Multi-Scale Integrated Analysis of Sustainability: a methodological tool to improve the quality of narratives

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DRAFT

Abstract (300 words)

The goal of this paper is to illustrate an innovative methodology, ***Multi-Scale Integrated Analysis,*** developed for dealing with the new challenges implied by multi-criteria analysis of sustainability: (i) An integrated assessment of sustainability requires a multi-dimensional and multi-scale analysis. This translates into the need of handling technical incommensurability [= dealing with non-equivalent perceptions and representations of the reality resulting from the adoption of different criteria of observation and different scales]. (ii) When comparing human values it is not possible to define, in substantive terms, “the best course of action”. This translates into the need of handling social incommensurability [= dealing with the unavoidable existence of legitimate but contrasting perspectives found among social actors about what should be considered an improvement or a worsening]. (iii) It is not possible to generate accurate and relevant scenarios when forecasting the future of adaptive systems evolving across scales. This translates into the need of handling a heavy level of uncertainty and genuine ignorance when using science for governance.

The paper is divided in three parts. Part 1 introduces, from a theoretical point of view, the epistemological challenges implied by Multi-Dimensional, Multi-Scale analyses of sustainability. The peculiar characteristics of MSIA approach are contrasted with those of conventional tools developed within the reductionistic paradigm. Part 2 uses a simple example of application to illustrate the basic rationale of the MSIA approach and the type of results that it can provide. Finally, Part 3 introduces three key concepts derived from Complexity Theory, which are the building blocks of MSIA: (i) Multi-Scale Mosaic Effect across levels and dimensions (using a redundancy of external referents to back-up your assessment); (ii) Impredicative Loop Analysis (how to analyze autocatalytic loops across scales); (iii) Useful Narratives for Surfing Complex Time (models are good for simple systems, complex systems require a narrative).

Key words: Multi-Scale Integrated Analysis, Integrated Assessment, Multi-Criteria, Science for Governance, Impredicative Loop Analysis, Mosaic Effect, Complex Systems, Narratives, Sustainability, Post-Normal Science

Part 1
The challenge implied by Multi-Scale Multi-Dimensional analyses of sustainability

1.1 The epistemological predicament entailed by complexity

The epistemological predicament associated with the study of living systems is generated by two peculiar characteristics (Ahl and Allen, 1996; Allen and Starr, 1982; Allen and Hoekstra, 1992; Giampietro, 2003): (1) they are operating simultaneously on different hierarchical levels of organization, and (2) they are becoming in time, at different paces, across these different levels.

Therefore, hard scientists willing to do an analysis of living systems have to face two key problems: (i) the unavoidability of finding multiple useful descriptions of the same entity, which cannot be reduced to each other. These distinct descriptions are associated with different choices made by the observer to adopt either different scales or different criteria of observations; and (ii) the fact that the usefulness of all these non-equivalent descriptions and models sooner or later will expire. To make things worse, the validity of these different descriptions and models will expire at different paces. These two problems can be stated in general terms in the following way:

#1 – it is impossible to have a substantive representation of events. Humans (and any other living observer/agent) can only represent their specific perception and experience of the reality and not "the reality";

#2 - it is impossible to establish in substantive terms a linear causation among events. Observers can only establish a causal relation on the basis of what is encoded in a given set of records. The reliability of any prediction of any model depends on the validity of the underlying assumptions. The famous line of Box should be recalled here: "*All models are wrong, some are useful*" (Box, 1979). Nobody can guarantee the general validity of all the assumptions required to properly operate a formal system of inference used to predict future scenarios. Therefore, when analyzing the sustainability of living systems (socio-economic systems, ecological systems and their interaction) the only reasonable approach is to perform always a semantic check on the usefulness of the chosen models.

According to Rosen (1985; 1991, 2000), this epistemological predicament is at the root of complexity theory. That is, complexity in living systems is associated to the existence of multiple legitimate ways adopted by a population of non-equivalent observers for perceiving and representing their interaction. Any successful interaction of non-equivalent observers, when stabilized in time, implies the simultaneous use of non-equivalent and non-reducible models of the world. Models are needed by agents for obtaining relevant records (monitoring), for running simulations, and for guiding action. Accepting these two statements means exposing two systemic errors affecting current strategies of reductionism often followed by hard scientists when dealing with life and evolution:

(1) those willing to make models of living systems should not put all their eggs in the same epistemological basket. That is, it is unwise to look for "the model" which addresses all relevant aspects of a living system by using a large number of variables and very sophisticated inferential systems. The strategy of looking for more and more complicated models to run on bigger and bigger computers is a misleading myth. It is meaningless to look for ***the true formal identity*** of an observed system or for ***the right model***. Complexity, on the contrary, requires the ability of

handling the open and expanding set of non-reducible perceptions and representations of the interactions of non-equivalent observers/agents. This process cannot be fully captured by any formal information space no matter how big or sophisticated is the computer and/or how smart and lucky is the analyst (see also Rotmans and Rothman, 2003).

(2) any observer must be a part of the reality which is observed. Scientists, no matter how hard they are, cannot escape this predicament. This means that the scientific endeavor should be viewed as a continuous challenge. The task is to maintain a set of meaningful relations which are evolving in time within an observer/observed complex. An observer/observed complex in which both the observed and the observer are becoming in time. Complexity, according to the narrative suggested by Chaitin (1975), implies the impossibility of compressing the information space required to represent a given object/entity without losing relevant information about it. This is to say that the essence of complex systems cannot be fully captured by formal models. This explains why it is impossible to have a full anticipation of their behaviour using algorithms.

In relation to this predicament, the approach of Multi-Scale Integrated Analysis (Giampietro, 2000, 2001, 2003) represents an attempt to deal with the analysis of sustainability in a different way. This approach, as explained below, can only be applied to the study of metabolic systems organized in nested hierarchies. However, this class includes all living systems, ecosystems and socio-economic systems. The MSIA approach rather than just paying lip service to the complexity revolution, takes seriously the main message implied by it. As a result of this fact, it is an analytical tool with different goals and meanings.

The conventional paradigm of reductionism looks for models that, after formalizing the performance of the investigated system, are used to indicate the optimal solution. This paradigm assumes that it is possible to obtain both: (i) a substantive characterization of "***what the system under analysis is and what it does***" [but who is entitled to decide about that? What happens if several space-time scales are relevant for the analysis?]; and (ii) a substantive definition of "***what should be considered as an improvement***" according the final goal of the analysis [but what if there are legitimate but contrasting views among the users of this model?]. To make things worse, scientists dealing with sustainability deal always with events about which it is reasonable to expect a large dose of uncertainty and genuine ignorance [e.g. large scale changes which are occurring for the first time] that they do not account for.

The capital sin of reductionism, in this case, is to ignore that before getting into the step of developing and using formal models there is always a crucial pre-analytical step to be made. This pre-analytical step is associated to the selection of useful narratives. Formal models can only be developed within a given narrative about the reality. A narrative can be defined as a series of elaborate scaling operations that allow different processes occurring at different paces, and events describable at different space-time domains, to be made commensurable in our organization of perceptions and representations of events" (Allen – personal communication). The choice of a narrative therefore is a pre-analytical step which has to do with an "arbitrary" characterization of "***what the system under analysis is and does***". This characterization, always depends on the specific goals of the analysis, and therefore is closely related to the characterization of "***what should be considered as relevant in relation to an improvement to be achieved***". Simple systems can be dealt with in terms of models, but complex systems must have a narrative (Allen, 2003). This is a crucial point whenever the observer is a part of the observed whole. A narrative is something about which scientists have to take responsibility (Allen et al. 2001).

1.2 The peculiar characteristics of Multi-Scale Integrated Analysis

The approach of Multi-Scale Integrated Analysis is based on the initial acknowledgment that any representation of a complex system must be necessarily arbitrary and incomplete. Therefore it is an analytical approach that adopts: (a) a set of epistemological assumptions; (b) a set of criteria for defining the quality of the analysis; and (c) a set of expected characteristics for the observed systems, which is totally different from those adopted within the reductionism paradigm. The new meaning given to the MSIA analytical tool derives from the acknowledgment that:
(1) it is impossible to reduce to a single system of accounting information that refers to non-equivalent descriptive domains [= different views of the same reality, which are generated by the choice of either adopting different criteria of observation or focusing on different scales of analysis]. This means that when handling data referring to a picture of a microscope, or to a picture taken by a telescope, or to an ultrasound scan, we should not expect that it is possible to reduce these data to each other using an algorithm. This is not possible; no matter how smart is the analyst. The phenomenon of non-reducibility of patterns expressed (perceived and represented) at different scales is often referred to as “emergence” or “bifurcation in a system of mapping” (Rosen, 1985; 2000). When dealing with non-equivalent descriptive domains and non reducible models the task should be, rather, that of developing the ability of handling in a coherent way the resulting heterogeneous information space (Giampietro, 2003). This predicament in relation to Multi-Criteria Analysis has been called **Technical Incommensurability** by Munda (in press);
(2) it is impossible to rank and weight in a substantive way contrasting values and aspirations found in social interactions [= incommensurability of values within relevant social actors]. When dealing with legitimate but contrasting perspectives in relation to goals, fears and taboos, the task rather is to develop fair and transparent procedures to handle contrasting definitions of what is relevant [to be included in the analysis] and what is irrelevant [to be neglected]. A substantive definition of “the best course of action” is simply not possible when dealing with reflexive systems, such as human systems (Martinez-Alier et al., 1998). This predicament in relation to Multi-Criteria Analysis has been called **Social Incommensurability** by Munda (in press).
(3) non-equivalent descriptive domains are associated to different typologies of data. The difference in type of data can be related to the required time lag to be gathered, to the cost and effort required to be gathered, to their degree of reliability and accuracy. The implications of these differences have to be carefully evaluated when deciding the profile of investment of analytical resources to characterize an investigated system in relation to different dimensions of analysis (e.g. ecological, technical, economic, social, cultural). For example, if there is a clear taboo regarding a potential activity to be implemented in a given socio-economic system, it does not make sense to invest a lot of resources to gather empirical evidence about its technical feasibility (e.g. studying how to improve the efficiency of pig production within Israel).
(4) when dealing with sustainability, future scenarios and evolutionary trends, there is always an unavoidable degree of uncertainty and ignorance on both the ability to detect in time relevant signals of change, and characterize, predict and simulate future scenarios (Funtowicz and Ravetz, 1991). When dealing with genuine ignorance a blind trust in experts and optimizing procedures is just a sign of ignorance of its own ignorance. Marie Curie, the best possible expert of radioactivity

of her time (she won two Nobel Prizes for her outstanding knowledge of radioactive materials) died of leukemia because of her unsafe handling of it.

This is why MSIA was designed as an analytical tool having the following goals:

(1) Keeping clearly separated the descriptive from the normative aspect. This is an important departure from the hidden strategy adopted by reductionism to deal with sustainability. Analyses developed within the paradigm of reductionism try to collapse the descriptive side (characterization of performance) and the normative side (definition of best course of action) into a single step (e.g. cost/benefit analysis, and optimizing models looking for the best solution). Moreover, reductionism assumes that uncertainty and ignorance can be dealt with in substantive way by sound practices of science (e.g. more data, bigger computers and more sophisticated sensitivity analyses). This is so, since they adopt, without recognising it, only a given set of narratives for their analysis. MSIA on the contrary has the goal to represent in an integrated way changes in the performance of an investigated system in relation to different criteria, on different scales and in relation to different narratives. No attempt is made to establish a ranking of importance or priority among contrasting or non-equivalent indications. The existence of uncertainty and ignorance is explicitly acknowledged as an additional input to the process of analysis. Obviously, this implies that MSIA has to be used within a participatory process of integrated assessment. That is, it requires a simultaneous process of Societal Multi-Criteria Evaluation (Munda, in press) to deal with all the inputs of this process that refer to the normative side

(2) Maintaining a balance between the two contrasting tasks of: (i) compression (using typologies to represent individuals by filtering out details referring to special cases); and (ii) redundancy (forgetting about the Occam’s razor and keeping as much as possible details that can be relevant for special individuals operating in special situations). This can be done by adopting a flexible integrated package of models and indicators to be tailored on the specificity of the situation. Depending on the goal of the analysis a given MSIA can be tailored on both: (i) the type of problem to deal with; and (ii) the specific characteristics of the social and ecological system in which the investigated problem is occurring. In this way, it is possible to provide a reliable characterization of the situation (when using scientific knowledge based on types) and reflecting, at the same time, the legitimate perspectives found among the social actors (when considering the peculiarity of real situations, which are all special by definition).

(3) Acknowledging from the beginning the unavoidable arbitrariness implied by the step of modelling. The MSIA approach, in fact, is based on a meta-model of analysis (a metaphorical expected relation among parts and whole) that can have different legitimate formalizations (a family of useful non-reducible models) even when applied to the very same system. Therefore, the approach implies/requires an explicit discussion among the scientists and with the stakeholders (the users of the final model) about the implications associated to any particular choice of a given formalization. In order to characterize a given system in a Multi-Criteria Space (e.g. to calculate the values taken by a selected integrated set of indicators), analysts have to start by assigning a set of identities to the components of the system under analysis (deciding how to define parts, the whole and the context and their interactions). This is the pre-analytical step where the narrative is selected. This is the step in which an input from the stakeholders is explicitly required.

(4) Providing coherence in the chosen way of representing the interaction of human systems and socio-economic systems on: (a) different scales (e.g. when representing the perceptions of individuals, households, communities, provinces, national states, global interactions); and (b) different descriptive domains (e.g. when focusing on different selections of relevant attributes: economic interactions, biophysical interactions, cultural interactions). This can be obtained by establishing a holographic representation of these interactions. To do that the MSIA approach considers exchanges of flows of energy, matter, and added value among parts, wholes and contexts. These flows are represented as moving across compartments defined in cascade across different levels and scales. When moving across levels, these compartments can be viewed as either parts and/or wholes. The set of non-equivalent representations of these flows is then forced into congruence across levels, in the sense that the sum of the flows of the parts (as resulting from their representation at the *level **n-1***) must be equal to the flow of the whole (as resulting from its representation at the at the *level **n***). The definition of parts and wholes can be done by adopting different logics.

The rest of this paper is organized in two sections. Section two provides an example of the power of integration of this approach. It illustrates, using a hypothetical case study, how this holographic process of representation across scales and descriptive domains makes it possible to frame the issue of sustainability in a coherent way across disciplinary fields. In this example it is possible to appreciate how this particular system of integrated accounting is not based on a substantive definition of a protocol to be used do the accounting. In spite of this, the mechanism of accounting is still very effective and rigorous in handling the integrated set of data and assessments. Section three provides an overview of three innovative concepts, developed in the field of complex system theory by Robert Rosen ("mosaic effects across levels", "impredicative loop analysis", and "useful narratives to surf complex time"). These concepts are important since they are the theoretical building blocks of the MSIA approach. This section provides an overview of the technical aspects of the approach.

Part 2
Studying the dynamic budget of metabolic systems across scales

2.1 Societal Metabolism of an isolated society on a remote island

(the material of this section is taken by Chapter 7 of the book -Giampietro 2003)

2.1.1 The goal of the example

In order to express their functions all metabolic systems require a supply of input to sustain their metabolism. For examples: (a) humans need food to express human activity; (b) social systems need exosomatic energy carriers to express socio-economic activities; (c) economic agents need added value to express their economic preferences. In fact, economic agents can exert a degree of control on the process of consumption and production of goods and services by deciding how to produce and spend added value within the economic process.

The surviving of a metabolic system obviously depends on its ability to stabilize the supply of the required input. On the other hand, only a small fraction of the input consumed by a metabolic system as a whole is invested in activities aimed at the stabilization of such an input. Put in another way, all activities expressed by metabolic systems are based on the availability of a required input, but only a fraction of these activities is invested in stabilizing the supply of that input. This implies the existence of biophysical (and economic) constraints on the feasibility of a given metabolic budget for the whole. That is, the money spent over a year by the total hours of human activity associated with a given household (money spent by the whole) must be made available by those hours of human activity invested in economic activities generating a net return (money generated by that fraction of Total Human Activity invested in economic relevant tasks). This entails that, at a given level of expenditure, the smaller is the number of hours invested in activities with net economic return (e.g. Paid Work) the higher must be their return in terms of added value/hour. The same reasoning can be applied to other types of flows. The dramatic reduction in the number of agricultural workers in developed societies has been made possible only because of the dramatic increase in the economic productivity of labor in agriculture. Farmers in developed countries are 2% of the work force and produce hundreds of kg of grains per hour of labor. In poor developing countries, low-tech farmers produce a few kg of grains per hour; there they are more than 60% of the work force. The implications of the biophysical constraints associated to the dynamic budget of different types of flows are important for the expression of diversity of activities within a given socio-economic system. A society that must invest the vast majority of its work force just in feeding itself will never develop the ability of doing a diversified set of economic tasks. It will never become rich.

In general terms, we can say that in a metabolic system organized in nested compartments, it is possible to establish a relation between: (a) relative size of compartments (parts and whole) and (b) relative intensities of metabolized flows (according to typical values that can be associated with the identity of parts and the whole – e.g. expected technical coefficients or expected level of consumption). This analysis can be extended to include both typologies of compartments: (i) those responsible for the ***production*** (the parts generating the required inputs); and (ii) those responsible for the ***consumption*** of various metabolized flows (the parts contributing to the consumption at the level of the whole). In this way, it becomes possible to study the existence of constraints and bottlenecks in relation to different typologies of flows and to establish benchmark values.

Constraints can be detected when finding incongruence between the relative requirement and supply in the dynamic budgets of metabolized flows over different compartments at different levels. Biophysical constraints imply that if there are some compartments which have a throughput much higher than the average, we must find other compartments with a throughput much lower. This inverse relation in the relative value of throughputs is mediated by the relative size of the various compartments.

As soon as one admits that the very survival of metabolic systems is based on the stabilization of autocatalytic loops established across scales, one has to abandon the myth that it is possible to analyze them by using differential equations within a mono-scale analysis. The alternative proposed by MSIA is looking for sets of useful typologies of parts and wholes (characterized in terms of the relative size and specific throughputs) which are able to guarantee congruence of the flows associated to the autocatalytic loop across non-equivalent descriptive domains. This is called "Impredicative loop analysis" and can be defined as an analysis of how the characteristics of the whole ("size" and "throughput") can be distributed over the set of lower level parts (characterized also in terms of "size" and "throughput"), in a way that still makes possible the stabilization of the dynamic budget of the whole.

In the rest of this section we will present an example of "impredicative loop analysis" based on a hypothetical situation of 100 people living in a remote island, and we will apply an impredicative loop analysis to the stabilization of their metabolism in terms of food.

The flow of required food associated with the Total Human Activity of these 100 people has to be produced by the amount of hours invested in the compartment HA_{FP} (Human Activity in Food Production). It is important to be aware that any Impredicative Loop Analysis of this type checks the existence of biophysical constraints, but only in relation to the type of dynamic budget considered. In this example we deal only with the requirement and the supply of food. Obviously, the stability of any particular societal metabolism can also be checked in relation to a lot of other dimensions – i.e. alternative relevant attributes and criteria. For example: Is there enough drinking water? Can the population reproduce in the long term according to an adequate number of adult males and females? Are the members of the society able to express a coordinate behaviour in order to defend themselves against external attacks? Indeed, using an analysis that focuses only on the dynamic equilibrium between requirement and supply of food is just one of the many possible ways for checking the feasibility of a given societal structure.

2.1.2 Theoretical assumptions and basic rationale

This Impredicative Loop Analysis studies the stabilization of an autocatalytic loop of useful energy (the output of useful energy is used to stabilize the input). In this example, the characterization of the autocatalytic loop is obtained in terms of a reciprocal "entailment" of two resources: "human activity" and "food". The terms autocatalytic loop indicates a positive feed-back, a self-reinforcing chain of effects (the establishment of an egg-chicken pattern). Within a socioeconomic process we can define this autocatalytic loop as follows. (1) The resource "human activity" is needed to provide control over the various flows of useful energy (various economic activities both in producing and consuming), which guarantee the proper operation of the economic process (at the societal level). (2) The resource "food" is needed to provide favourable conditions for the process of re-production of the resource "human activity" (i.e. to stabilize the metabolism of human societies when considering elements at the household level). (3) The two resources, therefore, enhance each other in a chicken-egg pattern.

Within this framework our heuristic approach has the goal of establishing a relation between a particular characterization of this autocatalytic loop in relation to the whole (at the **level *n***), and in relation to the various elements of the socioeconomic system, perceived and represented at a lower level (**level *n-1***). The characterization of the elements (whole and parts) will be obtained by using two types of variables.

(A) a variable characterizing the throughput (a flow per unit of size) – kg of food per hour of human activity/year

(B) a variable characterizing the size (for assessing the size of parts and wholes). In the following example, in our socio-economic system, we can define the size of the whole in hours (**THA** = Total Human Activity) and the size of the parts (**HA_i** = Human Activity in the element i). "Hours of Total Human Activity" is a variable directly related to population size and is affected by demographic changes.

In this simplified example, we deal with an endosomatic autocatalytic loop (only human labour and food) referring to a hypothetical society of 100 people on an isolated, remote island. The numbers given in this example are not the relevant part of the analysis "per se". We are providing numbers - which are familiar for those dealing with this topic - just to help the reader to better grasp the mechanism of accounting. ***It is the forced relation among numbers (and the analysis of the mechanism generating this relation) which is the main issue here***. Two points are crucial:

#1 - establishing a clear link between the characteristics of the societal metabolism as a whole (characteristics referring to the entire loop – **level *n***) and the characteristics referring to lower-level elements and higher level elements – either defined at **level *n-1*** or at **level *n+1***).

#2 - closing the loop when describing societal metabolism in energy terms, instead of using linear representations of energy flows in the economic process (e.g. as done with input/output analyses). It is in fact well known that, in complex adaptive systems, the dissipation of useful energy must imply a feed-back, which has to be used to enhance the adaptability of their system of control (Odum, 1971, 1983, 1996). This task requires moving to a multi-scale analysis.

2.1.3 Technical assumptions and numerical data

We hypothesize a society of 100 people that uses only flows of endosomatic energy (food and human labour) for stabilizing its own metabolism. In order to further simplify the analysis, we imagine that the society is operating on a remote island (survivors of a plane crash). We further imagine that its population structure reflects the one typical of a developed country and that the islanders have adopted the same social rules regulating access to the work force as those enforced in most developed countries (that is, persons under 16 and those over 65 are not supposed to work). This implies a dependency ratio of about 50%, that is, only 50 adults are involved in the production of goods and social services for the whole population. A few additional parameters needed to characterize societal metabolism are specified below.

*** Basic requirement of food**. Using standard characteristics of a population typical of developed countries, we obtain an average demand of 9 MJ/day per capita of food, which translates into 330,000 MJ/year of food for the entire population.

*** Indicator of material standard of living**. We assume that the only "good" produced and consumed in this society (without market transactions) is the food providing nutrients in the diet. In relation to this assumption we can define, then, two possible levels of material standard of living, related to two different "qualities" for the diet. The two possible diets are: ***(1) Diet A***, which covers the total requirement of food energy (3,300 MJ/year per capita) using only cereals (supply of only vegetal proteins). With a nutritional value of 14 MJ of energy per kg of cereal, this implies the need of producing 250 kg of cereals/year per capita. ***(2) Diet B***, which covers 80% of the requirement of food energy with cereals (190 kg/year p.c.), and 20% with beef meat (equivalent to 6,9 kg of meat/year p.c.). Due to the very high losses of conversion (to produce 1 kg of beef meat you have to feed the herd 12 kg of grains), this double conversion implies the additional production of 810 kg of cereals/year. That is, Diet B requires the primary production of 1,000 kg of cereals per capita (rather than 250 kg/year of diet A).

*** Indicator of technology**. This reflects technological coefficients. In this case: (i) labour productivity and (ii) land productivity of cereal production. Without external inputs to boost the production, these are assumed to be 1,000 kg of cereal per hectare and 1 kg of cereal per hour of labour.

*** Indicator of environmental loading**. A very coarse indicator of environmental loading used in this example is the fraction "land in production/total land of the island". Since the land used for producing cereals implies the destruction of natural habitat (replaced with the monoculture of cereals). In our example the indicator of environmental loading is heavily affected by: (a) population; (b) the type of diet followed by the population (material standard of living) and (c) the technology used (recalling the I = PAT equation proposed by Ehrlich). Assuming a total area for the island of 500 hectares, this implies an index of EL = 0.05 for Diet A and EL = 0.20 for Diet B (EL = Environmental Loading = hectares in production/total hectares of available in the island).

*** Supply of the resource human activity**. We imagine that the required amount of food energy for a year (330,000 MJ/year) is available for the 100 people for the first year (let's assume it was in the plane…). With this assumption, and having the 100 people to start with, the conversion of this food into endosomatic energy implies (it is equivalent to) the availability of a total supply of human activity of 876,000 hours/year (= 24 hours/day x 365 x 100 persons). This is what is needed to stabilize the resource human activity in the short term. In addition to that, we can imagine that another form of investment is required to stabilize humans. The stability of a socio-economic system requires a certain investment of Human Activity for tasks associated with maintenance and reproduction of THA. This set of tasks must include sleeping, personal care, eating, dating, working out effective personal relations, giving birth to children and taking care of their education. This entails the existence of a Societal Overhead on Human Activity. That is, we should expect that on a given amount of THA a certain fraction will not be available for working in interacting with the context/environment, since it must be dedicated to the reproduction of THA.

*** Profile of investment of human activity of a set of typologies of "end uses" of human activity** (as in **Fig. 1**). These are: ***(1) "Maintenance and Reproduction"*** = As observed in the previous point, in any human society the largest part of human activity is not related to the stabilization of the societal metabolism (e.g. in this example producing food), but rather to "Maintenance and Reproduction" of humans (HA_{MR}). This fixed overhead includes: (a) sleeping and personal care for everybody (in our example a flat value of 10 hours/day has been applied to all 100 people leading to a consumption of 365,000 hours/year out of the Total Human Activity available). (b) activity of non-working population (the remaining 14 hours/day of elderly and children, which are important for the future stability of the society, but which are not available – according to the social rule established before – for the production of food, now). For our budget of THA this implies the consumption of 255,000 hours/year (14 x 50 x 365) in non-productive activities. ***(2) "Human Activity Disposable for Society"*** (HA_{DS}). This is obtained as the difference between "Total Human Activity" (THA = 876,000 hours) and the consumption related to the end use "Maintenance and Reproduction" (HA_{MR} = 620,000 hours). In our example the amount of Human Activity Disposable for tasks of self-organization is HA_{DS} = 256,000 hours/year. This is the budget of human activity available for stabilizing societal metabolism. This budget of human activity, expressed at the societal level has to be divided between two tasks: (1) guaranteeing the production of the required food input (for avoiding starvation now) - "Work for Food" (HA_{WF}); and (2) guaranteeing the functioning of a good system of control able to provide adaptability in the future and a better quality of life to the people - "Social and Leisure" (HA_{SL}).

At this point, we can get into the circular structure of the flows associated with the autocatalytic loop as shown in **Fig. 1**. The requirement of 330,000 MJ/year of endosomatic energy input (food at time t) entails the requirement of producing enough energy carriers (food at time t+1) in the following years. This translates into a biophysical constraint on the level of productivity of labour in the element HA_{WF} (the hours of HA invested in working for food). Therefore, if we want to preserve the characteristics of the whole (the total consumption of the society) it is necessary to invest a not-negotiable fraction of "Total Human Activity" in the end use "Work for Food" (HA_{WF}). The seriousness of this constraint will depend on technology and availability of natural resources. This implies that the fraction of "Total Human Activity" which can be allocated to the end use "Social and Leisure" (the value taken by HA_{SL}) is not a number that can be decided only according to social or political will. The circular nature of the autocatalytic loop entails that numerical values associated to the characterization of various identities defining elements on different hierarchical levels (at the level of individual compartments – extensive – segments on the axis: HA_i - and intensive variables – wideness of angles: throughput in HA_i) can be changed, but only respecting the constraint of congruence among flows over the whole loop. These constraints are imposed on each other by the characteristics and the size – extensive - and intensive variables – used to characterize the various elements.

2.2 Changing the characteristics of the components within a given impredicative loop

Different formalizations of the budget within the same meta-model

Let's imagine now to change, for example, some of the values used to characterize this autocatalytic loop of energy forms. For example let's change the parameter "material standard of living", which - in our simplified model - is expressed by the relevant attribute "quality of the diet" (formalized in the two options Diet A or Diet B). The different mix of energy vectors in the two diets (vegetal versus animal proteins), imply a quantitative difference in the "biophysical cost" of the diet expressed both in terms of a larger work requirement and in a larger environmental loading (higher demand of land). The production of cereals for a population relying 100% on diet A requires only 25,000 hours of labour and the destruction of 25 hectares of natural habitat (EL_A = 0.05), whereas the production of cereals for a population relying 100% on Diet B requires 100,000 hours of labour and the destruction of 100 hectares of natural habitat (EL_B = 0.20). However, to this assessment of work hours required for producing the agricultural crop, we have to add a requirement of work hours for fixed chores. Fixed chores are preparation of meals, gathering of wood for cooking, getting water, washing and maintenance of food system infrastructures in this primitive society. In this example we use the same flat value for the two diets = 73,000 hours/year (2 hours/day per capita = 2 x 365 x 100). This implies that if all the people of the island decide to follow the Diet A, they will face a fixed requirement of "Work for Food". The relative size of the HA_{WF} compartment would be 98,000 hours/year. Whereas, if they would all decide to adopt Diet B, they will face a different requirement of "Work for Food". That is, the relative size of the HA_{WF} compartment would be 173,000 hours/year. At this point, for the two options we can calculate the amount of "Human Activity" that can be allocated to "Social and Leisure". The size of the compartment HA_{SL} can be obtained by considering the difference (HA_{DS} - HA_{WF}). It is evident that the number of hours (HA_{SL}) that the people living in our island can dedicate to: (a) running social institutions and structures (schools, hospitals, courts of justice); and (b) develop their individual potentialities in their leisure time, is not only the result of their free choice. Rather, it is the result of a compromise between competing requirements of the resource "Human Activity Disposable for Social Self-Organization" in relation to different tasks of the economic process.

In this analytical approach, assigning numerical values to social parameters such as population structure (e.g. profile of distribution over age classes) and a dependency ratio for our hypothetical population implies affecting the definition of key characteristics of the autocatalytic loop. In this case, these parameters affect the value taken by: (a) requirement of food energy (330,000 MJ/year) – that is the throughput of the whole; and (b) the Social Overhead on Human Activity – that is the relative size of the compartment "Maintenance and Reproduction" (HA_{MR} = 620,000 hours/year). In this case SOHA = HA_{MR}/THA. In the same way, assigning numerical values to other parameters determining other socio-economic characteristics such as: (i) material standard of living (Diet A or Diet B), and (ii) technical coefficients in production (e.g. labour, land and water requirements for generating the required mix of energy vectors), implies defining additional key characteristics of the autocatalytic loop. Different characterization of the material standard of living (level of consumption per capita) will affect the size of the compartment "Work for Food". That is, depending on the diet, HA_{MR} = 98,000 hours/year for Diet A; and HA_{MR} = 173,000 hours/year for Diet B. Differences in the characterization of the material standard of living, in this system of accounting will also affect the level of environmental loading. In this example, the requirement of land, water as well as the possible generation of wastes linked to the production. This value can be linked, using technical coefficients, to the metabolic flows. In our simple example we adopted a very coarse formal definition of identity for environmental loading which translates into $EL_A = 0.05$ and $EL_B = 0.20$.

With the term internal biophysical constraints we want to indicate the obvious fact, that the amount of human activity that can be invested into the end uses "Maintenance and Reproduction" + "Social and Leisure" [(HA_{MR} + HA_{SL}] depends only in part on the aspirations of the 100 people for a better quality of life in such a society. The survival of the whole system in the short-term (the matching of the requirement of energy carriers input with an adequate supply of them) can imply forced choices. An example of this is given in **Fig. 2**. Depending on the characteristics of the autocatalytic loop, large investments of human activity in "Social and Leisure" – a large value of the size of HA_{SL} expressed in hours - can become a luxury. For example, if the entire society (with the set of characteristics specified above) wants to adopt Diet B, then for them it will not be possible to invest more than 83,000 hours of human activity in the end use "Social and Leisure". On the other hand, if they want together with a good diet also a level of services typical of developed countries (requiring around 160,000 hours/year per 100 people), they will have to "pay for that". This could imply renouncing to some politically important rules reflecting cultural identity and ethical believes (what is determining the Societal Overhead of Human Activity for Maintenance and Reproduction). For example, to reach a new situation of congruence they could decide either to introduce child labour, or increase the work load for the economically active population (e.g. working 10 hours a day for 6 days per week) – **Fig. 2**. In alternative, they can accept a certain degree of inequity in the society (a small fraction of people in the ruling social class eating diet B and a majority of ruled eating diet A). We can easily recognize that all these solutions are operating in these days in many developing countries and were adopted, in the past, all over our planet.

2.3 Lessons from this simple example

The simple assumptions used in this example for bringing into congruence the various assessments related to a dynamic budget of societal metabolism are of course not realistic (e.g., nobody can eat only cereals in the diet, and expected changes in the requirements of work are never linear). Moreover, by ignoring exosomatic energy we do not take in account the effect of capital accumulation (e.g. potential use of animals, infrastructures, better technology and know how which can affect technical coefficients). Capital and flows of exosomatic energy are always relevant for reaching alternative feasible dynamic points of equilibrium of the endosomatic energy budget. That is, there are other options to reach alternative points of equilibrium, beside those linked to changes population structure and size. Actually, following this approach, it is possible to make models for pre-industrial societies that are much more sophisticated than the one presented in **Fig. 1**. Models that take into account for different technologies, quality of natural resources, landscape uses, detailed profiles of human time use, as well as reciprocal effects of changes on the various parameters, such as the size and age distribution of society (Giampietro, 1997; Giampietro et al., 1993; Giampietro et al. 1997). These models, after entering real data derived from specific case studies, can be used for simulations, exploring viability domains and the reciprocal constraining of the various parameters used to characterize the endosomatic autocatalytic loop of these societies. However, models dealing only with the biophysical representation of endosomatic metabolism and exosomatic conversions of energy are not able to address the economic dimension. Economic variables reflects the expression of human preferences within a given institutional setting (e.g. an operating market in a given context) and therefore are logically independent from analysis reflecting biophysical transformations. This is why a Multi-Scale Integrated Analysis has to include and handle simultaneously the representation of economic and biophysical flows.

2.3.1. It enables to link characteristics defined across different levels and scales

Even after admitting its limitation, the example of the remote island clearly shows the potentialities of the Impredicative Loop Analysis. In the example of the island, it was possible to link the conditions determining the feasibility of the dynamic energy budget to the set of key parameters generally used in sustainability discussions. In particular, characterizing societal metabolism in terms of autocatalytic loops makes it possible to establish a "relation" among changes occurring in parallel in various parameters and variables, which are reflecting patterns perceived on different levels and scales. For example, how much would the demand of land change if we change the definition of the diet? What will happen to this society if demographic changes will increase the dependency ratio or if a political reform will affect the dependency ratio by changing work loads per year or retirement age? By adopting this approach, we can explore the viability domain of the dynamic budget (what combination of values of variables and parameters are not feasible according to the reciprocal constraints imposed by the other variables and parameters) in relation to a lot of possible changes referring to different disciplinary fields of analysis.

A technical discussion of the sustainability of the dynamic energy budget represented in **Fig. 1** and **Fig. 2** in terms of potential changes in characteristics (e.g. either the values of numbers on axis or the values of angles) requires considering non-equivalent dynamics of evolutions reflecting different perceptions and representations of the system. That is, the characteristics of the whole society (at **level *n***) in terms of size (THA) and throughput (total food per year) and the characteristics of the various elements (at **level *n-1***) in terms of size (HA_i) and throughput (total food per year either produced or consumed by the various elements) can be related to other relevant characteristics referring to different hierarchical levels of analysis.

For example, if the population pressure and the geography of the island imply that the requirement of 100 hectares of arable land are not available for producing 100,000 kg of cereal (e.g. a large part of the 500 hectares of the island are too hilly), the adoption of Diet B by 100% of population is simply not possible. The geographic characteristics of the island (let's say defined at the **level *n+2***) can be, in this way, related to the characteristics of the diet of individual members of the society (let's say at the **level *n-2***) going through the relation among parts (**level *n-1***) and whole (**level *n***) considered in the impredicative loop analysis. This relation between shortage of land and poverty of the diet is well known. This explains why, for example, all crowded countries depending heavily on the autocatalytic loop of endosomatic energy for their metabolism (such as India or China) tend to adopt a vegetarian diet. However, without adopting a multi-scale integrated analysis it is not easy to individuate and analyze relations across levels within disciplinary mono-scale analyses.

2.3.2 It can handle multiple non-equivalent formalizations of the same problem

To make another hypothesis of perturbation within the ILA shown in **Fig. 1**, let's imagine the arrival of another crashing plane with 100 children at board (or a sudden baby boom in the island). This perturbation translates into a dramatic increase of the dependency ratio. In this system of accounting this is translated in a double size of THA and a larger SOHA = HA_{MR}/THA. That is, a larger food demand, for the new population of 200 people, has to be produced by the same amount of 256,000 hours of "Human Activity Disposable for Society" (related to the disposable activity of the same 50 working adults). In this case, even when adopting Diet A, the larger demand of work in production will force such a society to dramatically reduce the consumption of human activity in the "end use" related to "Social and Leisure". The size of HA_{SL} =158,000 hours/year was feasible in a society of 100 "vegetarians" (adopting 100% Diet A) for this before. But after the new crash of the second plane full of children, the size of the compartment Social and Leisure can no longer be afforded. This could imply reducing the investments of human activity in schools and hospitals (in order to be able to produce more food), at the very moment in which these services should be dramatically increased (to provide more care to the larger fraction of children in the population). A similar forced choice could appear an "uncivilized behaviour" to an external observer (e.g. a volunteer of a NGO arriving on the island). This value judgment, however, can only be explained by the ignorance of such an external observer of the existence of biophysical constraints which are affecting first of all the very survival of that society.

We can generalize the usefulness of Multi-Scale Integrated Analysis of autocatalytic loops by saying that the information used to characterize an impredicative loop associated with a given societal metabolism of a society, translates into a definition of an integrated set of constraints over the value that can be taken by an organized set of two types of variables (extensive and intensive).

This approach can facilitate the discussion and the evaluation of possible alternative scenarios of development in terms of characterization of trade-off profiles. In fact, the congruence among the various numerical values of variables and parameters over the autocatalytic loop can be obtained by using different combinations. It is possible to play either with the value of parameters and/or the value of variables defined at different hierarchical levels, to explore the relative effects in relation to different dimensions of performance, looking for possible viable solutions.

For example, data used so far about the budget of the resource "human activity" (for 100 people) reflect standard conditions found in developed countries (50% of the population economically active, working for 40 hours/week x 47 weeks/year). Let's imagine, now, that for political reasons, we will introduce on the island a working week of 35 hours (keeping 5 or 6 weeks of vacation per year) – a popular idea nowadays in Europe. Comparing this new value to previous work-load levels, this implies moving from about 1,800 hours/year to about 1,600 hours/year per active worker (work absences will further affect both). This reduction translates into an increase in the size of the compartments HA_{SL}. This change would require an adjustment over the autocatalytic loop. That is, either a reduction in the size of HA_{WF} (possible only if the requirement of hours for Work for Food is reduced by better technical coefficients or a reduction in the quality of the Diet), or a reduction in the existing level of investments in the end uses "Maintenance and Reproduction" (the size of HA_{MR} determining SOHA). If this is not the case, depending on how strong is the political will of reducing the number of hours per week, the society has the option of altering some of the given characteristics to obtain a new congruence. One can decide to increase the retirement age or to decrease the minimum age required for entering in the work force (a very popular solution in developing countries, where children below 16 years generally work) to reduce the size of HA_{MR} (the non-working human activity included in the end use "maintenance and reproduction"). Another solution could be that of looking for better technical coefficients (e.g. producing more kg of cereals per hour of labour), but this would require both a lag-time to get technical innovations and an increase in investments of human work in research and development. But after admitting that when looking into future scenarios it is not clear what should be considered as dependent and independent variable, who decides what should be considered as a "given" attribute of the system and what should be considered as the characteristic to be changed when implementing a policy?

2.3.3 It enables to deal with the implications of non-equivalent narratives

When facing the need of adjusting the set of characteristics of an impredicative loop to obtain congruence, the most popular idea introduced by Enlightenment is that of looking for silver bullets able to provide win-win solution. To this respect the Enlightenment can be seen as a remarkable hegemonization on the possible narratives that can be used in a debate over sustainability. The gospel of western civilization implies that the standard solution to all kinds of dilemmas about sustainability has to be obtained by looking for better technical coefficients. This solution, in fact, makes it possible to avoid facing conflicts among the various identities making up an impredicative loop (humans, species, societies, ecosystems, values, beliefs). However, any solution based on adding more and better technology (a change in the characteristics related to intensive variables) does not come without side effects. It necessarily implies an adjustment all over the Impredicative Loop. Well known is the fact that improvements related to a given characteristic defined in terms of an intensive variable (e.g. more efficiency in using a given resource for a task) entail a worsening in relation to another characteristic defined in terms of an extensive variable (e.g. the given resource will be used more for the original task and for other). This is the well known Jevon's paradox (Jevons, 1965; for the relative analysis within the MSIA approach see Giampietro, 2003 – Chap. 1 and 7). The side effect of boosting the size of compartments expressing more efficient activities tends to translate into an increase in the environmental impact of societal metabolism. In our example, this could be the amplification of monocultures (a typology of land use associated with the highest productivity per hour of labour and per hectare). Framing the discussion of future options, within the framework of MSIA over an impredicative loop, implies that the various analysts are forced to consider, at the same time, several distinct effects (which require the simultaneous use of non-equivalent models and variables to be represented) belonging to different descriptive domains.

There are characteristics of the autocatalytic loop that have a very short typical lag time for change, for example economic prices. Other characteristics that have a lag time of changes of a few years are, for example, laws and technical coefficients, which can refer to a very location specific space-time scale (e.g. the yield of cereals at the plot level in a given year) or a large space-time domain (e.g. the efficiency of a gas turbine). Other characteristics, such as the dependency ratio (the ratio between non-working and working population) may reflect slower biophysical processes (those associated to demographic changes) having a time horizon of 20 years. Finally there are other factors – e.g. regulation imposed for ethical reasons such as compulsory school for children – which reflect values related to the specific cultural identity of a society, which have an even slower pace of change (values and taboos tend to be very resilient in human systems). If we admit this fact, then when considering possible ways of obtaining congruence over a MSIA of an impredicative loop associated to a societal metabolism, how to decide what is a variable and what is a parameter? What is the time horizon to be used as reference when making this decision? The very definition of what is a variable and what is a parameter in this type of analysis is associated to the pre-analytical selection of a narrative within which to frame the analysis - see **Fig. 3**.

As noted in the introduction, considering simultaneously events occurring on different levels (adopting a multi-scale reading) can imply finding multiple directions of causation in our explanations. That is, the direction of causality will depend on: (a) what we consider to be a "time independent" characteristic in the definition of the identity of parts and whole. In this case, the elements (parts and wholes within the impredicative loop) are characterized using attributes which are considered parameters; and (b) what we consider to be "time dependent" characteristics in the definitions of the identity of parts and whole. In this case, the elements (parts and wholes within the impredicative loop) are characterized using attributes which are considered variables.

Depending on the narrative some attributes play the role of parameters and other play the role of variables. For example, in a given narrative changes in technical coefficients are key factors driving changes in other system qualities: "population grew because better technology made available a larger food supply". In another narrative changes in technical coefficients are driven by changes in other system qualities: "technology changed because population growth required a larger food supply". These are two different narratives referring to the same impredicative loop. A formalization of a given narrative (a model representing a direction of causality) is only possible after the pre-analytical definition of what is a parameter and what is a variable. Therefore, when choosing a narrative the analyst decides to explore the nature of a certain mechanism of causation (its possible dynamics) by ignoring the nature of others. Using the Impredicative Loop Analysis of the dynamic budget of the remote island we can explain the small body size of a population (after thousands of year of evolution) with the fact that a small body size maximizes, at the level of the whole socio-economic system, the ratio Human Activity/Food Consumed. This is a result that can be considered as good, since it stabilizes the dynamic budget, at a given technology and level of natural resources. On the other hand, a small body size (and short life span) should be considered bad when other potential options enter into play. For example, the option of trade and new technology make it possible for islanders to consume more food escaping location specific biophysical constraints. In general terms, we cannot expect that it is always possible to decide in a substantive way what should be considered as the given set of option. Let alone deciding what priority should be given within a set attributes used to characterize the performance of a system.

This problem is crucial, and this is why we believe that a more heuristic approach to multi-scale integrated analysis is required. Reductionism is based on the adoption of models and variables which are usually developed in distinct disciplinary fields. These models can deal only with one causal mechanism and one optimizing function at the time. To make things worse, in order to be able to do so, these models bring with them a lot of ideological baggage. The ideology associated with the value calls required for choosing a narrative within which the reliability of the assumptions and the relevance of the models have been judged. This ideological baggage, very often, is not declared to the final users of models.

We believe that by adopting a Multi-Scale Integrated Analysis of Impredicative Loops to the study of the interaction of human societies and ecosystems, we can enlarge the set of analytical tools that can be used to check the existence of non-equivalent constraints (lack of compatibility with economic, ecological, technical, social processes) affecting the viability of considered scenarios.

Part 3

3. Going for something “completely different”: innovative concepts used when developing the MSIA approach

3.1 Different goals call for different analytical tools

The methodological approach of Multi-Scale Integrated Analysis (MSIA) has been proposed as an useful tool for representing and discussing “sustainability trade-offs” (overviews are available in Giampietro, 2000; 2001; Giampietro and Pastore, 2001; Giampietro, 2003). This approach is based on the simultaneous use of non-equivalent descriptive domains in order to: (1) cover different dimensions of analysis (social, economic, and ecological); (2) cover different hierarchical levels, which implies adopting different scales for perceiving and representing relevant processes (household, region, country, macroeconomic regions); (3) guarantee the quality of the resulting multi-objective integrated representation, which must be necessarily based on non-equivalent and non-reducible models. Such a boost in the reliability of available scientific descriptions can be obtained by generating redundancy in the information space (by bridging non-equivalent descriptions through the forced congruence of numerical assessment across scales).

In order to achieve these goals the approach uses a few innovative concepts developed in the field of complex systems thinking by the seminal work of Robert Rosen. In particular three innovative concepts have been proposed as building blocks of the approach of meta-analysis MSIA. These three innovative concepts - discussed at length in the book of Giampietro, (2003) – are illustrated in the rest of this section.

3.2 Multi-Scale Mosaic Effect

“forget about the Occam razor and look for a redundancy of external referents to back-up your numerical assessments” (from Chap. 6 – Giampietro, 2003)

3.2.1 Facing the unavoidable steps of “Reduzieren” and “Classifizieren”

In the first part of the Faust of Goethe, Mephistopheles makes fun of the academic agenda adopted by reductionism for dealing with the analysis of living systems. Such an agenda, no matter how complex is what is under analysis, requires always that any analysis should start from the two key steps of: “reduzieren” and “classifizieren”. It should be noted, however, that after more than a century, one of the gurus of hierarchy theory writing with other two complexity thinkers says: “*We should hasten to add that, according to our definition of holism, the holist does perform reductions. Because all explanations are a matter of reducing the system to a set of lower-level explanatory principles, when a holist offers an explanation, it is a matter of reduction*” Allen et al. (2003 pag. 43). Even when moving within the complexity paradigm, the two crucial steps of reducing and classifying cannot be escaped. The only difference, however, is that the implications of complexity entail the explicit acknowledgment that for any situation there are multiple legitimate choices about how to reduce and how to classify (Giampietro, 2003 section 7.3 for a discussion of this point). Therefore, the quality of the selection of a system of classification depends on its usefulness and its consistency. The need of this quality control can be immediately grasped by reading the following list of categories to be used to classify animals. In his essay "The Analytical Language of John Wilkins" Borges claims that such a list is taken from an ancient Chinese encyclopedia entitled

Celestial Emporium of Benevolent Knowledge. The list includes the following categories of animals: (a) those that belong to the Emperor; (b) embalmed ones; (c) those that are trained; (d) suckling pigs; (e) mermaids; (f) fabulous ones; (g) stray dogs; (h) those that are included in this classification; (i) those that tremble as if they were mad; (j) innumerable ones; (k) those drawn with a very fine camel's hair brush; (l) others; (m) those that have just broken a flower vase; (n) those that resemble flies from a distance.

The concept of multi-scale mosaic effect helps the search for useful ways of reducing and classifying complex objects across hierarchical levels. A first way of using redundancy is associated with a typical problem faced when dealing with multi-scale objects. They look different when perceived and represented on multiple scales (Mandelbrot, 1967). For example, looking at the various maps shown in **Fig. 4** it is evident that in order to know where Sri Lanka is located in the world, or where Colombo city is located in Sri-Lanka or where the local stadium is located within Colombo city, we have to use different types of information. On the other hand, it is necessary to keep a certain degree of redundancy across non-equivalent descriptive domains (different maps) in order to make possible to relate the information carried out by a given map to the information carried out by another map. This implies that the information of the map showing the streets around the stadium and the information of the map showing Sri Lanka close to India could never be related to each other without using the chain of overlapping information linking the different maps shown in **Fig. 4**.

A second way of using redundancy coincides with a very useful trick which is often used by experts, when dealing with data sources which are not totally reliable. In this situation, experts tend to back-up a given assessment by using in parallel non-equivalent procedures to generate it. For example, an estimate of the food eaten by a person over a week can be obtained by: (a) looking at a diary which reports the food consumed by that person over a week; and (b) calculating the amount of food that a person with similar characteristics would require in a week. None of the two methods in isolation could be trusted, but whenever the two assessments happen to coincide to an acceptable degree, the experts tend to trust the relative information.

When dealing with metabolic systems a way for obtaining this type of cross-check among data – a Multi-Scale Mosaic Effect can be obtained by establishing relations among assessment of flows based on a chain of **mathematical identities**. Let’s imagine for example to write the identity:

$$\text{Exo} \equiv \text{Endo} \times \text{Exo}/\text{Endo} \qquad (1)$$

In which:

* EXO is the amount of exosomatic energy consumed in a year by a country (fossil energy, and renewable energy). Exosomatic energy is energy used by humans in conversions occurring outside their body (energy metabolized by societal processes);

* ENDO is the amount of endosomatic energy consumed in a year (food energy) by humans in conversions occurring inside their body.

* EXO/ENDO is the ratio among the two flows (how much human activity is amplified by the use of technology).

Whenever a mathematical identity is backed-up by only an external referent (a given data source), the relative indication is basically a tautology. In fact, let’s imagine that we use statistical data to calculate either EXO (e.g. UN energy statistics) or ENDO (e.g. FAO food statistics). Then the identity (1) will collapse into a trivial identity ENDO = ENDO or EXO = EXO. If we use two data sources (e.g. UN energy statistics + FAO food statistics) we can get an assessment for the ratio EXO/ENDO. This is an useful information, but still does not generate any mosaic effect. Completely different is the case in which the two sides of the identity are related to non-equivalent external referents (different type of data source) using other identities. An example of this case is given in **Fig. 5**.

In this way, an interesting bridge can be established among system's attributes that generally are considered totally independent when considered within different scientific disciplines. For example, in relation to the assessment of ENDO: the 196 PJ/year of food reported by FAO statistics for Spain in 1995 have to be congruent with the consumption of food estimated when using a set of attributes relevant for a nutritional analysis. This implies that the combined value of the variables: Average Body Mass (ABM), Metabolic Flow (MF), Population (determining THA), and FLC (Food Losses in Consumption), in Spain in 1995, has to be congruent with the value of 196 PJ/year. The data source for these variables is totally independent from FAO statistics.

In the same way, when considering the assessment of EXO: the 4,240 PJ/year of exosomatic energy reported by U.N. statistics have to be congruent with the level of consumption of energy per hour of human activity in the set of different economic sectors making up the society. This consumption per hour reflects the level of technical capitalization – Exosomatic energy throughput per hours of human activity. This implies that the combined value of the variables: EMR_i (throughput of the various sectors) and HA_i (the size of the various sectors assessed in terms of THA, including the sector of final consumption - household), can be used to calculate in an alternative way the Total Exosomatic Throughput of Spain: 4,240 PJ/year $= \Sigma (EMR_i \times HA_i)$.

3.2.2 Bridging levels by writing a chain of identities across levels

The systemic procedure that can be applied to the analysis of metabolic systems to generate mosaic effects across levels requires two steps:

(1) define a set of compartments using two variables: (i) a variable to characterize the size; and (ii) a variable to characterize the throughput of the metabolic system. An examples of this is given in **Fig. 6** in which the metabolism of a human body is represented in parallel on two hierarchical levels. At the **level *n*** (the whole) and at the **level *n-1*** (the parts). In this example: (a) **kg of human mass** is used to characterize the size of the whole and parts; whereas (b) **Joules/kg of metabolized energy** is used to characterize the throughput of the whole (GJ/year) and parts (Watts). In this examples there are two different choices of how to reduce and classify. In the upper box of the figure, the whole body (**level *n***) is split (**level *n***) into two parts [brain versus rest of the body]. Whereas in the lower box the whole body (**level *n***) is split (**level *n***) into seven parts. The same approach is used in **Fig. 7**, but with a different selection of variables to define size. Land use, rather, than body mass is used for defining the size of whole and parts. In this example, the whole, a given area of a US county (indicated on the map) is divided in 5 parts, defined using 5 categories of land use, to which it is possible to associate an expected level of throughput of exosomatic energy per hectare. The two variables in this case are: (a) ***ha of land use*** to characterize the size of the whole and the parts; and (b) ***Joules/ha*** [(GJ = 10^9 Joules) and (PJ = 10^{15} Joules)] ***of exosomatic energy per year*** – to characterize the throughput of the whole and parts. When organizing a multi-scale representation in this way, there is a certain level of "free information" in the resulting information space, which is due to the innate redundancy of this system of accounting. That is, a

missing value of Exosomatic Metabolic Density (EMD_i) in Fig. 7 could be easily guessed by checking at the statistics of the County about energy consumption of the sector ***i*** and the total area accounted in the relative category of land use. In alternative, characteristics of the lower level elements (e.g. housing and relative life styles) can be gathered by empirical studies and used to estimate the same number.

(2) select a combination of categories that provide the closure across levels in relation to size. As illustrated in the previous examples, the sum of the size of the elements defined at the **level *n-1*** must be equal to the sum of the size of the elements defined at the **level *n***. The category "others" can be used, whenever needed, to obtain such a closure. In this way, it becomes possible to establish a relation between the throughput of the whole assessed at the **level *n*** and the various throughputs of parts assessed at the **level *n-1***. However, it should be noted, that the two different assessments of throughput on different levels (at the **level *n*** and at the **level *n-1***) are not always necessarily reducible to each other. In the example of Fig. 6, for example, the throughput of the whole body can be measured in terms of a flow of MJ of food consumed per year. Whereas, the relative throughput is measured in Watts (Joules per second) of ATP energy in the assessment referring to the brain. In the case of an analysis of energy consumption of a county we can use aggregate assessments of primary energy (Tons of Oil Equivalent) for the whole, whereas for individual elements we can use assessments of consumption of energy forms related to specific end uses, such as electricity. In most of the cases, however, it is possible to establish a mechanism of conversion (using given factors and protocols of calculations) to move from one assessment to another.

The simultaneous accounting of: (a) size; and (b) throughput; for both parts and wholes within a nested metabolic system, translates into the establishment of a double system of mapping for the size of these parts and wholes. That is, we can define the size of parts and whole in two non-equivalent ways: (1) as perceived from within (in relation to the variables used for establishing a multi-level matrix); (2) in relation to the required input from the environment (the aggregate input required from the context). That is, we can say that: the brain is $1/50^{th}$ of the body (2%) in terms of mass (an assessment of size as perceived from the inside). At the same time, we can say that: the brain is $1/5^{th}$ of the body (20%) in terms of energy dissipation (an assessment of size as perceived from the outside). This translates into the fact that, when defining the relative size of parts in terms of requirement of food per year (how much they imply dependency on favorable boundary conditions)1 kg of brain is consuming like 10 kg of average body mass.

3.2.3 Using dendograms to build redundancy across descriptive domains

This approach can be generalized by imagining an analysis in which several throughputs can be considered (e.g. added value flow, endosomatic and exosomatic flows, critical mass flows) in a common skeleton of equations of congruence against the same multi-level matrix.

For example **Fig. 8** and **Fig. 9** show two similar dendograms based on the same variable determining a multi-scale matrix for the size of compartment: Human Activity and two variables for the throughput: (i) exosomatic energy and (ii) added value. These figures will be illustrated in detail in the paper of Ramos-Martin and Giampietro, (2004).

The formation of this skeleton is based on three logical steps.

(1) The socioeconomic system is divided into a set of relevant compartments, whose size is

characterized in terms of investments of Human Activity (the common matrix that provides closure). That is THA at the **level *n***, must be equal to the sum of HA_i (the investments of human activities in the various sectors) defined at the **level *n-1***, following a nested hierarchical structure. For example: [whole country – **level *n***] → [economic sectors **level *n-1***] → [economic sub-sectors **level *n-2***] → . . . → [individual economic activities **level *n-x***].

(2) Each compartment can be characterized in terms of: (i) expected throughput; and (ii) size.

(3) After having implemented this mechanism of characterization, it is possible to establish a relation between the size of each compartment – parts and whole - expressed in two perceptions of size from the inside – using hours of Human Activity - and from the outside – using either assessments of GDP or assessments of Exosomatic Energy:

* EMRi = Exosomatic Metabolic Rate of the compartment ***i*** (exosomatic energy per unit of human activity in the compartment **i**);

* ELPi = Economic Labor Productivity of the compartment ***i*** (added value per unit of human activity in the compartment **i**)

Generalizing the hierarchical frame to be used for representing the relative relations (assuming α and $\alpha-1$ as two contiguous hierarchical levels) we can write:

* $X_i = HA_i / HA_k$ = the *fraction* of “human activity HA_k” invested in the i-th sector.

[elements ***i*** belongs to the level ($\alpha-1$), element ***k*** belongs to the level (α)]

* $ET_i = HA_i \times EMR_i$ = the exosomatic energy spent in the i-th sector - at the level ($\alpha-1$)

* $EMR_i = ET_i / HA_i$ = the exosomatic metabolic rate in the i-th sector - at the level ($\alpha-1$)

* $GDP_i = HA_i \times ELP_i$ = the added value productivity of the i-th sector - at the level ($\alpha-1$)

* $ELP_i = GDP_i / HA_i$ = the economic labor productivity of the i-th sector **-** at the level ($\alpha-1$)

* $ET_{\alpha} = \sum (ET_i)_{\alpha-1}$ e.g. $TET = (ET_{PS} + ET_{SG} + ET_{HH})$

* $HA_{\alpha} = \sum (HA_i)_{\alpha-1}$ e.g. $THA = (HA_{PS} + HA_{SG} + HA_{HH})$

* $GDP_{\alpha} = \sum (GNP_i)_{\alpha-1}$ e.g. $GDP = (GDP_{PS} + GDP_{SG})$

In these examples, the values referring to the whole country ($TET = ET_{AS}$; $THA = HA_{AS}$; $GDP = GDP_{AS}$) - the α level - are related to the values taken by the same variable in the lower level - ($\alpha-1$) – over the compartments: PS (productive sector); SG (service and government); and HH (Household Sector). In any case, when looking at the common dendogram of ET_i supporting both the economic and the biophysical reading – Fig. 10 - it is easy to understand the power of integration of this approach (for more details see Giampietro and Mayumi, 2000a; 200b)

3.2.4 Moving from a multi-scale mosaic effect to a multi-scale holographic effect

In the examples given in **Fig. 8**, **Fig. 9** different assessments of throughputs were mapped against the same multi-level matrix of sizes of Human Activity. This generates a multi-scale mosaic effect across descriptive domains - **Fig. 10**. In this way changes in EMRi can be related in some way to changes in ELPi because they are occurring within the common matrix of HAi, as discussed with practical examples in the paper of Ramos-Martin and Giampietro, (2004). By following this rationale we can imagine to increase the level of internal entailment of this information space by mapping the same selection of throughputs (exosomatic energy and added value) across levels simultaneously against two independent characterizations of the multi-level matrix generating dendograms of sizes. That is, we can have two multi-scale mosaic effects based on two different mechanisms of definition of whole and compartments, using two multi-level matrices based on: (a) **the variable hours of human activity**. This analysis establishes a link between the represented changes and socioeconomic narratives; and (b) **the variable hectares of land use**. This analysis establishes a link between the represented changes and ecological narratives.

This double multi-scale mosaic effect, even if referring to non-equivalent logics for the definition of size (human activity versus land use) must respect the congruence of flows of added value, energy, food and matter across the two multi-level matrices. We can call this a sort of ***multi-scale holographic effect*** which is able to establish a link across levels and descriptive domains in relation to two different logics used for defining elements, whole and parts (typologies of human activities and typologies of land use). Within this multi-scale integrated analysis the set of values of the variables considered in one side of the analysis (when mapping throughputs against compartments and wholes made of typologies of human activity) must change in coordination with the set of values of variables considered in the other side (when mapping throughputs against compartments and wholes made of typologies of land uses). Obviously, it is not possible to obtain a substantive, formal correlation among changes in the values of variables within such a holographic representation. This organization of the relative information implies too many degrees of freedom. There are many different ways that can be adopted to get a congruent formalization of the representation of flows in parallel across levels and non-equivalent characterizations. In spite of this fact, we still believe that a Multi-Scale Integrated Analysis based on a multi-scale holographic effect, does increase the quality of the representation, by eliminating scenarios which are not consistent, by enabling cross-checks among analyses, by establishing relations among changes occurring within non-equivalent descriptive domains. Examples of this approach are given below, and can be found in Giampietro, 2003; Gomiero and Giampietro, 2001; Pastore et al, 2000; Ramos-Martin and Giampietro, 2004.

3.3 Impredicative Loop Analysis (Dynamic Budget Analysis) (from Chap. 7 - Giampietro, 2003)

"rather than denying the existence of chicken-eggs mechanisms, explore their nature"

3.3.1 Definition

Impredicativity has to do with the familiar concept of chicken-egg problem, or what Bertrand Russel called "vicious circle"(quoted in Rosen, 2000 p. 90). Even the latest developments of theoretical physics – e.g. superstring theory – represents a move toward the very same concept. Introducing such a theory Gell-Mann (1994) makes first reference to the *bootstrap principle* (based on the old say about the man that could pull himself up by his own bootstraps) and then describes it as follows: "*the particles, if assumed to exists, produce forces binding them to one another; the resulting bound states are the same particles, and they are the same as the ones carrying the forces. Such a particle system, if it exists, gives rise to itself*". (Gell-Mann, 1994 p. 128). The passage basically means that you have to assume the existence of a chicken to get the egg that will generate the chicken and vice-versa. As soon as the various elements of an autocatalytic loop – defined in parallel on different levels - are at work, such a process is able to define (assign an identity) to it-self. The representation of this process, however, requires considering dynamics and identities that can only be perceived and represented by adopting different space-time scales.

A more technical definition of impredicativity provided by Kleene and related more to the epistemological dimension is reported by Rosen (2000, p. 90): "*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*" (Kleene, 1952 pag. 42).

Impredicative loops can be explored by explicitly acknowledging the fact that they are in general occurring across self-entailing processes operating (perceived and represented) in parallel over different hierarchical levels. That is, definitions based on impredicative loops refer to mechanisms of self-entailment operating across levels and which therefore require a set of representations of events referring to both parts and wholes in parallel over different scales. Exactly because of that they are out of the reach of reductionist analyses (Giampietro, 2003; section 7.3). That is, they are out of the reach of analytical tools developed within a paradigm that assumes that all the phenomena of the reality can be described **within the same descriptive domain, just by using a set of reducible models referring to the same substantive definition of space and time**.

3.3.2 Meta-analysis of autocatalytic loops across levels

Let's define now a procedure which can be used, in general terms, to represent autocatalytic loop of energy forms in hierarchically organized metabolic systems.

Let's imagine that the elements of a socio-economic systems considered for drawing the dendograms represented in **Fig. 8** and **Fig. 9** are grouped using a different logic. This can be obtained by dividing the components described at the **level *n-1*** into two different classes: (1) those which do not stabilize the throughput consumed by the whole. These elements are aggregated in a new compartment labelled as "indirect" in; (2) those which do stabilize the throughput consumed by the whole. These elements are aggregated in a new compartment labelled as "direct" - **Fig. 11.a**. In this view, the black box – seen as a whole (at the **level *n***) - can receive an adequate supply of the required input thanks to the activity of the direct compartment (at the **level *n-1***). Then the variable used to assess the size of the whole (the one used for defining the multi-level matrix) is used to assess a profile of investments – within the black box - over lower level compartments. In order to do that, we adopt the view **from the inside** to assess the size of the parts in relation to the whole. At this point, we can represent that the total input is dissipated within the black box in three distinct flows (indicated by the 3 arrows in dark green in **Fig. 11.a**):

(1) spent for an overhead required for the stability of the whole (reproduction and maintenance);
(2) spent for the operation of the compartment labelled as indirect (at the **level *n-1***);
(3) spent for the operation of the compartment labelled as direct (at the **level *n-1***).

The favourable conditions perceived at the **level *n+1*** are exploited thanks **to the tasks performed by the components belonging to the direct compartment** (the representation of energy transformations) at the **level *n-1***. There is a crucial characteristic: the return between the energy input made available to the whole system (at the **level *n***) per unit of useful energy invested by the direct compartment (at the **level *n-1***) into the interaction with the environment. This return will determine the strength of the autocatalytic-loop of energy associated with the exploitation of the resources.

This integrated use of non-equivalent representations of relations among energy transformations across levels is at the basis of the Impredicative Loop Analysis shown in the example of the island.

The general template for performing this congruence check is shown in **Fig. 11.b**. The 4-angle figure combines intensive (throughputs) and extensive (sizes) variables used to represent and bridge the characterization of metabolic process across levels. The 4-angle figure establishes a relation between a set of formal identities (= given sets of proxy variables associated with relevant attributes used to characterize the investigated systems), which are used to represent inputs to parts, parts, whole and the interaction of both whole and parts with the environment across scales.

The two angles on the left side (α and β) refers to the profile of distribution of the total available supply of human activity [or colonized land], indicated on the upper part of the vertical axis, over the three flows of internal consumption, according to the mapping provided by an extensive variable used for size. The angle α refers to the fraction of the total supply that is invested in overhead (e.g. for structural stability of the system). The angle β refers to the profile of distribution of the fraction of the total left after the reduction, which is implied by the angle α, between direct and indirect components. What is left of the original total – after the second reduction implied by the angle β - for operating the direct compartment, at this point, is the value indicated on the lower part of the vertical axis. This represents the amount of extensive variable (using still a mapping related to the internal perception of size) that is invested in the direct interaction with the environment.

The two angles on the right (γ and δ) are used for a characterization of the interaction of the system with the environment (the relation between the blue and red arrows in **Fig. 11a** and **Fig. 11b**).

The set of formal identities used to represent the autocatalytic loop define which variables have to be used in such a representation in terms of both *throughput* and *size*. The selected set of typologies has to fulfil the double task of making possible to relate the perception and representation of relevant characteristics of parts in relation to the whole in relation to the two complementing perspectives: (i) from the inside - what is going on inside the black box; (ii) from the outside –what is going on between the black box and the environment. This second task implies considering characteristics (and variables) relevant to study the stability of boundary conditions, in the interaction with the context (economic viability, energy self-sufficiency, biophysical constraints affecting critical material flows).

3.3.2 Examples of ILA

Impredicative Loop Analysis implies establishing a general relation of congruence among different types of flows of energy forms which are self-entailing within an autocatalytic loop across scales. An example of four applications of this approach is given **Fig. 12**. The general meta-representation based on 4-angle given is applied to four realization of autocatalytic loops of exosomatic energy in: (1) Spain 1976; (2) Spain 1996; (3) Ecuador, 1976; and (4) Ecuador 1996 (Ramos-Martin, 2001; Falconi 2001).

The combined use of two type of variables (throughput – intensive; and size – extensive) makes it possible to make a distinction between growth (an increase in size while maintaining the same set of values for the throughputs) – what happened to Ecuador in this time window - and development (a re-adjustment of the relative value of throughputs across levels) – what happened to Spain. In particular this approach makes possible to study the mechanism determining this different evolutionary trajectories – these issue are discussed in Ramos and Giampietro, 2004.

In more general terms, MSIA can be used to study how the value of throughputs at the **level *n*** and **level *n-1*** – that is, the value of the various angles – can be related to the characteristics of typologies defined at the **level *n-2***. The general meta-model based on the analysis of a nested chain of typologies is given in **Fig. 13**. This approach can also be used to study the effect of technological changes and demographic changes (e.g. demographic transition, Kuznet curves, I=PAT equation) – Giampietro, 1998; Giampietro and Mayumi, 2000b.

Another application of the MSIA approach is in farming system analysis. In this field, it can be used to individuate relevant typologies of units at different levels (e.g. household types, village types). Typologies can be individuated by checking the biophysical constraints on economic viability that can be associated to the profile of investment of either human activity – **Fig. 14a** - or colonized land – **Fig. 14b**. The same analysis can be applied in relation to food self-sufficiency when adopting food as the variable used for the throughput (for additional examples see Chap. 9 of Giampietro, 2003).

This approach can be applied at the level of a household type – see **Fig. 15a** and **Fig. 15b** - to establish a relation between: (a) a multi-criteria characterization of performance, based on an integrated set of indicators; and (b) the relative pattern of land uses associated to such a performance. This means establishing a bridge between socio-economic narratives (linked to discussions of sustainability in relation to socio-economic processes) with ecological narratives (linked to discussions of sustainability in relation to ecological processes).

This bridge can be moved up across hierarchical levels maintaining the mosaic effect across scales. An example (taken from the same study), is provided in **Fig. 16a**, in which the same analysis is performed at the level of the village (seen as a whole made by lower level elements, characterized as typologies of households in terms of human activities and land use), and in **Fig. 16b**, in which the same analysis is performed at the level of the Commune (an administrative unit that includes three villages).

3.4 Looking for useful narratives for surfing complex time (Chapter 8 - Giampietro, 2003)

"what remains the same in a system that is becoming something else?"

3.4.1 Introducing the concept of complex time

To introduce the concept of complex time, let's have a look at the two sets of 4 pictures given in **Fig. 17** (***left*** and ***right***). We **can imagine** that the 4 pictures on the left refer to 4 different persons, and that these pictures have been taken in the same day. Whereas, we can imagine that the 4 pictures on the right refer to the same person, and that these pictures have been taken at different points in time. If this is true, then, in the first case, we are looking at 4 different individuals, each having a given metabolic pattern associated to their identity/typology of human being. The 4 typologies considered are: child, adult woman, lady, old lady. Obviously, we know that the identities of these individuals are all becoming in time (they are all ageing). However, when studying these systems at a given point in space and time, we can characterize these four individuals (using the relative perception and representation) as 4 actual realizations of 4 different typologies of human being. These 4 typologies are, therefore, useful categories which can be used to perceive and represent human beings within models. In the second case, we are looking at a given individuality that is moving – in the series of 4 pictures - across a predictable trajectory of typologies: child, adult woman, lady, old lady. This means that the same individual can become a realization of different types, at different points in time. In this case, the same individual will require the use of different formal identities of the observation space for being characterized against the expected standards of the relative type. We have to use a set of expected values to say whether the motility of a given child is higher or lower than the average. Obviously, the same type of analysis applied to the old lady would require a different set of benchmarks and models.

The concept of complex time implies acknowledging the existence of 4 relevant time differentials in relation to the usefulness of an observer/observed complex:

(1) dt - time differential adopted within the models used to represent the observed. For example this is the dt adopted by differential equations used to represent the dynamics relative to observable qualities associated to the metabolism of a given individual human being. The **dt** used in differential equations used to describe the process of respiration or the dynamics associated to hart beats for each of the 4 types – either child or old lady. Such a **dt** could be in the order of seconds.

(2) dτ - time differential relative to the need of updating models within a given narrative. In the example of the representation of a human being, this would be the time differential required to deal with the fact that during the process of ageing an individual human being moves across different types (e.g. child, old lady). Analytical models and benchmarks useful for dealing with a child do not maintain their validity when used for dealing with an old lady. The time differential useful for detecting the process of ageing (**dτ**) – in this example 30 years - is not compatible with the time differential used to represent with differential equations (**dt**) the rhythm of respiration or of hart beat of individuals of different ages.

(3) dθ - time differential relative to the need of changing the choice of observation criteria determining the relevance of narratives and models within the observer/observed complex. The existence of this third relevant time differential is often neglected by reductionism. But this is a dangerous mistake. The observer must be part of an observation process, an observer/observed complex. Within such a complex the observer is becoming in time as the reality she/he is observing. Relevant changes of the observer refer to her/his interests, knowledge, fears and values, which do change in time. Changes in the observer translate into a change in the priorities and the definitions of what is relevant in relation to given beliefs and taboos. The most problematic aspect of changes occurring in the observer is related to the fact that they have a nature and a tempo often totally logically independent from those affecting the first two time differentials considered so far. A self-explanatory example is given in **Fig. 18**.

(4) dT – time differential relative to the maintenance of meaning within an observer/observation complex in relation to its ability to evolve in time. This fourth relevant time differential is related to the stability of the process able to generate meaning for the narratives within which models are developed. This has to do with the ability to guarantee that the relative knowledge is useful for guiding action. A self-explanatory example of this fact is given in **Fig. 19**.

3.4.2 *The distinction between models and narratives*

There is a deep problem with the two interpretations given to the two sets of pictures of **Fig. 17**. If the two sets of pictures were of the same technical quality, nobody would be able to decide for sure which one of the two interpretations is the right one. That is, without first-hand knowledge of these persons it is not possible to know whether or not each of the two series of 4 pictures is showing: (a) a given individuality becoming in time a realization of 4 different types; or (b) a set of 4 distinct individualities expressing in parallel the same set of 4 different types. In order to be able to decide that, we should be an observer that knows directly about the special history of the individualities depicted in the pictures and that uses a variety of types of information to back-up such knowledge. This is a deep epistemological challenge associated to the concept of ***sameness*** in living systems.

Science can only perceive and represent the characteristics of an equivalence class (types). This is why error bars are required for the relative assessment. On the other hand, each living system (socio-economic systems considered at all levels, and ecological systems considered at all level) is special. Individuals are special realizations which can only be known in the form of types. This is why redundancy, mosaic and holograms across non-equivalent mechanisms of mapping are so popular among living beings (Rosen, 2000). Because of this fact, we can expect to find two types of useful knowledge for living observers/agents:

(i) a knowledge based on types; this is made of general laws applied to expected relations among types. This is the knowledge of medical doctors about human types;

(ii) a knowledge tailored on the special history and characteristics of individuals. This is the knowledge of a mother about her child.

Both types of knowledge are required by a living agent/observer. Models and laws based on types are able to give a good power of compression and prediction. You study "dogs" and you can guess a lot about an incoming dog, even when you are meeting that dog for the first time. At the same time, it is important to use wisdom whenever applying general laws at a given point in space and time. This process of contextualization requires the definition of rules, used to guide action in a given situation and in relation to the specificity of the individualities interacting in it.

The distinction between models and metaphors introduced by Rosen (1985) is useful here.

(1) **model**, a useful relation established among values of variables by an inferential system, which makes it possible to simulate perceived patterns of causality in the reality. Models rely on the form of knowledge based on types. They imply four steps (a) encoding relevant observable qualities of the observed system into proxy variable; (b) apply an inferential system to these variables to generate a pattern of formal entailment on the value taken by these variables; (c) decoding the result obtained on the variables into an expected behaviour in the qualities of the modelled system. (d) validate the model by checking the predictions of the model against the perceived causality in the reality. The operation of models can only be done in a universe of types representing dynamics in simple time.

(2) **metaphor**, a useful meaning carried out by a model which helps to make prediction in relation to a given situation. Metaphors are based on a combined use of the two forms of knowledge (those referring to types and individuals). They represent the tuning of a form of knowledge based on types on a form of knowledge that considers the specificity of context and observer/agent. Such a tuning is required to contextualize the indications of a model in a specific situation. Metaphors imply a step of decoding of reality without a preliminary step of encoding. This means that we can not validate the usefulness of metaphor in formal terms, but only in semantic terms.

Through the distinction between models and metaphor, we can explore better the definition of narrative. Selecting a narrative has to do with selecting potential useful perspectives across scales (recall the discussion about Fig. 3). With the definition of types, rate-dependent processes are re-scaled to become rate-independent representations of perceptions and events. A narrative is a series of elaborate scaling operations that allows different processes of different sizes and rates to be made commensurable in our organization of perceptions and representations of events (Allen, 2004). Because of this, narratives are never substantive, they are always "observer and observed specific". That is, to be useful they have to reflect the characteristics of the observer/observed complex. This implies two crucial points: (1) any selection of a useful narrative, which is a mandatory preliminary step to the selection and development of models, has to be checked in terms of quality. This check has to be done with the users of the analysis. Selecting a narrative implies a large dose of arbitrariness and therefore it requires the assumption of responsability (Allen et al. 2001). (2) any useful narrative, even if validated by previous experience and already agreed upon by all relevant actors, tends to expire. This implies that the quality check on the narratives used in a given problem structuring has to be continuously updated. Humans in their struggle for sustainability have to continuously look for useful narrative to surf complex time.

3.4.2 How to surf complex time: the endless iteration among MSIA and SMCE

Recalling what discussed in Part 1, we can say that when dealing with multi-scale integrated analysis of sustainability it is not possible to define in substantive terms the "right problem structuring" on the descriptive side and "the best course of action" on the normative side. According to the paradigm shift implied by Post-Normal Science (see Ravetz and Funtowicz, 1999; and Chapter 4 and Chapter 5 in Giampietro, 2003), Science for Governance when applied to sustainability has to face the crucial predicament of Quality Assurance. This translates into an iterative use of two different tool kits required for performing a quality check on both the descriptive and the normative side. :

(A) A tool kit for '**Discussion Support**'

In this activity scientists are the main actors and social actors the consultants: the goal is the development of integrated packages of analytical tools (indicators, models, protocols for data analysis) required to do a good job on the descriptive side. This information space has to be constructed according to an EXTERNAL input received from the social actors about what should be considered as relevant and/or good and bad. The social actors, as consultants, have to provide a package of questions to be answered. But the scientists are those in charge to process such an input according to the best available knowledge of the issues under analysis.

(B) A tool kit for '**Decision Support**'

In this activity stakeholders and other social agents are the main actors and scientists the consultants: the goal is the development of an integrated package of procedures required to do a good job on the normative side. The resulting process should make possible to decide, through negotiation: (1) what is relevant and what should be considered as good and bad in the decision process, (2) what is an acceptable quality in the process generating the information produced by the scientists (e.g. definition of quality criteria: relevance, fairness in respecting legitimate contrasting views, no cheating with the collection of data or choice of models), and (3) deciding for a solution, a scenario or a policy to be implemented. This process requires an EXTERNAL input (given by scientists) consisting of a qualitative and quantitative representation of the situation on different scales and dimensions. Scientists have to include also, in their input, information about expected effects of changes induced by the decision under analysis (discussion of scenarios and reliability of them). The social actors are those in charge to decide how to process such an input. This is what we introduced before as ***Social Multi-Criteria Evaluation***.

A self-explanatory overview of how the MSIA tool kit can be used within such a structured iteration between these two tasks of quality control is provided in **Fig. 20**.

Conclusions

This paper does not claim that the analytical approach MSIA is a silver bullet. MSIA does not get rid of all the problems faced by scientists willing to generate quantitative analyses to be used in a debate over sustainability. On the other hand, we claim that MSIA is an honest attempt to take seriously the implications of complexity, that is, it does not just pay lip services to the need of a paradigm shift.

By adopting a set of innovative concepts developed within the field of complex system thinking MSIA can provide:

(1) an organized procedure for handling a set of useful representations of relevant features of the system reflecting stakeholders views - e.g. definition of a set of models which use non-equivalent identities and boundaries for the same system. In this way it becomes possible to represent over different descriptive domains different structures and functions – a multidimensional, multiscale analysis;

(2) a definition of the feasibility space (= range of admissible values) for each of the selected indicators of performance. A definition of feasibility should consider the reciprocal effect across hierarchical levels of economic, biophysical, institutional and social constraints;

(3) a multicriteria representation of the performance of the system, in relation to a given set of incommensurable criteria. This requires calculating the value for each indicator included in the package selected by social actors. In this way it becomes possible to represent: (i) Targets - what should be considered an improvement when the value of the relative variable changes, (ii) Benchmarks - how the system compares with appropriate targets and other similar systems, (iii) Critical non-linearity - what are possible critical, threshold values of certain variables where non-linear effect can be expected to play a crucial role.

(4) a strategic assessment of possible scenarios. This implies addressing explicitly the problem of uncertainty and the implications of expected evolutionary trends. In relation to this point, the scientific representation can no longer be based only on steady-state views and on a simplification of the reality represented considering a single dimension at a time (an extensive use of the "ceteris paribus hypothesis"). Conventional reductionistic analyses have to be complemented by analyses of evolutionary trends. A sound mix of non-equivalent narratives has to be looked for. That is knowledge based on expected relations among typologies (laws based on types are out time), have to be complemented by knowledge of the *particular history* of a given system.

References

Ahl V. and Allen T. F. H., 1996 *Hierarchy Theory* . New-York: Columbia University Press.

Allen, T.F.H. 2003 *For simple systems we can use models, but complex systems must have narrative* Paper presented at the International Workshop Interfaces Between Science and Society: Collecting Experiences for Good Practice Milan, **http://alba.jrc.it/interfaces/** Organized by the European Commission, Joint Research Center, Ispra 27-28 November, 2003

Allen, T.F.H. and T.W. Hoekstra 1992. *Toward a Unified Ecology*. New York: Columbia University Press.

Allen, T., Starr, T. ,1982. *Hierarchy: Perspectives for Ecological Complexity*. University of Chicago Press, Chicago .

Allen, T. F. H., Tainter, J. A., and Hoekstra T. W. 2003 *Supply Side Sustainability* New York: Columbia University Press

Allen, T. F. H., Tainter, J. A., Pires J. C. and Hoekstra T. W. 2001 Dragnet Ecology, “Just the facts Ma’am”: the privilege of science in a post-modern world. *Bioscience* **51**:475-485

Box, G.E.P., 1979 Robustness is the strategy of scientific model building. In R.L. Launer and G.N. Wilkinson (Editors) *Robustness in Statistics* Academic Press N.Y. pp. 201-236

Chaitin, J.G., 1975. Randomness and mathematical proof. *Scientific American*, 232 (5): 47-52.

Falconi-Benitez, F., 2001. Integrated assessment of the recent economic history of Ecuador, *Population and Environment*, 22 (3): 257-280.

Funtowicz S.O., Ravetz J. R. (1991) - A new scientific methodology for global environmental issues, in R. Costanza (ed.)- *Ecological Economics,* New York, Columbia, pp. 137-152.

Gell-Man, M. 1994. *The Quark and the Jaguar.* Freeman, New York.

Giampietro, M. 1997 Linking technology, natural resources, and the socioeconomic structure of human society: A theoretical model. In: L. Freese (Ed.), *Advances in Human Ecology,* Vol. 6. JAI Press, Greenwich (CT), pp. 75-130.

Giampietro, M. 1998. Energy budget and demographic changes in socioeconomic systems. In: U. Ganslösser and M. O'Connor (Eds.), *Life Science Dimensions of Ecological Economics and Sustainable Use*, Filander Verlag, Fürth. Pag: 327-354

Giampietro, M. (guest editor) 2000. Special issue of ‘Population and Environment’ on Societal Metabolism—Part 1 of 2: Introduction of the Analytical Tool in Theory, Examples, and Validation of Basic Assumptions. *Population and Environment* 22 (No. 2).

Giampietro, M. (guest editor) 2001. Special issue of *Population and Environment* on Societal Metabolism-Part 2 of 2: Specific Applications to Case Studies. *Population and Environment* 22 (No. 3).

Giampietro M. 2003. *Multi-Scale Integrated Analysis of Agro-ecosystems* [Series of Advances in Agroecology - C. Edwards Editor] CRC Press Boca Raton 472 pp.

Giampietro, M., Bukkens, S.G.F. and Pimentel, D. 1993. Labor productivity: A biophysical definition and assessment. *Human Ecology* 21 (3): 229-260.

Giampietro, M., Bukkens S.G.F. and Pimentel D. 1997. Linking technology, natural resources, and the socioeconomic structure of human society: Examples and applications. In: L. Freese (Ed.), *Advances in Human Ecology,* Vol. 6. JAI Press, Greenwich (CT), pp. 131-200.

Giampietro M. and Mayumi K. 2000a Societal Metabolism and Multiple-Scales Integrated Assessment: introducing the approach – *Population and Environment* Vol.22 (2): 109-153

Giampietro, M. and Mayumi K. 2000b Multiple-Scale Integrated Assessment of Societal Metabolism: integrating biophysical and economic representation across scales - *Population and Environment* Vol. 22 (2): 155-210

Giampietro, M., and Pastore, G. 2001. Operationalizing the concept of sustainability in agriculture: characterizing agroecosystems on a multi-criteria, multiple-scale performance space. In: S.R. Gliessman (editor), *Agroecosystem Sustainability: Developing Practical Strategies*. CRC Press, Boca Raton, pp. 177-202

Gomiero, T. and Giampietro, M. 2001. Multiple-scale integrated analysis of farming systems: The Thuong Lo commune (Vietnamese uplands) case study. *Population and Environment* 22 (3): 315 -352.

Jevons, W.S., [1865] 1965. *The Coal Question: an inquiry concerning the progress of the nation, and the probable exhaustion of our coal-mines*. A. W. Flux (Ed.), 3rd ed. rev. Augustus M. Kelley, New York.

Mandelbrot, B.B. 1967. How Long is the Coast of Britain? Statistical Self-Similarity and fractal dimensions *Science* 155: 636-638

Martinez-Alier, J., Munda, G., O'Neill J., 1998. Weak comparability of values as foundation for ecological economics. *Ecological Economics*, 26:277-286.

Munda, G. (in press) Social Multi-Criteria Evaluatin (SMCE): Methodological Foundations and Operational Consequences *European Journal of Operational Research* available on line (using the number of reference: doi:10.1016/S0377-2217(03)00369-2)

Odum, H.T. 1996. *Environmental Accounting: EMergy and Decision Making*. John Wiley New York.

Odum, H.T 1983. *Systems Ecology*. New York: John Wiley.

Odum, H.T. 1971. *Environment, Power, and Society* New York: Wiley-Interscience

Pastore, G., Giampietro, M. and Mayumi, K. 2000. Societal metabolism and multiple-scales integrated assessment: Empirical validation and examples of application. *Population and Environment* 22 (2): 211-254.

Ramos-Martin, J. 2001, Historical analysis of energy intensity of Spain: From a "conventional view" to an "integrated assessment", *Population and Environment* **22** (3): 281-313

Ramos-Martin, J. and Giampietro 2004 Multi-Scale Integrated Analysis of Societal Metabolism: learning from trajectories of development and building robust scenarios Paper presented at the Millennium Ecosystem Assessment International Conference Bridging Scales and Epistemologies – Panel 2 - Session 11.4.

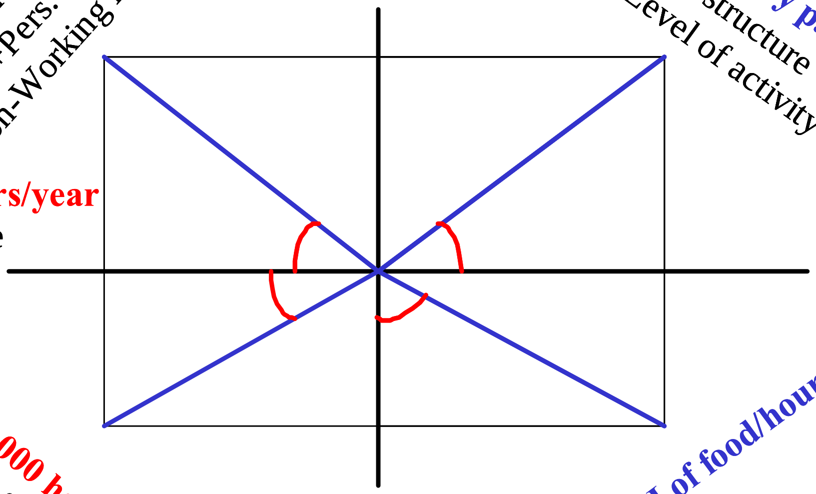
Ravetz J.R. and Funtowicz, S.O., 1999 (guest editors) Special Issue of *Futures* dedicated to Post-Normal Science [*Futures*: vol. 31]

Rosen, R. 1985. *Anticipatory Systems: Philosophical, Mathematical and Methodological Foundations*. New York: Pergamon Press.

Rosen, R. 1991 *Life Itself: A Comprehensive Inquiry Into the Nature, Origin and fabrication of Life* Columbia University Press New York 285 pp.

Rosen, R. 2000 *Essays on Life Itself* Columbia University Press, New York

Rotmans J. and D.S. Rothman (Eds.) 2003 *Scaling Issues in Integrated Assessment*. Swets & Zeitlinger B.V. Lissen The Netherlands



No work
> 65
< 16

620,000 hours/year
Overhead
Sleep+Pers.Care
Non-Working Pop.

Total Human Activity
876,000 hours/year

9 MJ/day p.c.
Age structure
Level of activity

256,000 hours/year
Available
Human
Activity

330,000 MJ/year
Required
Food Energy

158,000 hours/year
Off-farm work
Leisure

98,000 hours/year
Required Work
for Food

3.4 MJ of food/hour

Technical Coefficients:
* Technology in production
1 kg grain per hour of labour
2 hours chores p.c. day

Acceptable
level of
services

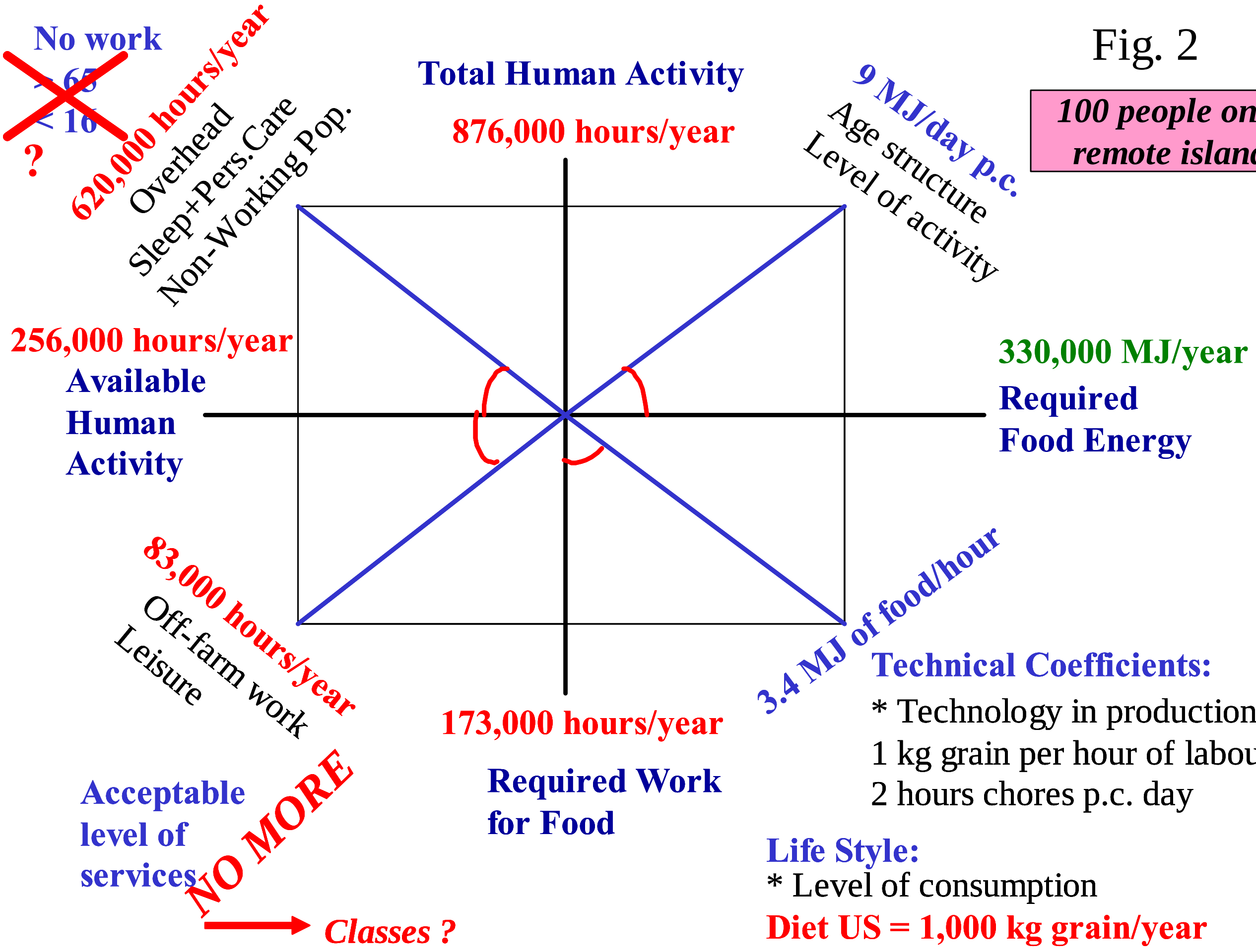
Fig. 1

100 people on a remote island

Life Style:
* Level of consumption
Diet China = 250 kg grain/year

Fig. 2

100 people on a remote island



Technical Coefficients:

* Technology in production

1 kg grain per hour of labour

2 hours chores p.c. day

Life Style:

* Level of consumption

Diet US = 1,000 kg grain/year

Fig. 3

Arbitrariness associated to a choice of a time differential

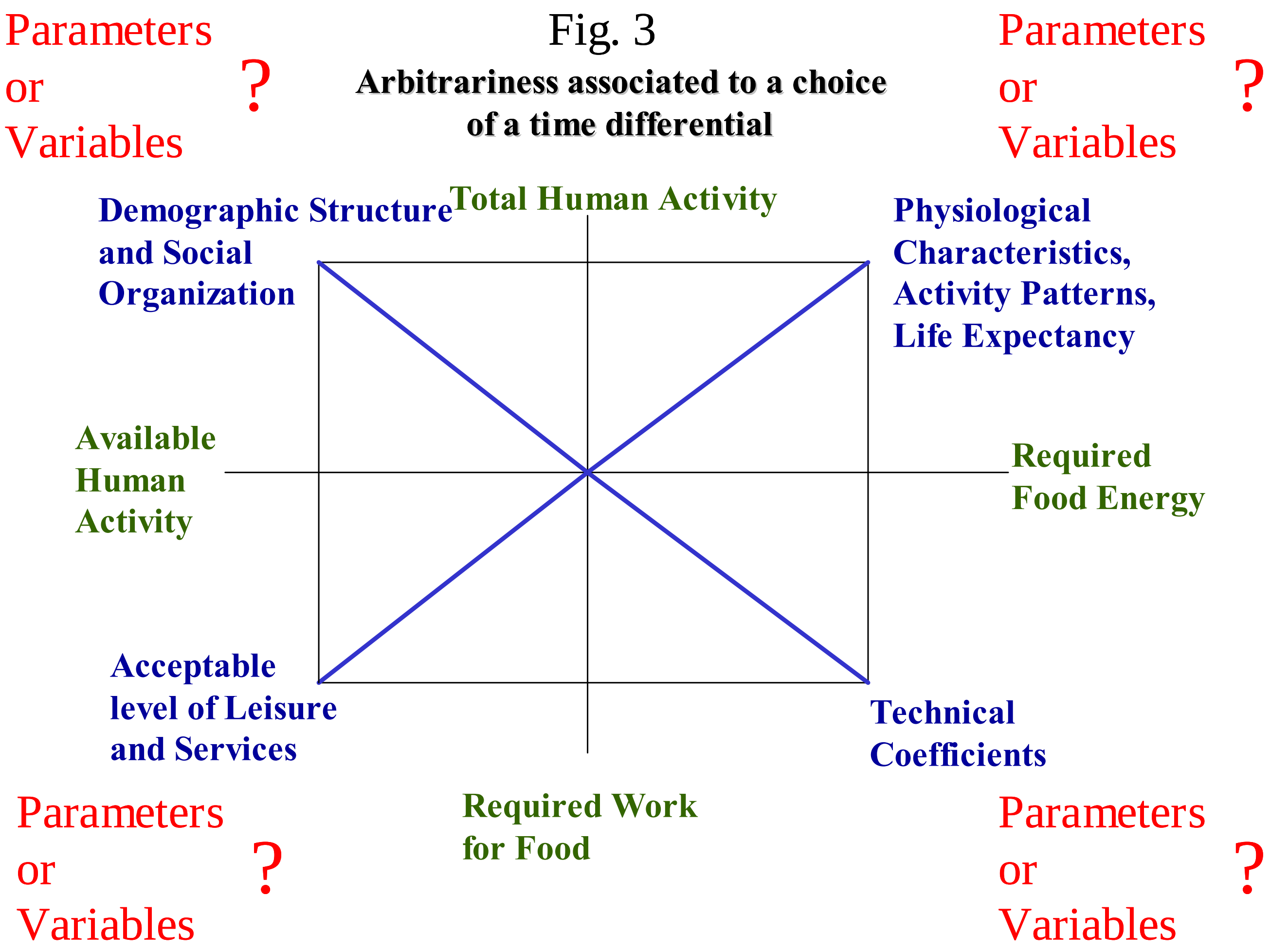
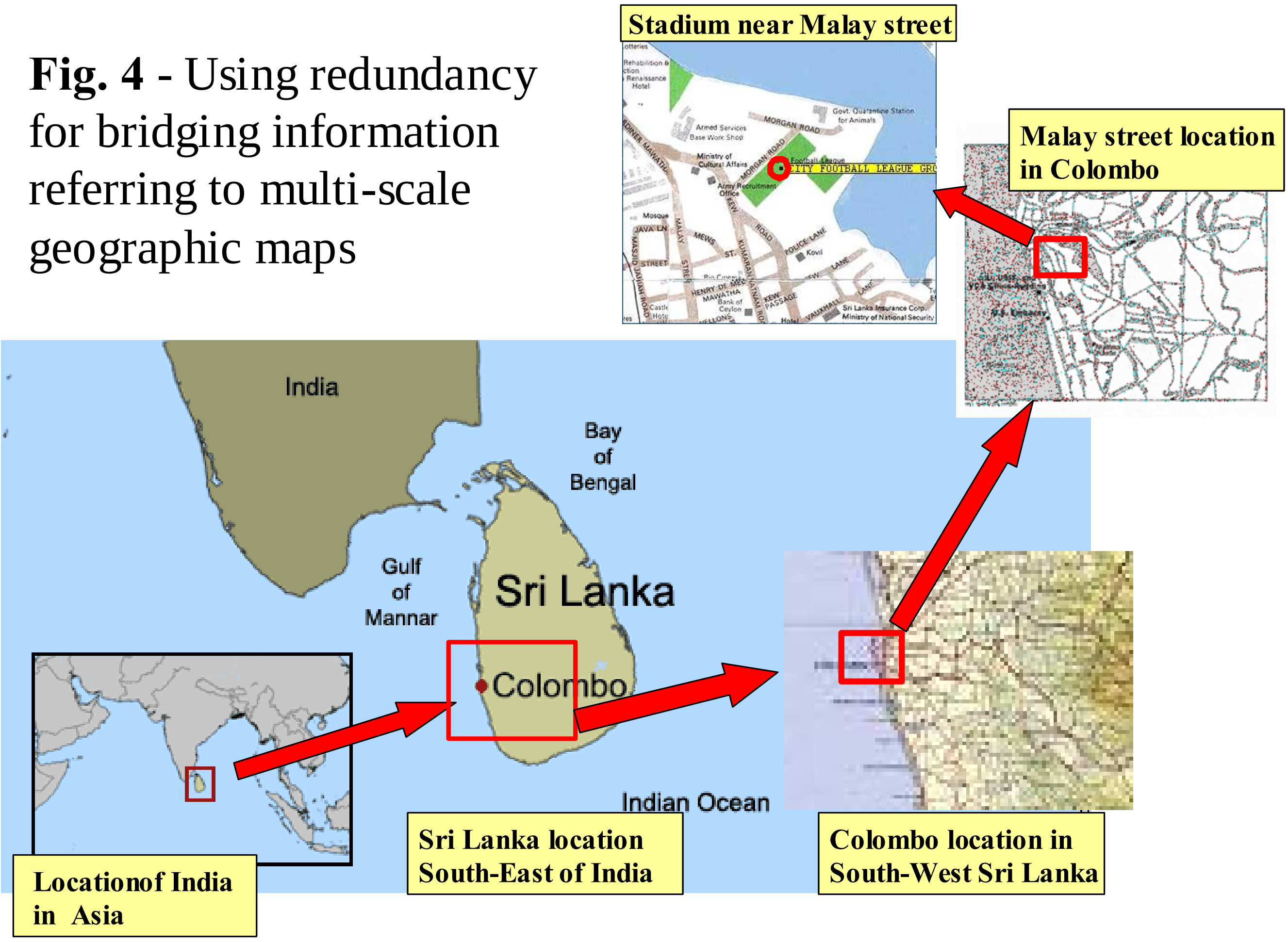
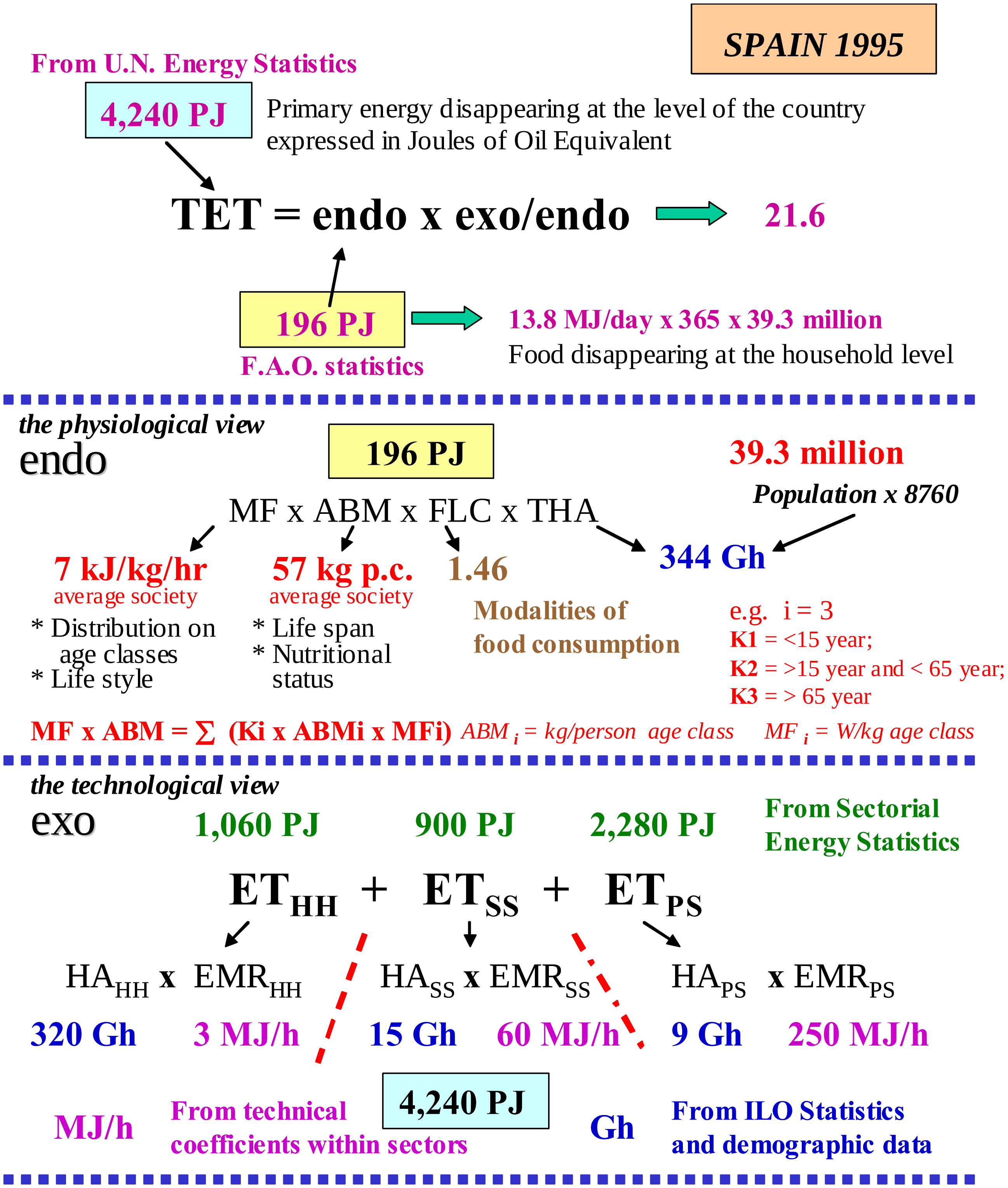


Fig. 4 - Using redundancy for bridging information referring to multi-scale geographic maps





SPAIN 1995

From U.N. Energy Statistics

4,240 PJ Primary energy disappearing at the level of the country expressed in Joules of Oil Equivalent

TET = endo x exo/endo → **21.6**

196 PJ → **13.8 MJ/day x 365 x 39.3 million**
Food disappearing at the household level

F.A.O. statistics

the physiological view
endo

196 PJ

39.3 million
Population x 8760

MF x ABM x FLC x THA

344 Gh

7 kJ/kg/hr
average society
* Distribution on age classes
* Life style

57 kg p.c.
average society
* Life span
* Nutritional status

1.46
Modalities of food consumption

e.g. i = 3
K1 = <15 year;
K2 = >15 year and < 65 year;
K3 = > 65 year

MF x ABM = ∑ (Ki x ABMi x MFi) *ABM_i = kg/person age class* *MF_i = W/kg age class*

the technological view
exo

1,060 PJ **900 PJ** **2,280 PJ**

From Sectorial Energy Statistics

$ET_{HH} + ET_{SS} + ET_{PS}$

HA_{HH} x EMR_{HH} | HA_{SS} x EMR_{SS} | HA_{PS} x EMR_{PS}

320 Gh **3 MJ/h** | **15 Gh** **60 MJ/h** | **9 Gh** **250 MJ/h**

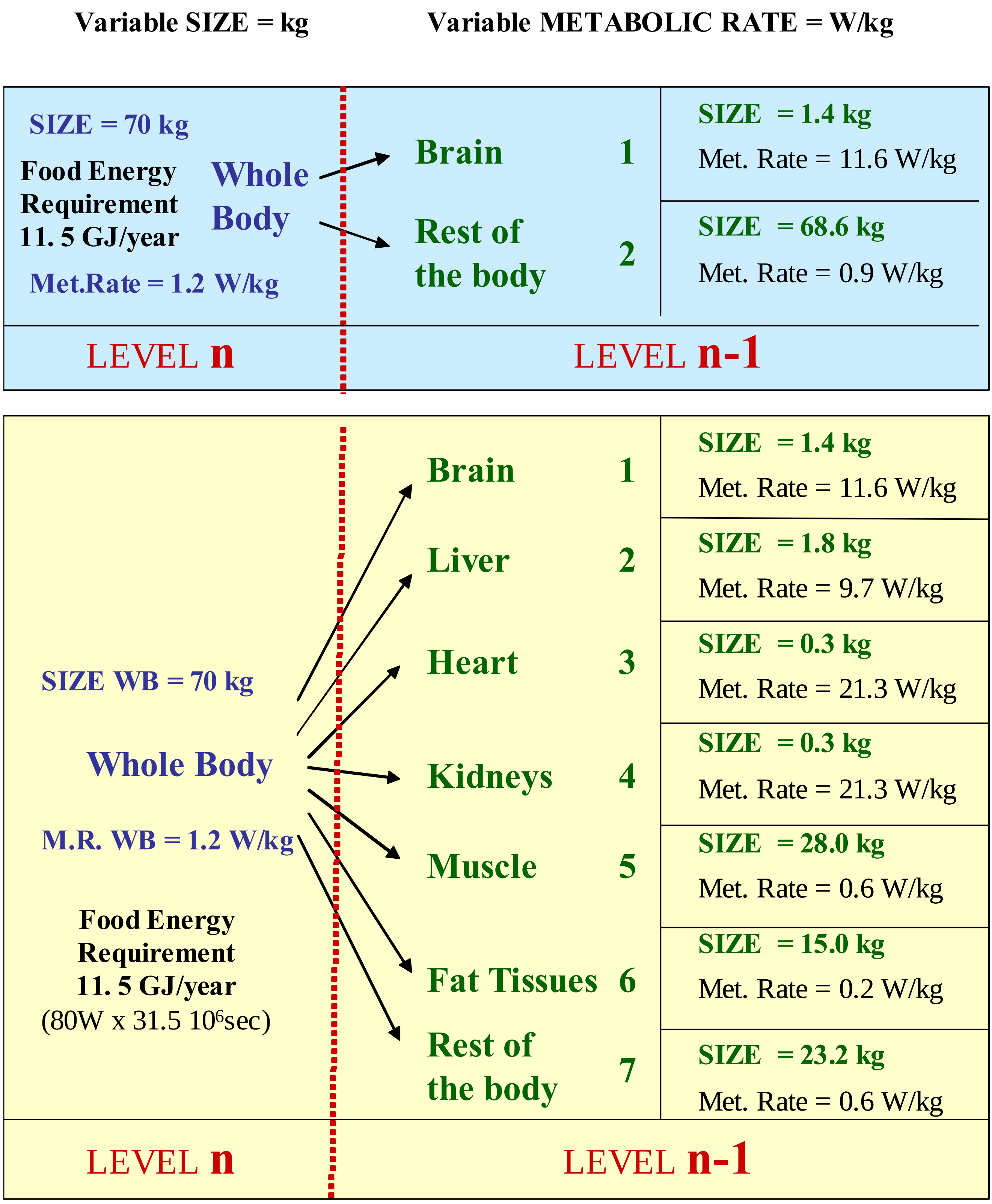
MJ/h **From technical coefficients within sectors**

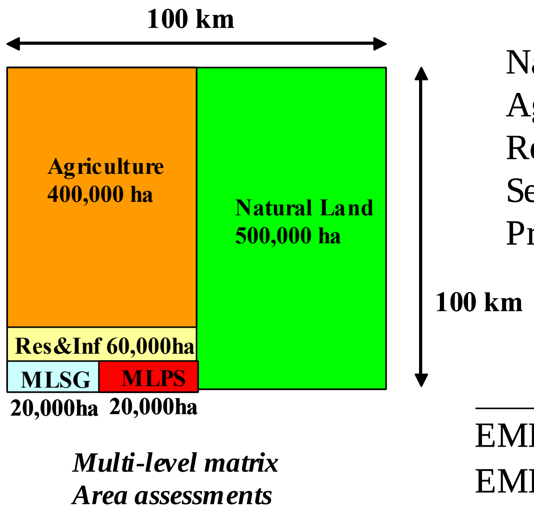
4,240 PJ

Gh **From ILO Statistics and demographic data**

Fig. 5 Using redundancy to link non-equivalent assessments taking advantage of non-equivalent external referents

Fig. 6 Characterization across levels of a metabolic system





	Size in		*Size out*
Natural Land	500,000 x EMD_{NAL}	= **ET_{NAL}**	0 PJ
Agriculture	400,000 x EMD_{AGL}	= **ET_{AGL}**	5 PJ
Resid.&Infrast.	60,000 x $EMD_{R\&I}$	= **$ET_{R\&I}$**	6 PJ
Servic.&Gov.	20,000 x EMD_{MLSG}	= **ET_{MLSG}**	3 PJ
Prod.Sector	20,000 x EMD_{MLPS}	= **ET_{MLPS}**	6 PJ

Level n-1 - components

EMD_{NAL} = 0 GJ/year; *Throughputs*

EMD_{AGL} = 12.5 GJ/year; $EMD_{R\&I}$ = 100.0 GJ/year;
EMD_{MLSG}= 150.0 GJ/year; EMD_{MLPS} = 300.0 GJ/year;

Fig. 7 Categories used to define whole and components in

Level n - whole

TAL x EMD_{AC} = TET_{AC}

1,000,000 ha x 20 GJ/ha = 20 PJ/year

County area: 1,000,000 ha = extensive#1 (size from within)
Total Exosomatic throughput : 20 PJ/year = extensive#2 (size from outside)
Exosomatic Metabolic Density: 20 GJ/ha /year = intensive#3 (throughput)

Fig. 8 Examples of Dendograms based on a Multi-Level Matrix: Human Activity Variable for the Throughput: Exosomatic Energy → EMR_i

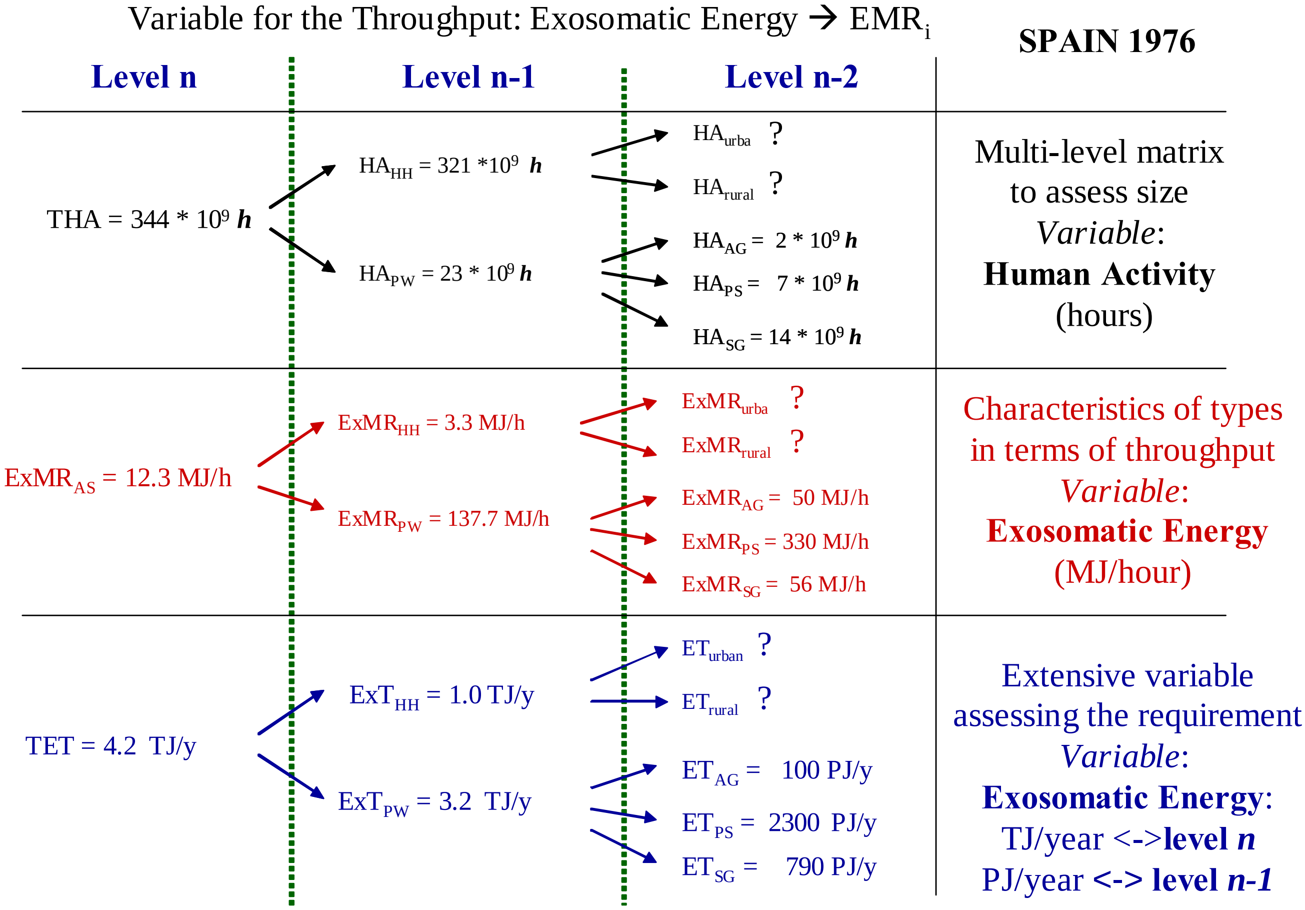


Fig. 9 Examples of Dendograms based on a Multi-Level Matrix: Human Activity Variable for the Throughput: US$ → ELP_i

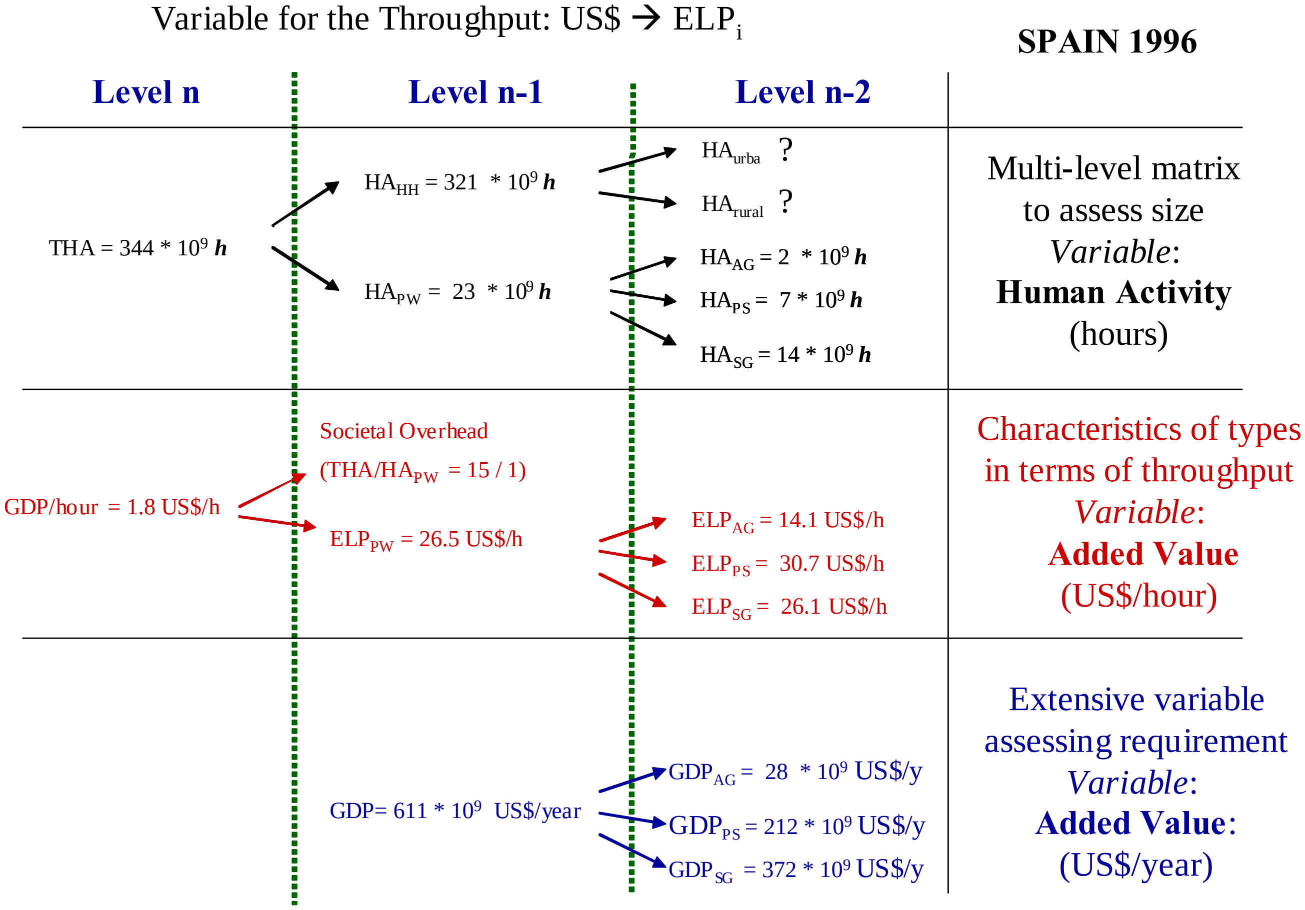
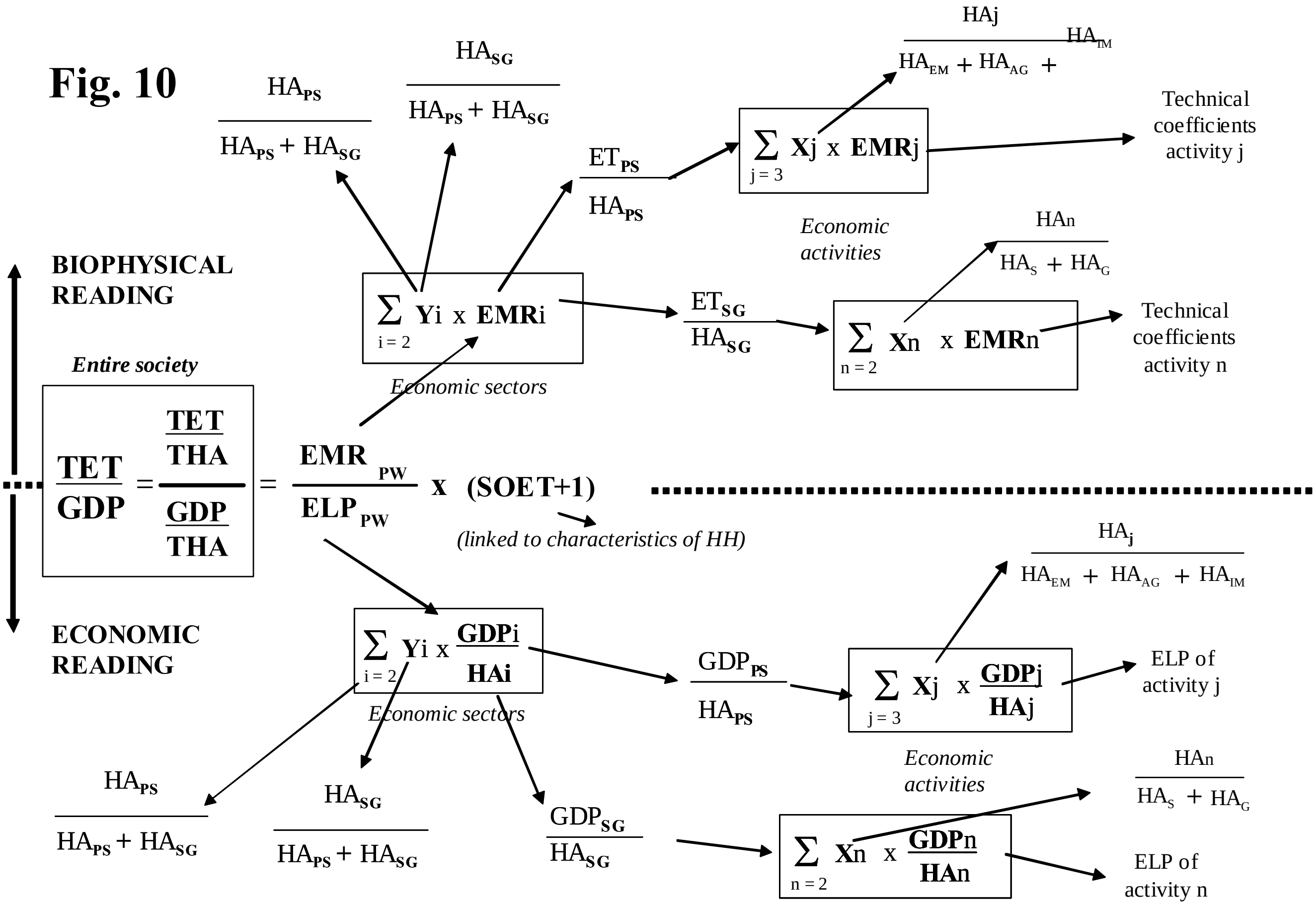


Fig. 10


BIOPHYSICAL READING
ECONOMIC READING
Entire society
$\frac{TET}{GDP} = \frac{TET/THA}{GDP/THA} = \frac{EMR_{PW}}{ELP_{PW}} \times (SOET+1)$
(linked to characteristics of HH)
$\sum_{i=2} Yi \times EMRi$
Economic sectors
$\frac{HA_{PS}}{HA_{PS} + HA_{SG}}$
$\frac{HA_{SG}}{HA_{PS} + HA_{SG}}$
$\frac{ET_{PS}}{HA_{PS}}$
$\frac{ET_{SG}}{HA_{SG}}$
$\sum_{j=3} Xj \times EMRj$
$\frac{HAj}{HA_{EM} + HA_{AG} + HA_{IM}}$
Technical coefficients activity j
Economic activities
$\sum_{n=2} Xn \times EMRn$
$\frac{HAn}{HA_{S} + HA_{G}}$
Technical coefficients activity n
$\sum_{i=2} Yi \times \frac{GDPi}{HAi}$
Economic sectors
$\frac{HA_{PS}}{HA_{PS} + HA_{SG}}$
$\frac{HA_{SG}}{HA_{PS} + HA_{SG}}$
$\frac{GDP_{PS}}{HA_{PS}}$
$\frac{GDP_{SG}}{HA_{SG}}$
$\sum_{j=3} Xj \times \frac{GDPj}{HAj}$
$\frac{HA_{j}}{HA_{EM} + HA_{AG} + HA_{IM}}$
ELP of activity j
Economic activities
$\sum_{n=2} Xn \times \frac{GDPn}{HAn}$
$\frac{HAn}{HA_{S} + HA_{G}}$
ELP of activity n

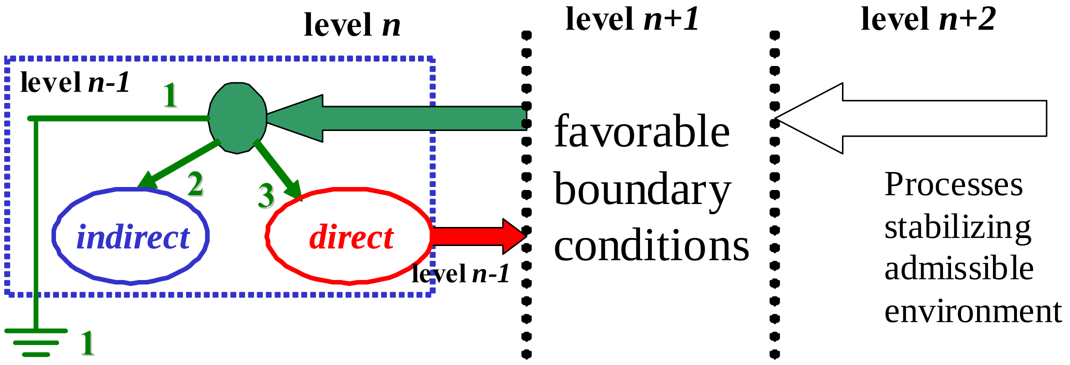


Fig. 11.a

ILA: the rationale of the meta-model

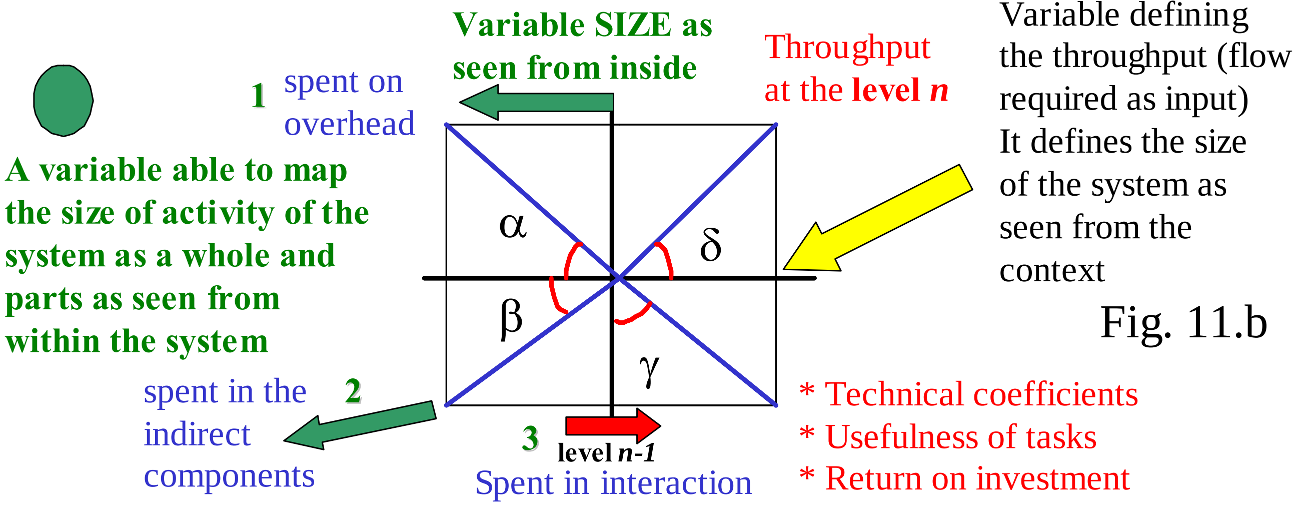


Fig. 11.b

Fig. 12

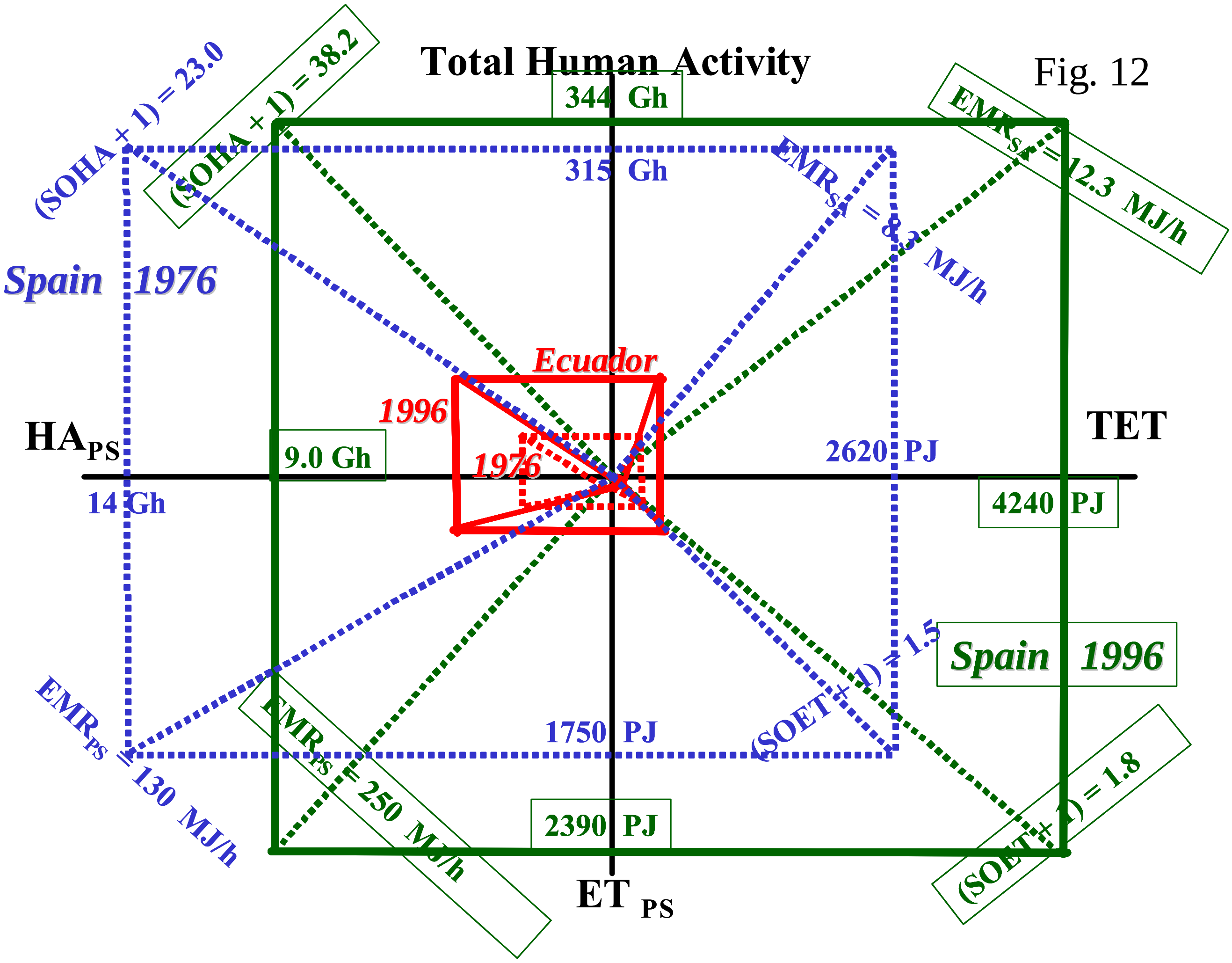

Total Human Activity
344 Gh
315 Gh
(SOHA + 1) = 23.0
(SOHA + 1) = 38.2
EMR$_{SA}$ = 12.3 MJ/h
EMR$_{SA}$ = 8.3 MJ/h
Spain 1976
Ecuador
1996
1976
HA$_{PS}$
9.0 Gh
14 Gh
TET
2620 PJ
4240 PJ
Spain 1996
(SOET + 1) = 1.5
(SOET + 1) = 1.8
EMR$_{PS}$ = 130 MJ/h
EMR$_{PS}$ = 250 MJ/h
1750 PJ
2390 PJ
ET $_{PS}$

Fig. 13 Choosing how to define and aggregate typologies over the ILA
[in this example: Multi-Level Matrix for SIZE: Human Activity]

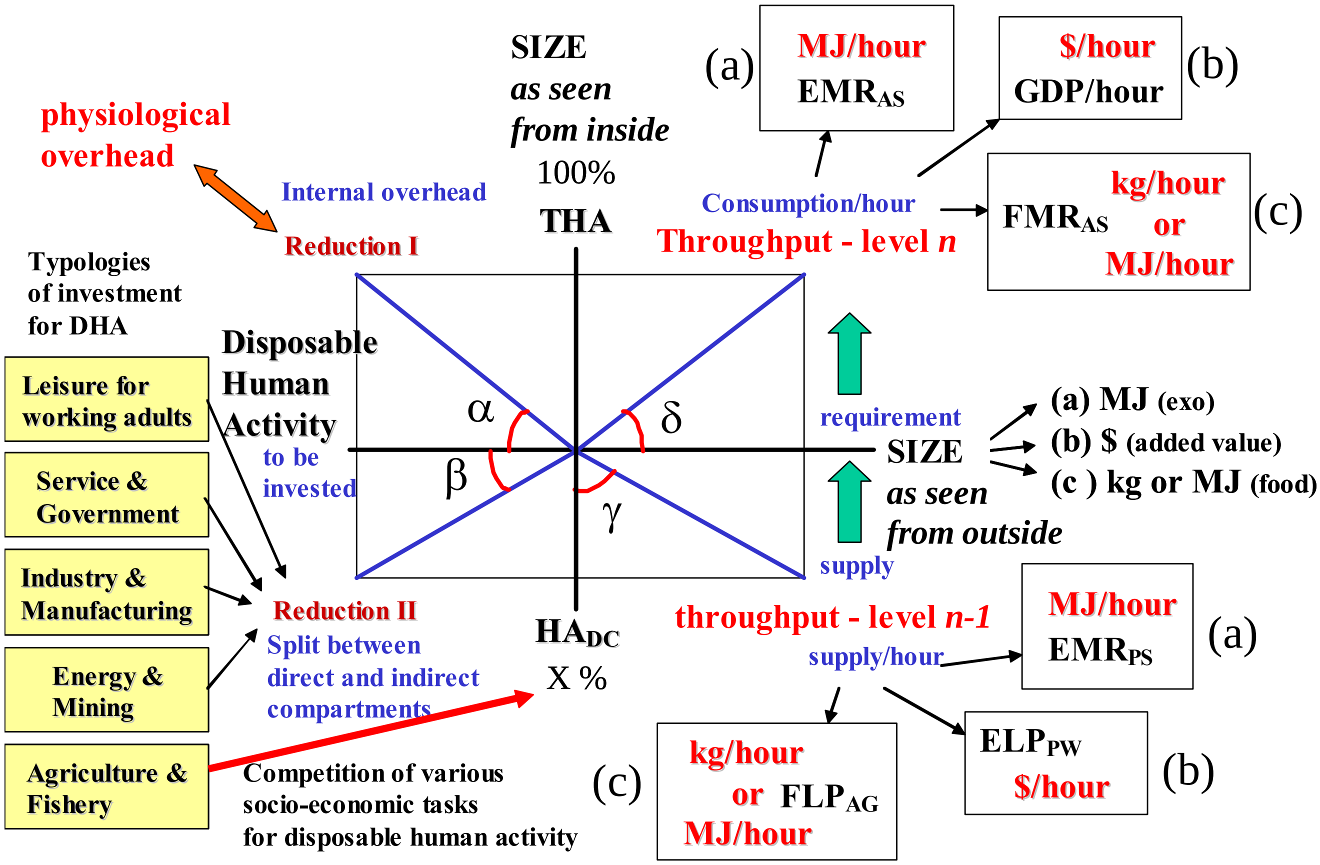


Fig. 14a Application of ILA to farming system analysis
[SIZE: hectares of land, THROUGHPUT: Yuan/year]

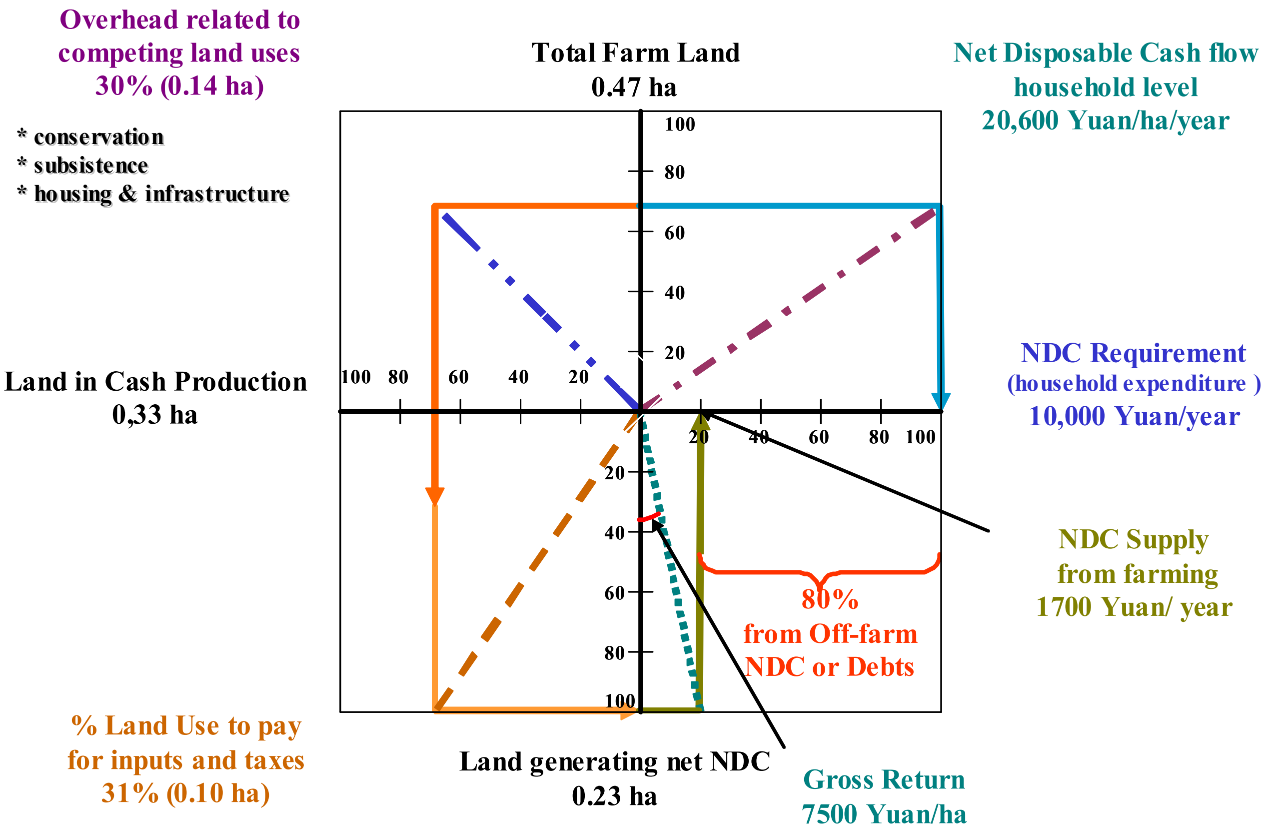


Fig. 14b Application of ILA to farming system analysis
[SIZE: Hours Human Activity, THROUGHPUT: Yuan/year]

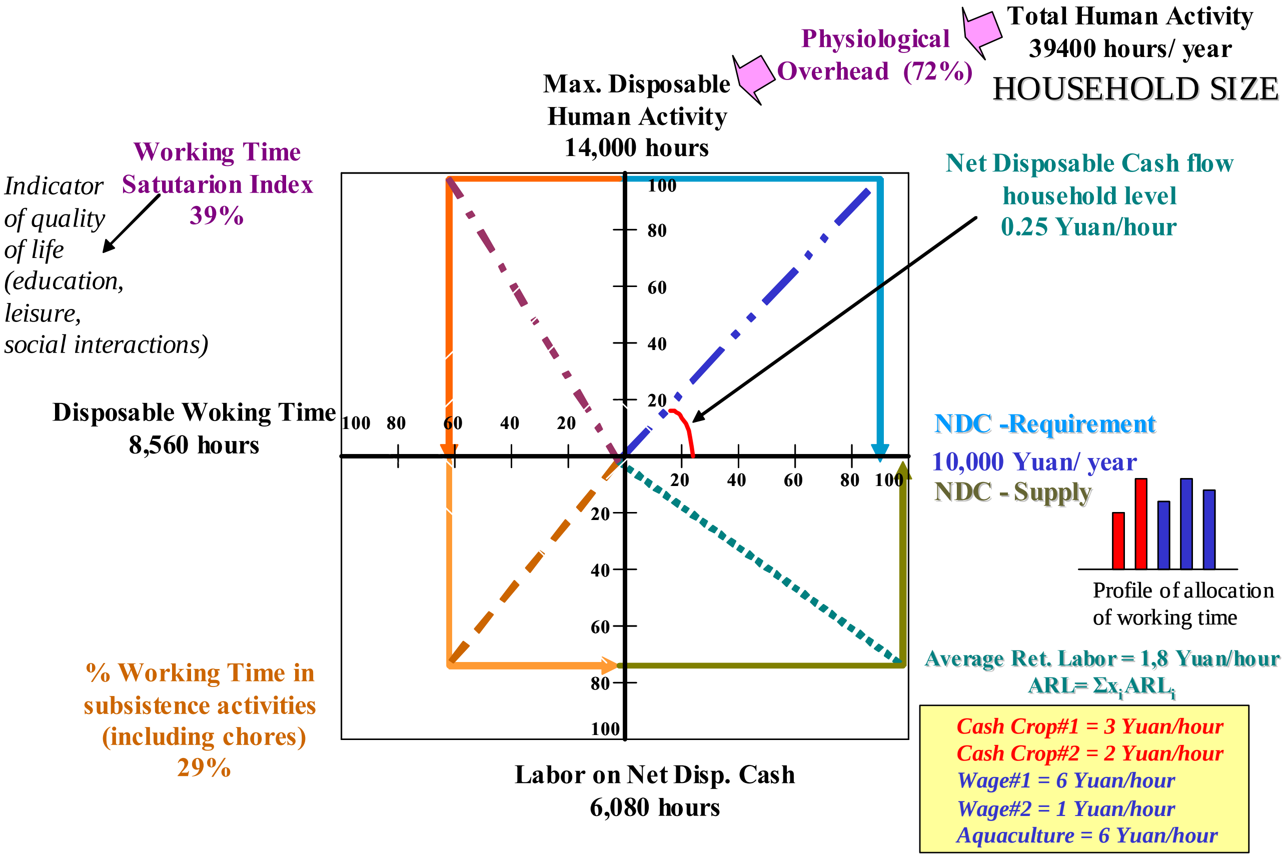
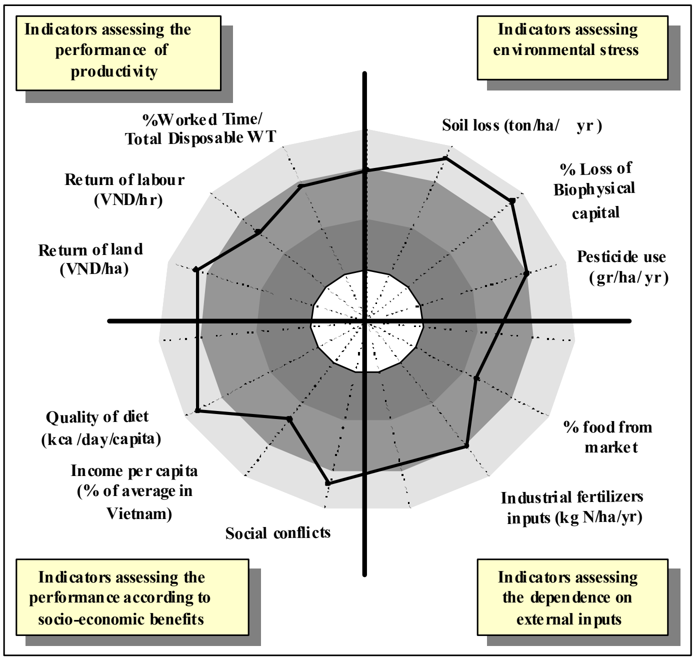


Fig. 15a Household type #1 - Vietnam Upland

Characterization of household types on a Multi-Criteria Space

Gomiero and Giampietro, 2001

HH Type 1 (Off-farm+Crop$_{mix}$)



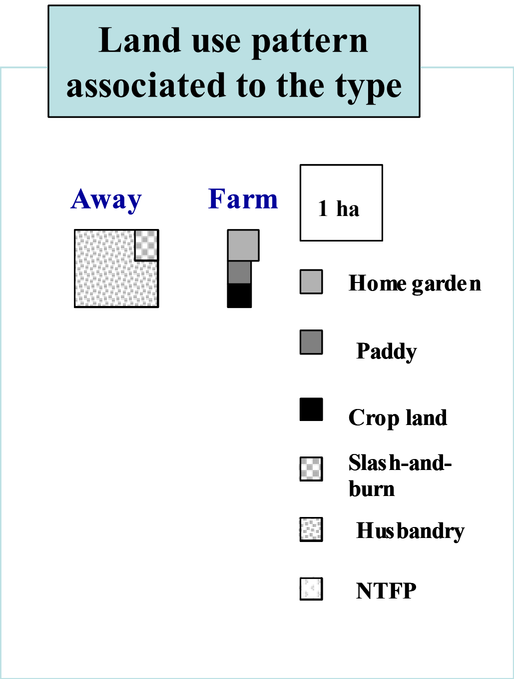
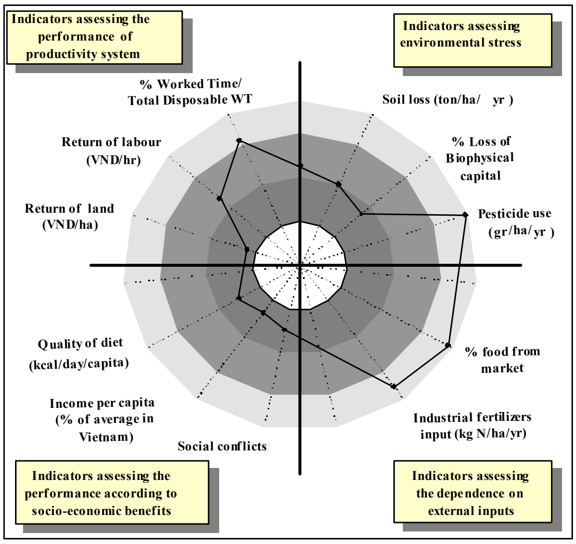


Fig. 15b Household Type #3 - Upland Vietnam

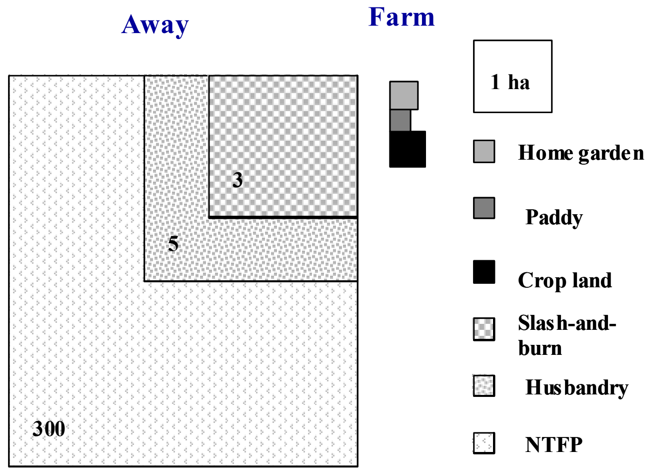
Gomiero and Giampietro, 2001

Characterization of household types on a Multi-Criteria Space

HH Type 3 (Slash-and-Burn+Crop$_{mix}$)

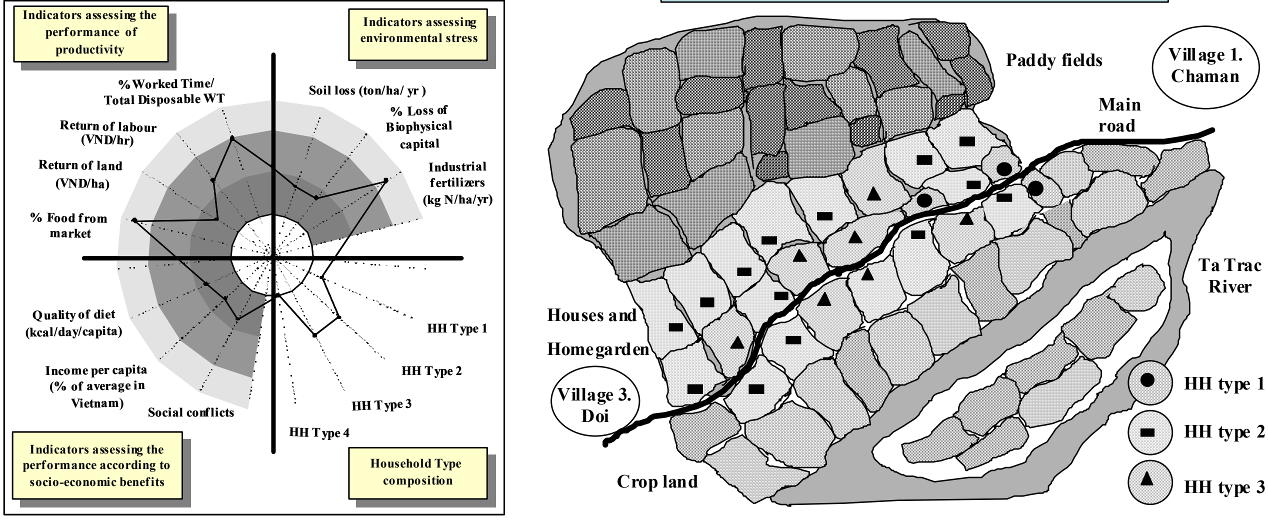


Land use pattern associated to the type



Characterization on a Multi-Criteria Space

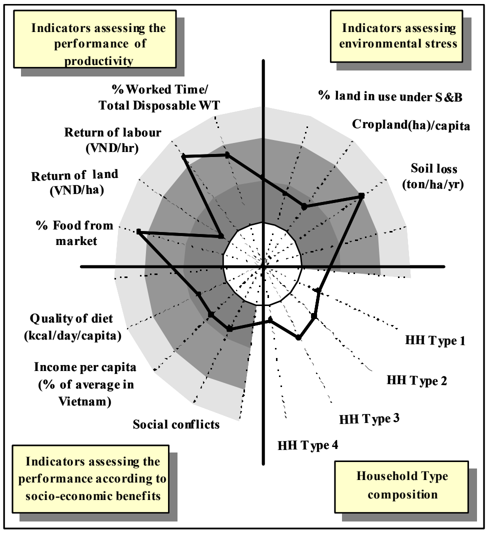
Characterization based on land use typologies



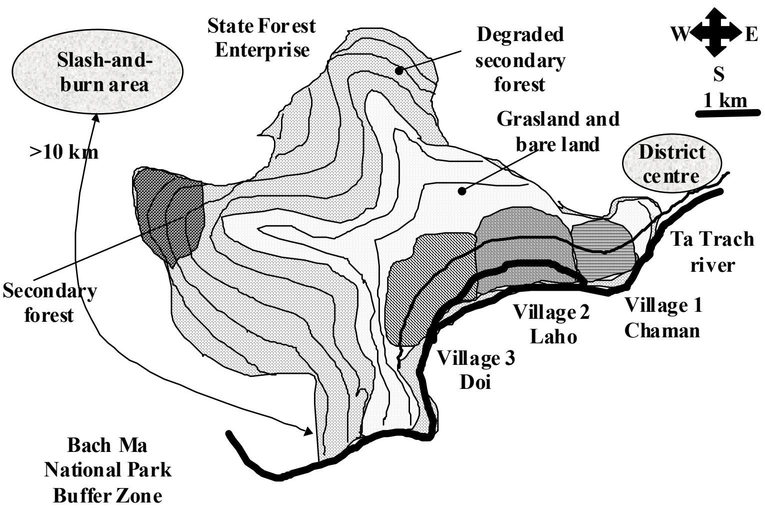
Gomiero and Giampietro, 2001

Fig. 16a Village 2 (Laho) - Upland Vietnam

Characterization on a Multi-Criteria Space



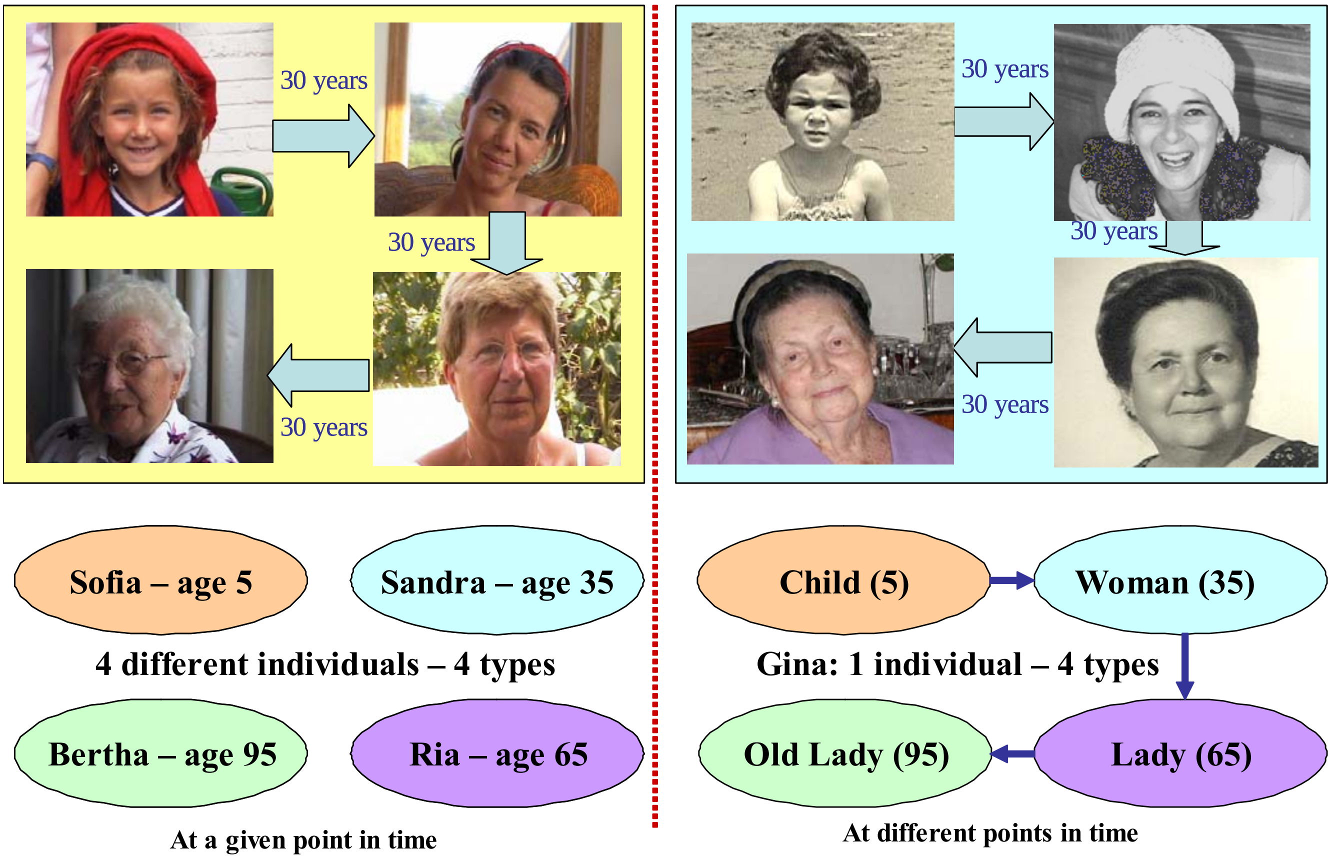
Characterization based on land use typologies



Gomiero and Giampietro, 2001

Fig. 16b - “Thuong Lo” commune - Upland Vietnam

Fig. 17 Types versus Individuals: Who wants to sustain what?



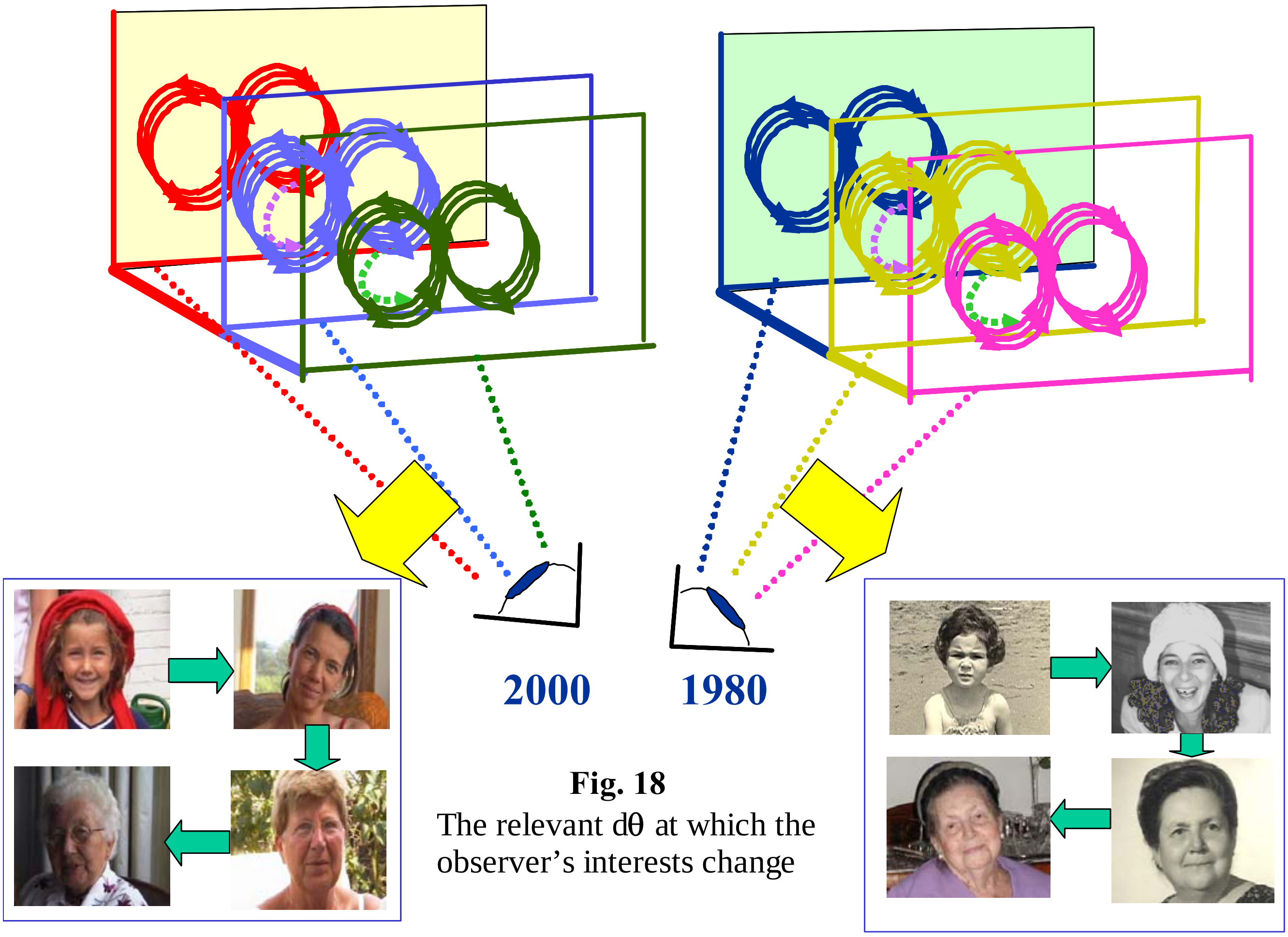


Fig. 18
The relevant dθ at which the observer's interests change

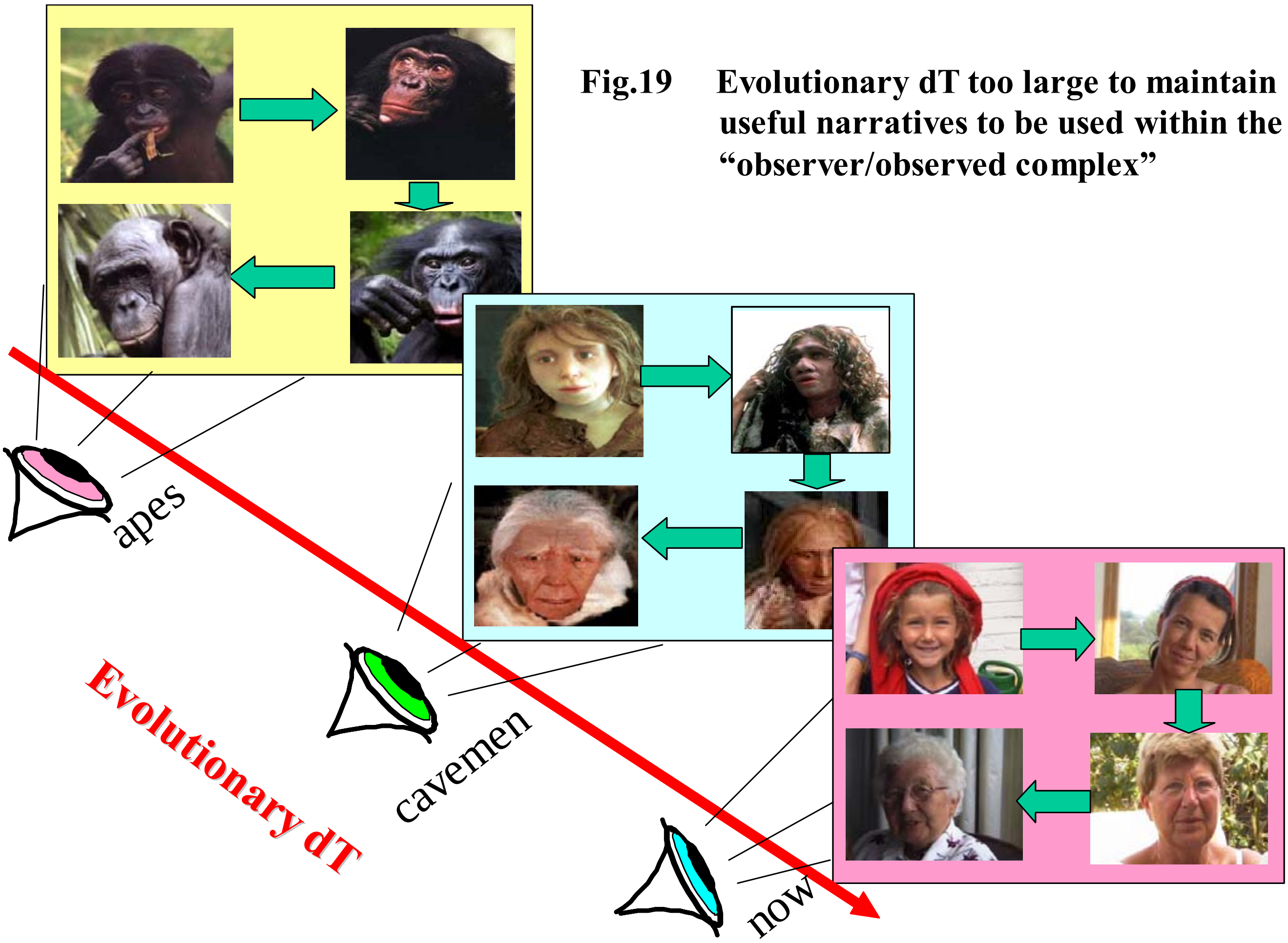


Fig.19 Evolutionary dT too large to maintain useful narratives to be used within the "observer/observed complex"

Fig. 20

Iterative procedure mixing quantitative and qualitative analyses in an iteration MSIA ← → SMCE for Quality Assurance