be useful, the representation of the budget has to be based on a given selection, a set of semantic categories—what is relevant in the analysis. Relevant categories could be ‘‘total amount of money to be spent’’, ‘‘the fraction of the money which has to be paid by an external sponsor’’, and ‘‘the overhead going to the administrative unit of the University’’. In the working sheet, these relevant categories are put in relation with other categories referring to the structural elements of the budget. An example of these other categories should include different types of costs such as: (i) for personnel; (ii) travel; (iii) durables, etc. Finally, a set of production rules is included in the spreadsheet. Two simple examples of production rules could be:

(1) ‘‘cost of a post-doc’’ = ‘‘months of work’’ x ‘‘gross salary per month’’;

(2) ‘‘cost of travel’’ = ‘‘number of trips’’ x ‘‘average cost of each trip’’.

At this point this grammar can be used in different ways:

(A) By entering the data about the given set of activities expected for this project. This means that the various costs of the various inputs are considered as tokens. Then the grammar is used to calculate the value of the set of semantic categories considered as names: ‘‘total cost of the project’’, ‘‘the fraction of the total spent on personnel cost’’, etc.;

(B) By entering the data about budget constraints. This means assuming the amount of money allocated in the various categories as a token. Two outputs are possible after making this choice: (B1) keeping the cost per unit constant (e.g. the gross salary per month of the post-doc; the average cost of a trip are tokens) and calculate how many months a given post- doc or how many trips can be paid, given the budget. In this way the number of months of contract for the post-doc and the number of trips are considered as ‘‘names’’. (B2) Assuming the amount of money allocated in the various categories, the months of contract and the number of trips as ‘‘tokens’’. This entails considering as ‘‘names’’ the value assigned to the two categories: ‘‘gross salary of a post-doc’’ and ‘‘average cost of a trip’’, they will be considered dependent variables in this application of the grammar.

3.3. Using MuSIASEM to check the desirability and feasibility of a dynamic budget of exosomatic energy in relation to internal constraints

The MuSIASEM approach makes it possible to perform a check on the feasibility of the dynamic budget of exosomatic metabolism of social systems by considering the congruence over the values assigned to the categories of funds and flows over two grammars determining an impredicative loop [6,7]. The two grammars are used to characterize:

(A) the metabolism of the consumption sector (requirement of services and products with an associated supply of working time) and

(B) the metabolism of the production sector (supply of services and products with an associated requirement of working time).

To perform such a check a ''key'' flow/fund ratio is used to verify the congruence over two non-equivalent definitions of ''names'' and ''tokens'' over the same set of categories.

Bio-economic pressure = $(TET/HA_{PS})_{consumption} \rightarrow$ this value indicates the degree of pressure generated by the expected life style and the structure of the consumption sector on the technical performance of the PS. The higher this pressure, the higher is the requirement of products and other material inputs for the sector of final consumption and the lower is the fraction of HA that can be allocated in the form of PW in the primary sectors of the economy.

Strength of the exosomatic hypercycle = $(TET/HA_{PS})_{production} \rightarrow$ this value indicates the ability of the PS to generate a biophysical surplus of products, using only a small fraction of TET and THA for its own operation. The concept of hypercycle has been introduced in ecological theory by Eigen [29]. A network of matter and energy flows making up an ecosystem can be divided into two parts: one part is a hypercycle and the other is a purely dissipative part. The hypercycle part is a net energy supplier for the rest of the ecosystem. Since dissipation is always ''necessary to build and maintain structures at [the] sub-compartment level'' [11, p. 119], the part producing a net supply of energy for the rest must comprise activities that generate a positive feedback by taking advantage of gradient of free energy outside the system. When applied to the metabolism of socio-economic systems the concept of SEH indicates the ability to deliver a large amount of products and useful energy to the rest of the economy per unit of useful energy required to run the PS sector. The higher the strength of the exosomatic hypercycle [11] the larger is the fraction of HA, which can be invested in services, education, leisure, and social interactions.

By developing the MuSIASEM approach across the various compartments of a socio-economic system it becomes possible to define a set of expected relations constraining the values that can be assigned to the set of extensive and intensive variables discussed in Section 2. When considering the fund HA and the flow exosomatic energy across three hierarchical levels and across the production and consumption side, Giampietro and Mayumi [6,7] determined such a set which can be used for the ILA. The various categories included in the set of expected relations across compartment can be considered either names or tokens in such an analysis.

The concept of ''Sudoku effect'' can be related to a forced congruence over quantitative assessments referring to: (i) differ- ent levels and compartments and (ii) different dimensions of analysis. The congruence is verified using an expected set of relation over the characteristics of the parts and the whole, typical of the game ''Sudoku'' or ''crosswords puzzle''. The concept of multi-purpose grammar can be related to an agreement on a given choice of relevant semantic categories generating a shared meaning when performing a quantitative analysis across levels and dimensions. By combining these two concepts it becomes possible to establish a relation between: (i) *desirability*—the perceived performance of a given pattern of metabolism (characterized at the different levels by using the chosen set of relevant semantic categories as indicators) and (ii) *feasibility*—the con- gruence over the set of internal constraint determined by the internal structure represented over different compartments (checked using the Sudoku effect) operating at different EMRs.

The mechanism of accounting implemented with the MuSIA- SEM approach should be noted:

- It is not deterministic—the chosen set of extensive and intensive categories referring to representation on different levels (n, n-1, and n-2) may be considered either as a variable or parameter. Any change in any variable (or parameter) belonging to a particular level can/must be associated with (is affecting/is affected by) changes in other variables (or parameters) belonging to other levels. So, any change in any variable (or parameter) will result in an overall change in configuration among various variables (or parameters). Within this framework it is impossible to make ''by default'' an a priori choice of division between variables and parameters, contrary to the case of linear causation typical in optimization procedures in neoclassical economics. This distinction will depend on the task of the analysis and the narrative chosen by the analyst—e.g. ''what could happen if this parameter is changed'', or ''what should be changed to get this result'', or ''what would represent the bottleneck if we try to change the overall result of these integrated set of relations''. On the contrary, the usual procedure in neoclassical economics is conducted to look for an optimal set of values of a set of objective functions subject to a set of constraints. This requires, however, that the set of causal relations, based on a clear division between variables and parameters, must be already chosen in the pre-analytical stage. Due to this particular nature of linear causation, dynamical systems in conventional economics cannot deal with real structural changes that are intrinsic to evolving systems [1–3,30]. In fact, dynamical systems within themselves cannot deal with identification of both structural causality and functional causality for evolving systems *endogenously*.

- It is semantically open—ILA allows us to visualize the existence of a set of reciprocal constraints affecting the forced equilibrium of the dynamic budget in societal metabolism characterized using two complementary grammars. A plausi- ble configuration of human time allocation and exosomatic energy distribution among various variables (or parameters) using two four angle representations can be obtained by coordinated changes of the characteristics of parts in relation to the characteristics of the whole, and changes in the characteristics of the whole in relation to the characteristics of the parts. Within the given grammar things can change because of: (i) a change in the distribution of instances over the various types; (ii) a change in the production rules; and also (iii) because of the introduction of new categories—the representation changes since the system became something else! This makes it possible to add new ''external referents'' (new meanings) to the definition of ''what the system is and does'' while retaining the same integrated structure of external and internal constraints. That is, the system can ''become something else'', but the representation can still keep memory of its history and the original structure of internal constraints. This is to say that by taking advantage of the redundancy in: (a) the definition of categories—which must be relevant for describing the consumption and production side and (b) the definition of ''feasible values''—which must be compatible with constraints coming both from the characteristics of lower- or higher-level processes; the MuSIASEM approach can be effectively used to characterize the desirability and feasibility of future scenarios of the metabolism of socio- economic systems. Moreover, after having identified a lack of feasibility in the scenario, it can help in thinking what type of innovation and novelties can be expected—at different levels—to get out of unfeasible states.

3.4. Outlook for further development of the approach: checking the desirability and feasibility of a dynamic budget of exosomatic energy in relation to external constraints

Finally, the MuSIASEM approach makes it possible to perform a check also on the feasibility and desirability of the metabolism of socio-economic systems in relation to the existence of ecological constraints. This can be obtained by looking at the interference that the metabolism of matter and energy flows controlled by HA induces on the expected pattern of metabolism of matter and energy flows associated with the self-organization of natural ecosystems. This requires introducing another type of multi-level matrix based on a different type of fund: ''land use'' [1]. In this way, it becomes possible to define expected values of density of material and energy flows per hectare, which can be associated to land uses coupled to compartments defined using categories of HA (HH, PW, AG, SG). The land areas in which the density of energy and material flow is controlled by HA are defined as belonging to the compartment ''colonized land''. On the contrary the areas in which we can expect a density of material and energy flows per hectare, which are associated with the self-organization of typologies of natural ecosystems, are defined as belonging to the compartment ''non-colonized land''. Reasons of space make it impossible to elaborate a full presentation of an application based on the analysis of metabolism of flows per unit of the fund ''land use''. Very briefly, by adopting the same distinction between ''extensive'' and ''intensive'' variables and performing an analysis across a multi-level matrix of land uses it is possible to develop a Sudoku effect capable of describing, across levels, different characteristic benchmarks of density of biophysical flows to be used for assessing the relative environmental stress [1,6,7]. Then, the characterization of environmental stress can be obtained by combining two types of information: (i) intensive index (disturbance per unit of area associated to the intensity of the flows controlled by human) and (ii) extensive index (size of the area of disturbance) within each of the selected categories of land use/land cover, defined at different scales. In this way, the MuSIASEM approach naturally makes it possible to address the issue of scaling when handling the various assessments across levels. In fact, the distribution of instances over the selection of categories can be handled with GIS techniques.

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