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

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Abstract: 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:

• an integrated assessment of sustainability requires a multi-dimensional and multi-scale analysis (technical incommensurability)

• when comparing human values it is not possible to define, in substantive terms, 'the best course of action' (social incommensurability)

• it is not possible to generate accurate and relevant scenarios when forecasting the future of adaptive systems evolving across scales.

Part 1 introduces the epistemological challenges implied by analyses of sustainability. 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.

Keywords: multi-scale integrated analysis; integrated assessment; multi-criteria; science for governance; impredicative loop analysis; mosaic effect; complex systems; narratives; sustainability; post-normal science.

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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):

• they operate simultaneously on different hierarchical levels of organisation

• they become in time, at different paces, across these different levels.

Therefore, dedicated scientists, willing to do an analysis of living systems have to face two key problems:

• The unavoidability of finding multiple useful descriptions of the same entity, which cannot be reduced any further. These distinct descriptions are associated with different choices made by the observer to adopt either different scales or different criteria of observations.

• 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:

• It is impossible to have a substantive representation of events. Humans (and any other living observers/agents) can only represent their specific perception and experience of the reality and not 'the reality'.

• 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 analysing the sustainability of living systems (socio-economic systems, ecological systems and their interaction) the only reasonable approach is to always perform a semantic check on the usefulness of the chosen models.

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

• 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 irreducible perceptions and representations of the interactions of unequal observers/agents. This process cannot be fully captured by any formal information space, no matter how big or sophisticated the computer is and/or how smart and lucky the analyst may be (see also Rotmans and Rothman, 2003).

• Any observer must be a part of the reality which is observed. Scientists, no matter how thorough their background is, cannot escape this predicament. This means that the scientific endeavour should be viewed as a continuous challenge. The task is to maintain a set of meaningful relations which evolve in time within an observer/observed complex. An observer/observed complex is one in which both the observed and the observer are become 'something different' 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 organised in nested hierarchies. However, this includes all living systems, ecosystems and socio-economic systems. The MSIA approach rather than just paying lip service to the complexity revolution, takes the main message implied by it seriously. 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 formalising the performance of the investigated system, are used to indicate the optimal solution. This paradigm assumes that it is possible to obtain both:

• A substantive characterisation 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?]

• 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 always deal 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 with 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 in different space-time domains, to be made commensurate with our organisation of perceptions and representations of events." (Allen, 2003)

The choice of a narrative therefore is a pre-analytical step which has to do with an 'arbitrary' characterisation of "what the system under analysis is and does". This characterisation, always depends on the specific goals of the analysis, and therefore is closely related to the characterisation 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 epistemological predicament entailed by complexity*

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 set of epistemological assumptions

• a set of criteria for defining the quality of the analysis

• 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:

• It is impossible to reduce to a single system of accounting, information that refers to non-equivalent descriptive domains, i.e., 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 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 (2004).

• It is impossible to rank and weight in a substantive way, the 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 (2004).

• Non-equivalent descriptive domains are associated with 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 characterise an investigated system in relation to different dimensions of analysis (e.g., ecological, technical, economic, social and 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 for internal supply within Israel).

• When dealing with sustainability, future scenarios and evolutionary trends, there is always an unavoidable degree of uncertainty and ignorance in both the ability to detect in time, relevant signals of change, and characterise, predict and simulate future scenarios (Funtowicz and Ravetz, 1991). When dealing with genuine ignorance, a blind trust in experts and optimising procedures is just a sign of ignorance of one's 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 leukaemia because of her unsafe handling of it.

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

• Keeping the descriptive aspect distinctly separate 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 condense the descriptive side (characterisation of performance) and the normative side (definition of best course of action) into a single step (e.g., cost/benefit analysis, and optimising models looking for the best solution). Moreover, reductionism assumes that uncertainty and ignorance can be dealt with in a substantive way by sound practices of science (e.g., more data, bigger computers and more sophisticated sensitivity analyses). Without recognising it, many researchers adopt only a limited 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 unequal 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, 2004) to deal with all the inputs of this process that refer to the normative side

• Maintaining a balance between the two contrasting tasks of:

  • compression (using typologies to represent individuals by filtering out details referring to special cases)

  • keeping 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:

  • the type of problem to deal with

  • 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 characterisation 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).

• 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 the whole) that can have different legitimate formalisations (a family of useful irreducible 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 formalisation. In order to characterise 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.

• Providing coherence in the chosen way of representing the interaction of human systems and socio-economic systems on:

  • different scales (e.g., when representing the perceptions of individuals, households, communities, provinces, national states and global interactions)

  • different descriptive domains (e.g., when focusing on different selections of relevant attributes: economic interactions, biophysical interactions and cultural interactions).

This can be obtained by establishing a holographic representation of these interactions. In order to do this, 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 a cascade across different levels and scales. When moving across levels, these compartments can be viewed as either parts and/or wholes. The set of unequal 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). This congruence across levels must hold even when the definition of parts and wholes is done by adopting different logics (economic vs. biophysical).

Section 2 of this paper 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 to do the accounting. In spite of this characteristic, the mechanism of accounting is still very effective and rigorous in handling the integrated set of data and assessments.

2. Studying the dynamic budget of metabolic systems across scales

2.1 Societal metabolism of an isolated society on a remote island

2.1.1 The goal of the example

In order to express their functions all metabolic systems require a supply of inputs to sustain their metabolism. For example:

• humans need food to express human activity

• social systems need exosomatic energy carriers to express socio-economic activities

• 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 survival of a metabolic system obviously depends on its ability to stabilise 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 stabilisation 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 stabilising 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 implies that, at a given level of expenditure, the smaller 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 (e.g., the salary per 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 and biophysical productivity of labour in agriculture. Farmers in developed countries are 2% of the work force and produce hundreds of kg of grains per hour of labour. In the least developed countries, low-tech farmers produce a few kg of grains per hour; because of this, there they constitute around 60% of the work force. The implications of the biophysical constraints associated with 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. A subsistence society will never become affluent in monetary terms.

In general terms, we can say that in a metabolic system organised in nested compartments, it is possible to establish a relation between:

• relative size of compartments (parts and whole)

• relative intensities of metabolised flows of parts and the whole.

This can be done 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:

• those responsible for the production (the parts generating the required inputs)

• those responsible for the consumption of various metabolised flows (the parts contributing to the consumption at the level of the whole).

Large sized parts do influence the value of the whole more than small sized parts. In this way, it becomes possible to study the existence of constraints and bottlenecks in relation to different typologies of flows occurring within parts of different sizes and to establish benchmark values (e.g., economic compartments which are more or less capital intensive than the average). Constraints can be detected when finding incongruence between the relative requirement and supply of a given metabolised flow in its dynamic budget 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.

Assuming that the very survival of metabolic systems is based on the stabilisation of autocatalytic loops established across scales, one has to abandon the myth that it is possible to analyse them by using differential equations within a mono-scale analysis framework. The alternative proposed by MSIA is looking for sets of useful typologies of parts and wholes (characterised in terms of the relative size and specific throughputs) which are able to guarantee congruence of the flows associated with the autocatalytic loop across unequal 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 (characterised also in terms of 'size' and 'throughput'), in a way that still makes possible the stabilisation of the dynamic budget of the whole.

In 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 stabilisation 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 HAFP (Human Activity in Food Production). It is important to be aware that any Impredicative Loop Analysis of this type can check the existence of biophysical constraints, but only in relation to the particular type of dynamic budget under consideration. In this example we deal only with the requirement and the supply of food. Moreover, the analysis is valid only for the type of food produced and consumed which has been specified in this example. 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 cooperative 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.

2.2. Theoretical assumptions and basic rationale

This Impredicative Loop Analysis studies the stabilisation of an autocatalytic loop of useful energy (the output of useful energy – human activity–is used to stabilise the energy input–food). Therefore, in this example, the characterisation 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.

• 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)

• the resource 'food' is needed to provide favourable conditions for the process of re-production of the resource 'human activity' (i.e., to stabilise the metabolism of human societies when considering elements at the household level).

• 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 characterisation 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 characterisation of the elements (whole and parts) will be obtained by using two types of variables.

• An intensive variable characterising the throughput (a flow per unit of size) – kg of food per hour of human activity/year;

• An extensive variable characterising 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 (HAi = 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. The same mechanism of accounting can be applied to exosomatic energy (e.g., fossil energy and technical capital), monetary flows (e.g., added value generation and human activity) and, water (e.g., water flows and human activity).

Two points are crucial in this example:

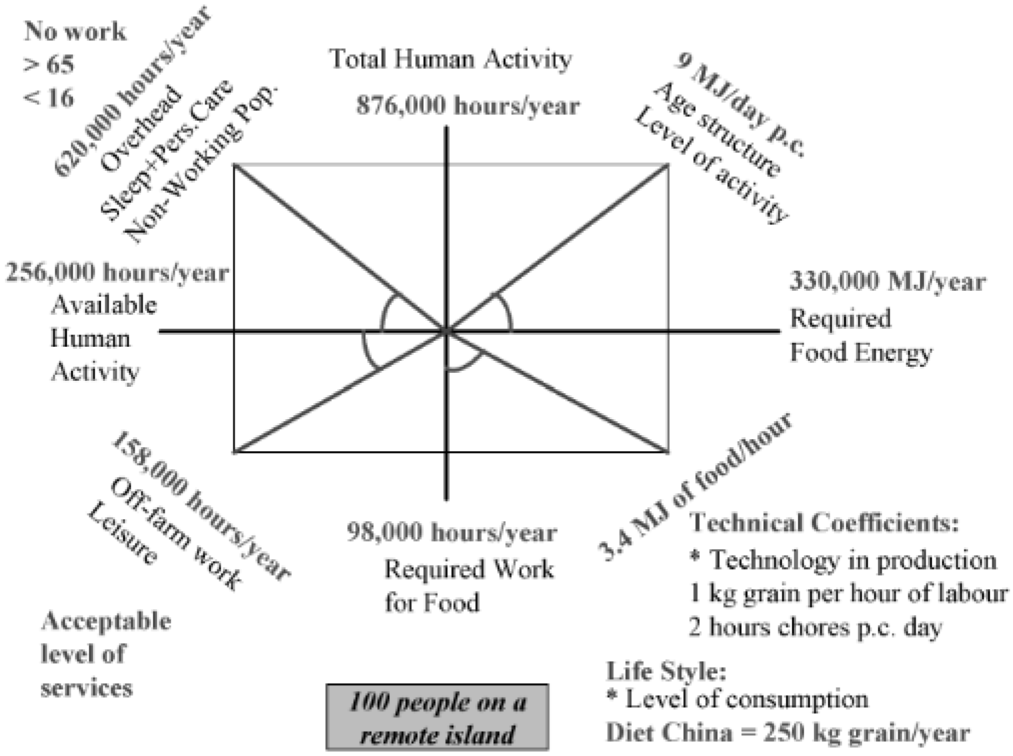
• Establishing a clear link between the characteristics of the societal metabolism as a whole (characteristics referring to the entire loop – level n) and the characteristics referring to lower-level elements and higher level elements – either defined at level n – 1 or at level n + 1.

• Closing the loop when describing societal metabolism in energy terms. In this approach the energy accounting is done in terms of loops 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, 1996, 1971, 1983). However, facing this task requires moving to a multi-scale analysis.

2.3. Technical assumptions and numerical data

We hypothesise a society of 100 people that uses only flows of endosomatic energy (food and human labour) for stabilising its own metabolism (see Figure 1). In order to further simplify the analysis, we imagine that the society is operating on a remote island (e.g., 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 characterise societal metabolism are specified below.

Figure 1 One hundred people on a remote island. Integrated representation of human activity and food energy requirement



• 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:

• 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 for producing 250 kg of cereals/year per capita.

• 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 67.5 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:

  • labour productivity

  • 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 of 'land in production/total land of the island'. 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:

- • population
- • the type of diet followed by the population (material standard of living)
- • the technology used (recalling the I = PAT equation proposed by Ehrlich (1968)).

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 land in the island).

• Supply of 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. 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 × 365 × 100 persons). This is what is needed to stabilise the resource, human activity, in the short term. In addition to that, we can imagine that another form of investment is required to stabilise the system. The stability of a socio-economic system requires a certain investment of Human Activity for tasks associated with maintenance and reproduction of total human activity (THA). This set of tasks must include sleeping, personal care, eating, 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 Figure 1). These are:

• 'Maintenance and reproduction'. As observed in the previous point, in any human society the largest part of human activity is not related to the stabilisation 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:

> • 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).
>
> • 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 × 50 × 365) in non-productive activities.

• '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-organisation is HA_{DS} = 256,000 hours/year. This is the budget of human activity available for stabilising societal metabolism. This budget of human activity, expressed at the societal level, has to be divided between two tasks:

• guaranteeing the production of the required food input (for avoiding starvation now) – 'Work for Food' (HA_{WF})

• 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 the lower part of Figure 1. The requirement of 330,000 MJ/year of endosomatic energy input (food at time [t]) entails the requirement for producing enough energy carriers (food at time [t+1]) in the following years. In the higher graph the same structure of relations among values taken by intensive and extensive variables is obtained using an intensive variable defined as 'kg of cereals per capita' rather than 'MJ/year'. Obviously, the two assessments can be reduced to each other. Actually, this makes it possible to look for a biophysical constraint on the level of productivity of labour in the element HA_{WF} (the hours of HA invested in 'working for food'). That is, if we want to preserve the characteristics of the whole (the total consumption of the society) it is necessary to invest a given not-negotiable fraction of 'Total Human Activity' in the end use, 'Work for Food' (HA_{WF} = 98,000 hours/year). 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 – lower Figure 1 – entails that numerical values associated with the characterisation of various identities defining the elements on different hierarchical levels (at the level of individual compartments – extensive – segments on the axis: HAi – and intensive variables – wideness of angles: throughput in HAi) may be changed. However, changes must respect 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 characterise the various elements across levels (the parts in relation to the whole and the whole in relation to the parts).

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

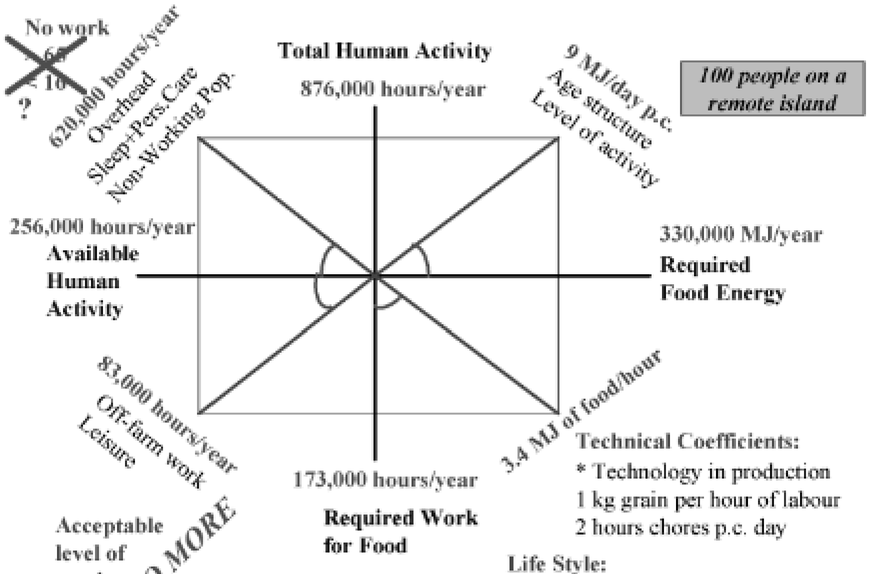
2.4.1. Different formalisations of the budget within the same meta-model

Let us imagine now to change, for example, some of the values used to characterise this autocatalytic loop of energy forms (as shown in Figure 2). For example, let us change the parameter 'material standard of living', which – in our simplified model – is expressed by the relevant attribute 'quality of the diet' (formalised in the two options Diet A or Diet B). The different mix of energy vectors in the two diets (vegetable vs. 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 same 330,000 MJ/year of food, with this diet requires the production of 1,000 kg of grain per capita (due to the double conversion of grains into meat). As a consequence of this fact, whereas 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 (ELA = 0.05), 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 (ELB = 0.20). Moreover, to this assessment of work hours required for producing the agricultural crop used as input for the whole system, we have to add a requirement of work hours for fixed chores. Fixed chores include preparation of meals, gathering of wood for cooking, fetching water, washing and maintenance of food system infrastructures in this primitive society. In this simplified example we use the same flat value for the two diets = 73,000 hours/year (2 hours/day per capita = 2 × 365 × 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 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:

• running social institutions and structures (schools, hospitals, courts of justice)

• develop their individual potentialities in their leisure time, is not only the result of their free choice.

Figure 2 One hundred people on a remote island. Possible scenarios for adjustments between human activity and food energy requirement



Rather, it is the result of a compromise between competing requirements of the resource 'Human Activity Disposable for Social Self-Organisation' 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:

• requirement of food energy (330,000 MJ/year) – that is the throughput of the whole

• 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:

• material standard of living (Diet A or Diet B)

• 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 characterisation 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 characterisation 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 is 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 ELA = 0.05 and ELB = 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 Figure 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 resorting to some politically important rules reflecting cultural identity and ethical beliefs (what determines 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 ten hours a day for six days a week) – lower part of Figure 2. Alternatively, they could accept a certain degree of inequality 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 recognise that all these solutions are operating in these days in many developing countries and were adopted, in the past, all over our planet.

2.5. Lessons from the 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 the 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 Figure 1. Models that take into account 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, 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 characterise 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 reflect 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 analyses reflecting biophysical transformations. This is why a Multi-Scale Integrated Analysis has to include, and handle simultaneously, the representation of economic and biophysical flows.

2.6. It enables linking of characteristics defined across different levels and scales

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 is 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, characterising 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 reflect 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 increase the dependency ratio or if a political reform affects 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 several possible changes referring to different disciplinary fields of analysis.

A technical discussion of the sustainability of the dynamic energy budget represented in the lower graphs of Figures 1 and 2 in terms of potential changes in characteristics (e.g., either the values of numbers on axis or the values of angles) requires considering the unequal 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 (HAi) 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 (e.g., defined at the level n + 2) can be, in this way, related to the characteristics of the diet of individual members of the society (e.g., at the level n – 2) going through the relation among parts (level n – 1) and the 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 densely populated 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 individualise and analyse relations among characteristics affecting each other across levels while remaining within disciplinary mono-scale analyses.

2.7. It can handle multiple non-equivalent formalisations of the same problem

To make another hypothesis of perturbation within the ILA shown in Figure 1, let us imagine the arrival of another crashing plane with 100 children on 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 translates into doubling the size of THA and increasing the value of SOHA = HA_{MR}/THA. That is, the system will face a larger food demand, for the new population of 200 people, which 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). But after the new crash of the second plane full of children, that size for 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 as 'uncivilised 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 affect first of all, the very survival of that society.

We can generalise the usefulness of Multi-Scale Integrated Analysis of autocatalytic loops by saying that the information used to characterise 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 two integrated sets of variables (extensive and intensive variables).

This approach can facilitate the discussion and the evaluation of possible alternative scenarios of development in terms of characterisation 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 for the budget of 'human activity' (for 100 people) reflect standard conditions found in developed countries (50% of the population is economically active, working for 40 hours/week × 47 weeks/year). Let us imagine, now, that for political reasons, we will introduce on the island a working week of 35 hours (keeping five or six 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 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 kgs. of cereals per hour of labour), but this would require both:

- a lag-time to acquire technical innovations
- an increase in investments of human work in research and development.

If we admit that each of these solutions are feasible, we have also to admit that when looking into future scenarios using impredicative loop analysis, it is not clear what should be considered as a dependent and/or an independent variable. Who decides what should be considered as a 'given' attribute of the system and what should be considered as the characteristic that will be changed when implementing a policy?

2.8. It enables dealing with the implications of non-equivalent narratives

Whenever humans face the need for adjusting the set of characteristics of an impredicative loop, they tend to go for the most popular idea introduced by the era of Enlightenment to obtain congruence. They always look for the silver bullet able to provide a win-win solution. In this respect, Enlightenment can be seen as a remarkable hegemonisation on the possible narratives that can be used in a debate over sustainability. The 'gospel' of Western civilisation 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. 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, and finally the requirement of the loop on its environment. 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 Jevons' paradox ((1965) for the relative analysis within the MSIA approach see Giampietro, (2003) – Chapters 1 and 7). The counterintuitive side effect of expressing more efficient activities is the boosting of the size of the relative compartments. This tends to translate into an increase in the environmental impact of societal metabolism. In our example, this could be the amplification of agricultural practices based on monocultures (a typology of land use associated with the highest productivity per hour of labour and per hectare) associated with the elimination of poly-cultural systems. Framing the discussion about 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.

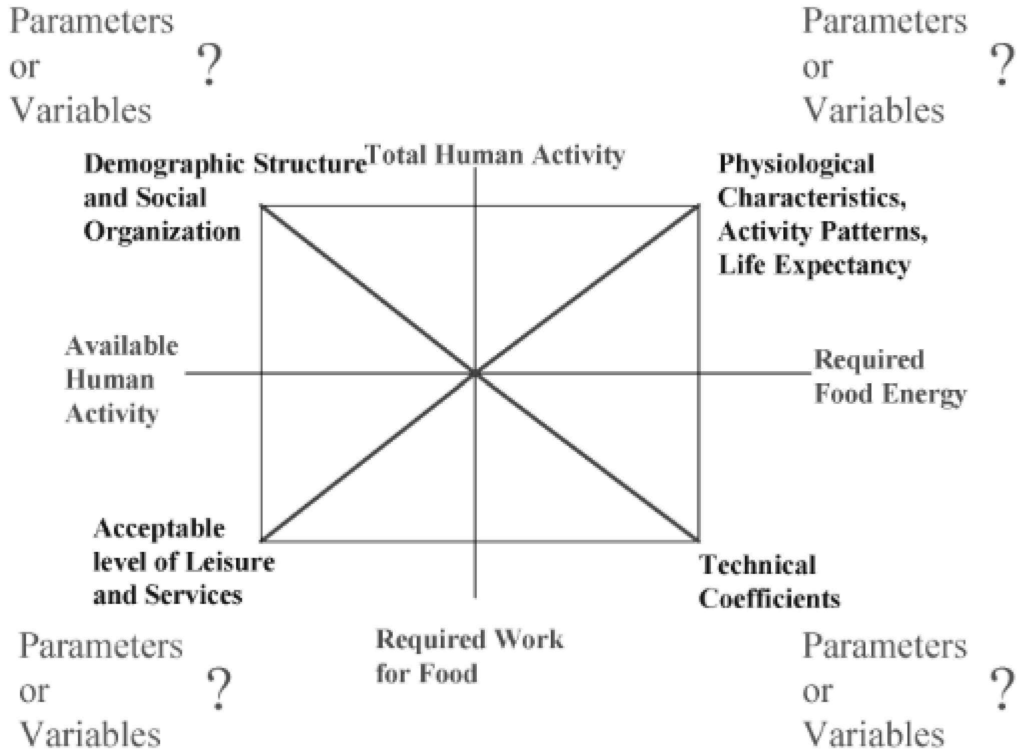
There are characteristics of the autocatalytic loop that have a very short typical lag time for change, for example when adopting economic prices in the analysis. Other characteristics may have a lag time of changes of a few years, as in the case of analysis based on laws and technical coefficients, 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., regulations for compulsory schooling for children or religious taboos – 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, when do we consider 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 with the pre-analytical selection of a narrative within which the analysis can be framed – see Figure 3.

As noted in the introduction, considering simultaneous 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:

• 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 characterised using attributes which are considered parameters.

• What we consider to be 'time dependent' characteristics in the definitions of the identity of parts and the whole. In this case, the elements (parts and wholes within the impredicative loop) are characterised using attributes which are considered variables.

Figure 3 Arbitrariness associated with a choice of a time differential



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 a larger food supply available'. 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. The formalisation 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 a remote island, we can explain the small body size of a population (after thousands of year of evolution) with the fact that small body size maximises the ratio Human Activity/Food consumed at the level of the whole socio-economic system. This is a result that can be considered as good, since it stabilises 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 arise. For example, the option of trade and new technology make it possible for islanders to consume more food, avoiding 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 options, let alone deciding what priority should be given within a set of attributes used to characterise 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 optimising function at a 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 unequal constraints (lack of compatibility with economic, ecological, technical, social processes) affecting the viability of considered scenarios.

3. 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:

• An organised 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, multi-scale analysis.

• 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.

• A multi-criteria 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:

  • targets: what should be considered an improvement when the value of the relative variable changes

  • benchmarks: how the system compares with appropriate targets and other similar systems

  • critical non-linearity: what are possible critical, threshold values of certain variables where a non-linear effect can be expected to play a crucial role?

• 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 reductionist 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, Columbia University Press, New York.

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

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. (2003) Personal Communication.

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

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, Vol. 51, pp.475–485.

Box, G.E.P. (1979) 'Robustness is the strategy of scientific model building', in Launer, R.L. and Wilkinson, G.N. (Eds.): Robustness in Statistics, Academic Press, NY, pp.201–236.

Chaitin, J.G. (1975) 'Randomness and mathematical proof', Scientific American, Vol. 232, No. 5, pp.47–52.

Ehrlich, P.R. (1968) The Population Bomb, Ballantine Books, New York.

Funtowicz, S.O. and Ravetz, J.R. (1991) 'A new scientific methodology for global environmental issues', in Costanza, R. (Ed.): Ecological Economics, New York, Columbia, pp.137–152.

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

Giampietro, M. (2003) 'Multi-Scale integrated analysis of agro-ecosystems', Series of Advances in Agroecology, in Edwards, C. (Ed.): CRC Press Boca Raton, p.472.

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, Vol. 22, No. 2, pp.97–254.

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, Vol. 22, No. 3, pp.257–352.

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 Freese, L. (Ed.): Advances in Human Ecology, JAI Press, Greenwich CT, Vol. 6, pp.131–200.

Giampietro, M., Bukkens, S.G.F. and Pimentel, D. (1993) 'Labor productivity: a biophysical definition and assessment', Human Ecology, Vol. 21, No. 3, pp.229–260.

Jevons, W.S. [1865] (1965) The Coal Question: An Inquiry Concerning the Progress of the Nation, and the Probable Exhaustion of Our Coal-Mines, in Flux, A.W. (Ed.): 3rd ed., rev., Augustus M. Kelley, New York.

Martinez-Alier, J., Munda, G. and O'Neill, J. (1998) 'Weak comparability of values as foundation for ecological economics', Ecological Economics, Vol. 26, pp.277–286.

Munda, G. (2004) 'Social multi-criteria evaluatin (SMCE): methodological foundations and operational consequences', European Journal of Operational Research, Vol. 158, No. 3, pp.662–677, Available on line (using the number of reference: doi:10.1016/S0377-2217(03)00369-2).

Odum, H.T. (1971) Environment, Power, and Society, Wiley-Interscience, New York.

Odum, H.T. (1983) Systems Ecology, John Wiley, New York.

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

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

Rosen, R. (1991) Life Itself: A Comprehensive Inquiry into the Nature, Origin and fabrication of Life, Columbia University Press, New York, p.285.

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

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