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Complexity and Scales: The Challenge for Integrated Assessment

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ABSTRACT

"Complexity," in science, can be linked to the need of using, in parallel, not reducible models (= the coexistence of non-equivalent descriptive domains required) for a useful representation of a certain phenomenon. This is always the case, when dealing with: (1) nested hierarchical systems (= in which relevant patterns are detectable only on different space-time scales); and (2) socioeconomic systems (= in which agents are not only non-equivalent observers, but also reflexive).

Keywords: hierarchy theory, complexity, scaling, integrated assessment, non-equivalent descriptive domains, post-normal science.

1. INTRODUCTION – THE EPISTEMOLOGICAL DIMENSION OF COMPLEXITY

An intriguing definition of "complexity," given by Rosen [1: p. 229], can be used to introduce the topic of this paper: "a complex system is one which allows us to discern many subsystems . . . (a sub-system is the description of the system determined by a particular choice of mapping only a certain set of its qualities/properties) . . . **depending entirely on how we choose to interact with the system**." Two important points in this quote are: (1) the concept of "complexity" is a property **of the appraisal process** rather than a property inherent to the system itself. That is, Rosen points at an epistemological dimension of the concept of complexity, which is related to the unavoidable existence of different relevant "perspectives" (= relevant attributes in the language of integrated assessment) that can not be all mapped at the same time by a unique modeling relation. (2) models can see only a part of the reality, that part the modeler is interested in. Put it in another way, any scientific representation of a complex system is reflecting only a subset of our possible relations (potential interactions) with it. "A stone can be a simple system for a person kicking it when walking in the road, but at the same time be an extremely complex system for a geologist examining it during an investigation of a mineral site" [1].

This implies that when using formal systems of inference we should always be aware that the equation of perfect gas ($PV = nRT$) can say a lot about some properties of gases, but it does not say anything about how they smell. Smell can be a non-relevant system quality (attribute) for an engineer calculating the range of stability of a container under pressure. On the other hand, it could be a very relevant system quality for a chemist doing an analysis or a household living close to the chemical plant. The unavoidable existence of non-equivalent views about what should be the set of "relevant qualities" to be considered when modeling a natural system, is a crucial point in the discussion of science for sustainability. In fact, scientific tools that proved to very useful in the past – e.g., reductionist analyses, which were able to send a few humans on the moon – will not necessarily be also adequate to provide all the answers to new concerns expressed today by humankind – e.g., how to sustain a decent life of 10 billion humans on this planet. When discussing sustainability we are dealing with issues where: (1) large levels of uncertainty are affecting the modeling of the various dynamics of interest and (2) different but legitimate perspectives on what is relevant and what is "better" can be found among the stakeholders. Under these conditions it is very unlikely that reductionist analyses can be used to indicate "the best" possible course of action (For whom? On which hierarchical level? For how long? How to be sure that the predictions are right?).

Another interesting way to point at the deep epistemological implications of complexity in relation to scale has been given by Mandelbrot [2] in his seminal paper in Science "How long is the coast of Britain?" His provocative statement was that it is impossible to measure the length of

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the coast line of Britain, without specifying first the scale of the map that will be used for representing it. The more detailed is the map, the longer will result the assessment of the same segment of coast. This implies that, in last analysis, the numerical assessment of the length of a given segment of coast **will be affected** by the choice of the map used for the assessment. Obviously, this pre-analytical choice will depend on **why** the analysis is done in the first place. Mandelbrot conclusion is that, when dealing with fractal objects (and as argued later on in this paper, the same applies to nested hierarchical systems) one deals with objects that do not have a "clear cut identity." When characterizing them with numerical variables, the numerical assessment will always reflect not only their intrinsic characteristics (the "real length" of the coastline?) but also the goals (interests and beliefs) of the analysts reflected by the "arbitrary" selection of a mapping procedure used for the description of the object.

"Epistemological complexity" is in play every time the interests of the observer (the goal of the mapping) are affecting what the observer sees (the formalization of a scientific problem and the resulting model). That is, when pre-analytical steps (= (1) the choice of the "space-time scale" at which the reality should be observed and (2) the previous definition of what should be considered as "the system of interest" in relation to a given selection of encoding variables) are affecting the resulting numerical representation of system's qualities. If we agree with this definition, we have to face the obvious fact that, basically, any scientific analysis of sustainability is affected by such a predicament. Modern developments in physics (quantum theory) proved that even the most simple equations and laws of mechanics, validated by many successful applications in the last hundreds of years, remain valid only under a certain set of assumptions (only within a certain range of space-time windows at which they can be applied). As soon as we try to stretch them across too many scales they get in trouble.

In spite of this basic problem, there are a lot of applications of reductionist scientific analysis in which the problems implied by "epistemological complexity" can be ignored. These are cases in which the particular relation between "observer" and "observed" can be neglected without losing general validity for the relative numerical assessments. This requires an agreement without reservations among the various stakeholders that will use the scientific output on: (1) the choice of a "space-time scale" at which the reality should be observed (e.g., when adopting a "ceteris paribus" description, the system is not "becoming" something else at a speed which would require a complementing evolutionary analysis) and (2) a previous definition of what should be considered as "the system of interest" (e.g., what are the relevant qualities to be considered in the model). Put in another way, reductionist science works well in all cases in which power is effective for ignoring or suppressing legitimate but contrasting views on the validity of the pre-analytical problem structuring within the population of "users" of scientific information (Jerome Ravetz, personal communication).

The text of this paper is divided into 2 parts.

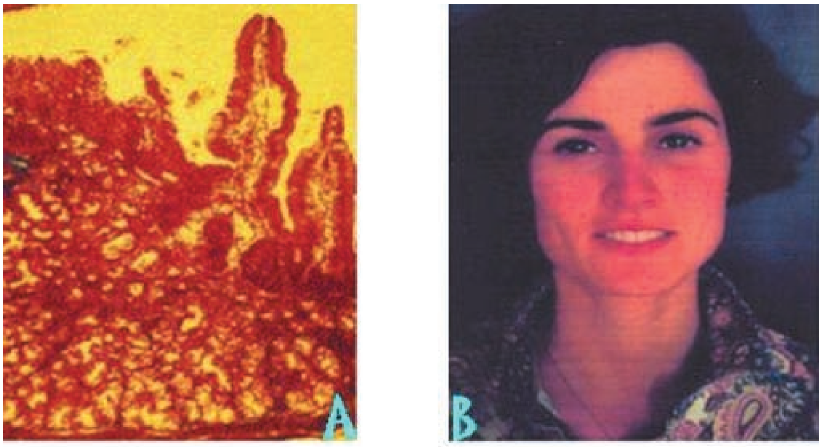
Part 1 presents general concepts emerging in the field of complexity which are related to the concept of hierarchical systems and scaling: (1) Holons and holarchies (related to the special nature of "adaptive nested hierarchical systems"). (2) "Non-Equivalent descriptive domains" (why we need to use in parallel different models). (3) "non-reducibility" and "incommensurability" of indicators obtained when using models belonging to non-equivalent descriptive domains (why we need to move to multicriteria analysis).

Part 2 deals with the practical implications of the set of concepts discussed in Part 1. In particular it deals with: (1) The root of the epistemological predicament of sustainability. Describing the sustainability issue in scientific terms requires compressing an infinite amount of information (that would be required to describe the various trade-offs reflecting different perspectives and different "qualities" of the reality on different scales) into a finite information space (that used in problem structuring and decision making in a finite time). This "mission impossible" requires a new paradigm for science for sustainability (Post-Normal Science). (2) The need for a different conceptualization of "sustainable development." We should move (as suggested by Herbert Simon [3]) from the paradigm of "substantial rationality" to that of "procedural rationality." That is, IF we acknowledge that: (a) uncertainty and ignorance are unavoidably linked to our scientific representation of sustainability trade-offs; and (b) incommensurability among the relative indicators of performance is entailed by the existence of different "value systems" found among the stakeholders; THEN the only option left is to look for a participatory procedure of decision making based on an **iterative** process of problem structuring and "value judgement." This procedure is aimed at a social negotiation of **satisficing solutions** (using again a term proposed by Herbert Simon [4]) rather than the computation of **optimal solutions**. Within this new context, scientists should try to help the society in doing this transition rather than represent an obstacle.

2. PART 1 – HOLARCHIES, NON-EQUIVALENT DESCRIPTIVE DOMAINS, AND NON-REDUCIBLE ASSESSMENTS

2.2. Self-Organizing Systems are Made of Nested Hierarchies and Therefore Entail Non-Equivalent Descriptive Domains

All natural systems of interest for sustainability (e.g., complex biogeochemical cycles, ecological systems and human systems when analyzed at different levels of organization and scales above the molecular one) are



Assessment (1) = 116 kg/year per capita

Assessment (4) = 345 kg/year per capita

Assessment (2) = 1,015 kg/year per capita

Assessment (3) = 1,330 kg/year per capita

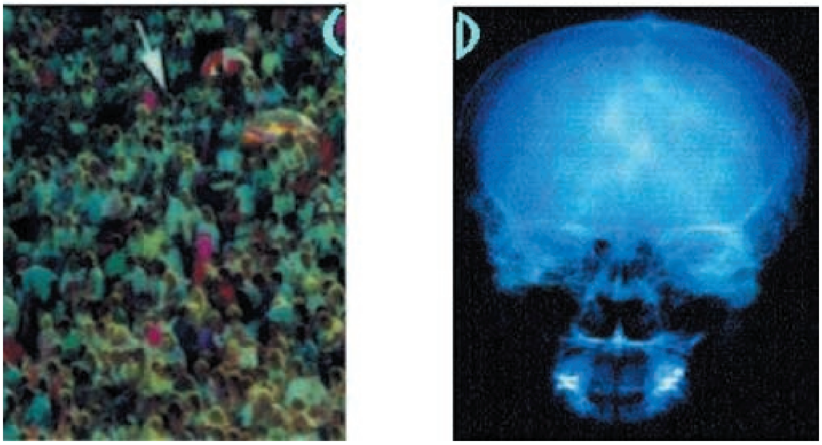


Fig. 1. Non-equivalent descriptive domains needed to obtain non-equivalent pattern recognition in nested hierarchical systems.

"dissipative systems" [5–7]. That is they are self-organizing, open systems, away from thermodynamic equilibrium. Because of this they are necessarily "becoming systems" [8], that in turn implies that they: (i) are operating in parallel on several hierarchical levels (where patterns of self-organization can be detected only by adopting different space-time windows of observation); and (ii) will change their identity in time. Put it in another way, the very concept of self-organization in dissipative systems (the essence of living and evolving systems) is deeply linked to the idea of: (1) **parallel levels of organization** on different space-time scales; and (2) **evolution** (which implies that the identity of the state space, required to describe their behaviour in a useful way, is changing in time).

Actually the idea of parallel levels of organization is directly linked to the definition of hierarchical systems given by O' Neill [9]: a dissipative system is hierarchical when it operates on multiple spatio-temporal scales – that is when different process rates are found in the system. Another useful definition of hierarchical systems referring to their analysis is: "systems are hierarchical when they are analyzable into successive sets of subsystems" [10: p. 468] – in this case we can consider them as near-decomposable. Finally a definition of hierarchical systems more related to the epistemological dimension: "a system is hierarchical when alternative methods of description exist for the same system" [11]. The existence of different levels and scales at which a hierarchical system is operating implies the unavoidable existence of non-equivalent ways of describing it.

For example (Fig. 1), we can describe a human being at the microscopic level to study the process of digestion of nutrients within her/his body. When we look at a human being at the scale related to the level of an intestine cell we can even take a picture of it with a microscope (Fig. 1A). However, this type of description is not compatible with the description which would be required to catch the quality "face" of the same human being (e.g., needed when applying for a driving license), the one given in Figure 1B. No matter how many pictures we will take with a microscope of a defined human being, the type of "pattern recognition" of that person which refers to the cell level (obtained at its relative space-time window with a microscope) is not equivalent to the description of human beings (“pattern recognition”) required to catch the quality “face.”

The ability to detect the identity of the face of a given person, in fact, is therefore an “emergent property” linked to: (I) the choice of a certain space-time window for looking at the system and (II) the choice of a given system of mapping system qualities (in this case our pattern recognition is based on using light at the wave length typical of human vision). The face presented in Figure 1B cannot be detected, when adopting a description linked to a different space-time window (either that of an individual cell – Fig. 1A – or a very large scale adopted by someone looking at the social interaction of our person – Fig. 1C). The same face cannot be detected either, if we look at the same head, but using X-rays (as done in the example given in Fig. 1D) – which is a different mechanism for mapping system’s characteristics. In conclusion, in Figure 1 we have 4 different examples of “pattern recognition” which, in a way, are reflecting the existence of “previous goals” for the analyst. That is, the pattern presented in Figure 1A – reflects the goal of studying the functioning of digestive cells. The pattern presented in Figure 1B – reflects the goal of identify the face of the person. The pattern presented in Figure 1C – reflects the goal of studying the social relation of the person. The pattern presented in Figure 1D – reflects the goal of performing a medical check on the selected person. Any recognized pattern, is not only reflecting some of the characteristics of the observed system (since in any given person there are a virtually infinite number of patterns overlapping across scales waiting for being recognized), but also the relation that the observed system has with the observer.

Human societies and ecosystems are generated by processes operating on several hierarchical levels over a cascade of different scales. Therefore, they are perfect examples of nested dissipative hierarchical systems that require a plurality of non-equivalent descriptions to be used in parallel in order to analyze their relevant features in relation to sustainability [12–15].

2.2.1. Defining a Descriptive Domain

Using the rationale proposed by Kampis [16: p. 70] we can define a system as “the domain of reality delimited by interactions of interest.” In this way one can introduce the concept of “descriptive domain” in relation to the analysis of a system organized on nested hierarchical levels. A descriptive domain is the representation of a domain of reality which has been individuated based on a pre-analytical decision on how to describe the identity of the investigate system in relation to the goals of the analysis. Such a preliminary and “arbitrary” choice is needed in order to be able to detect patterns (when looking at the reality) and model the behavior of interest (when representing it). In fact, any scientific representation is then based on: (i) a set of encoding variables (reflecting a selection of observable qualities, considered relevant); (ii) a defined space-time horizon for the behavior of interests (which is determined by the space-time differential most appropriate to investigate the causal relations of interest). (iii) a dynamic generated by an inferential system applied to the set of variables (within the state space used for the representation). (iv) a boundary (linked to the given time horizon) for the investigated system. The definition of a boundary finally completes the “identity” of the modeled system as an entity separated from its environment. The scientific representation is often used to simulate with a formal system of inference the perception of relevant patterns (the behavior of interest) at a particular hierarchical level (on a certain scale).

To discuss of the need of using in parallel non-equivalent descriptive domains we can use again the 4 views given in Figure 1 applying to them the metaphor of sustainability. Let’s imagine that the 4 non-equivalent descriptions presented in Figure 1 were referring to a country (e.g., the Netherlands) rather than to a person. In this case, we can easily see how any analysis of its sustainability requires an integrated use of these different descriptive domains. For example, by looking at socioeconomic indicators of development (Fig. 1B) we “see” this country as a beautiful woman (i.e., good levels of GNP, good indicators of equity and social progress). These are good system’s qualities, required to keep low the stress on social processes. However, if we look at the same system (same boundary), but using different encoding variables (e.g., biophysical variables) – Figure 1D in the metaphor – we can see the existence of a few problems not detected by the previous selection of variables (i.e., a sinusitis and a few dental troubles in the real picture). In the metaphor this picture can be interpreted, for the Netherlands, as an assessment of accumulation of excess of nitrogen in the water table, growing pollution in the environment, excessive dependency on fossil energy and dependence on imported resources for the agricultural sector. Put in another way, when considering the biophysical dimension of sustainability we can “see” some bad system’s qualities, which were ignored by the previous selection of economic encoding variables. Comparing Figure 1B and Figure 1D we can see that even while maintaining the same physical boundary for the system (looking at the same head) a different selection of encoding variables can generate a different assessment of the performance of the system. Things become much more difficult when we are forced to use also other assessments of performance, which must be referred to descriptive domains based on different space-time differentials. For example, Figure 1A is an analysis related to lower levels components of the system (= which require for their description a different space-time scale). In the Dutch metaphor, this could be an analysis of technical coefficients (e.g., input/output) of individual economic activities (e.g., the CO_2 emissions for producing electricity in a power plant). Clearly, this knowledge is crucial to determine the viability and sustainability of the whole system (= the possibility to improve or to adjust the overall performance of Dutch economic process if and when changes are required). In the same way, an analysis of the relations of the system with its larger context can imply the need of considering a descriptive domain based on pattern recognition referring to a larger space-time domain (Fig. 1C). In the Dutch metaphor this could be an analysis of institutional settings, historical entailments, or cultural constraints over possible evolutionary trajectories.

2.3. Holons, Holarchies and Near-Decomposability of Hierarchical Systems

Each component of a dissipative nested hierarchical system may be called a 'holon,' a term introduced by Koestler [17–19] to stress its double nature of "whole" and "part" of elements of these systems (for a discussion of this concept within hierarchy theory see also Allen and Starr [20: p. 8–16]). A holon is a whole made of smaller parts (e.g., a human being made of organs, tissues, cells, atoms) and at the same time it is a part of a larger whole (an individual human being is a part of a household, a community, a country, the global economy).

Elements of nested hierarchical systems have an implicit duality: (1) holons have their own composite "organized structure" at the focal level (they represent "emergent properties" generated by the organization of their lower level components within a given associative context). On the other hand, when interacting with the rest of the hierarchy, (2) holons perform "relational functions" that contribute to a different set of "emergent properties" expressed at a higher level of analysis (they are in turn just components of another higher level holon to which they belong). When dealing with these entities we face a standard epistemological problem. The space-time domain which has to be adopted for characterizing their "relational functions" – when considering higher-level perception/description of events – does not coincide with the space-time domain which has to be adopted for characterizing their "organized structure" (when considering lower-level perception/description of events).

For example, when using the word "dog" we refer to any individual organism belonging to the species "*canis familiaris*." The characterization of the holon "dog" however, refers to the set of relational functions (the niche of that species) expressed by members of an equivalence class (the organisms belonging to that species). This means that when using the word "dog" we loosely refer both to the characteristics of the niche occupied by the species in the ecosystem and to the characteristics of any individual organism belonging to it (including the dog of our neighbor). Every "dog," in fact, belongs to an equivalence class (the species "*canis familiaris*") even though, each particular individual, has some "special" characteristics (e.g., generated by stochastic events of its personal history) which make it unique. That is, any particular organized structure (the dog of the neighbor) can be identified as different from other members of the same class, but at the same time, it must be a legitimate member of the class.

Another example of holon, this time taken from social systems, could be the President of the USA. In this case Mr. Clinton is the lower level "organized structure" that has been the "incumbent" in the "role" of President of the USA for the last 8 years. Any individual human being has a time closure within this social function – under existing US constitution – of a maximum of 8 years (two 4-year terms). Whereas the US Presidency, as a social function, has a time horizon in the order of centuries. In spite of this fact, when we refer to the 'President of the USA' we loosely address the concept of such a holon, without making a distinction between the role (social function) and the incumbent (organized structure) performing it. The confusion is increased by the fact, that you cannot have an operational U.S. President without the joint existence of: (1) a valid role (institutional settings) and (2) a valid incumbent (person with appropriate socio-political characteristics, verified in the election process). On the other hand, the existence and the identity of Mr. Clinton as an organized structure (e.g., a human being) able to perform the specified function of 'US president' is totally logically independent (when coming to representation of its physiological characteristics as human being) from the existence and the identity of the role of the Presidency of the USA (when coming to representation of its characteristics as social institution) and viceversa. Human beings were present in America well before the writing of US constitution.

In the previous section I used different words for two similar concepts: "organized structure" and "relational function" are terms proposed by Herbert Simon [10] to describe in general terms the structure of complex systems. Whereas, "role" and "incumbent" are terms proposed by Kenneth Bailey [21] to be used when dealing with human societies. Salthe [22] suggests a similar selection of terms: "individuals" (as equivalent of "organized structures" or "incumbents") and "types" (as equivalent of "relational functions" or "roles"). Finally, Rosen [23] proposes, within a general theory of modeling relation, a more drastic distinction. He suggests to make a distinction between: "natural systems" (which are always "special" and which cannot be fully described by any scientific representation due to their intrinsic complexity) and "epistemological categories" (definition of equivalence classes used to represent elements of the reality). The use of epistemological categories makes possible a compression in the demand of computational capability when representing the reality (e.g., say "dog" and you include them all). But this implies generating a loss of 1 to 1 mapping (this implies confusing the identities of the individual members of equivalence classes).

The logical similarity between the various couplets of terms is quite evident.

A nested hierarchy of dissipative systems (a hierarchical system made of holons) can be called holarchy [18: p. 102]. Gibson et al. [24] call these systems “Constitutive Hierarchies” following the suggestion of Mayr [25].

Another way of looking at the root of the epistemological predicament faced when analyzing Self-organizing Adaptive Holarchies (SAH) is to try to understand how it is possible to describe a part of them, in isolation from the rest, as a ‘well defined entity’ (= with given boundaries and characteristic patterns of organization) in the first place.

Hierarchy theory sees self-organizing adaptive holarchies as entities organized through a system of filters operating in a cascade – a consequence of the ability to generate different process rates in the various activities of self-organization [20]. For example, a human individual makes decisions and change her/his daily behavior based on a time scale that relates to her/his individual life span. In the same way, the society to which she/he belongs also makes decisions and continuously changes its rules and behavior. “. . . slaves were accepted in the United States in 1850, but would be unthinkable of today. However, society, being a higher level in the hierarchy than individual human beings, operates on a larger spatio-temporal scale” [12]. This implies that the changes occurring at a lower frequency in the behavior of whole societies are perceived as “laws” (filters or constraints) when read from the time scale of which individual citizen are operating. That is, individual behavior is affected by societal behavior in the form of a set of constraints defining what individuals can or cannot do on their own time scale. Getting into Hierarchy Theory jargon: the higher level, because of its lower frequency, acts as a filter constraining the ‘higher frequency’ activities of the components of the lower level into some emergent property (for more see Allen and Starr [20]). Additional useful references on Hierarchy Theory are: Salthe [22, 26], Ahl and Allen [27], Allen and Hoekstra [28], Grene [29], Pattee [30], O’Neill et al. [31].

This method of organization in hierarchical systems results into ‘jumps’ or ‘discontinuities’ (called also “epistemic gaps” in the complexity community – [32]) in the rates of activity of self-organization (patterns of energy dissipation) across the levels of the holarchy. Hierarchical levels are, in fact, generated by differences in process rates related to energy conversions, which are determining the chain of relations among holons. This mechanism generating discontinuities in scales is at the real root of near-decomposability.

The principle of near-decomposability (terms suggested by Simon [10], see previous quote) explains why scientists are able to study systems over a wide range of order of magnitudes, from the dynamics of sub-atomic particles to the dynamics of galaxies in astrophysics using the same set of mechanic equations. When dealing with hierarchical systems we can study the dynamics of a particular process on a particular level by adopting a description that seals-off higher and lower levels of behavior. This has been proposed as an operation of “triadic reading” by Salthe [22]. This means that we can describe, for example, in economics, consumer behavior while ignoring the fact that consumers are organisms composed of cells, atoms and electrons; and also ignoring that economic activity necessarily requires higher-level holons including particular institutions and established patterns of trust. The concept of “triadic reading” refers to the “individuation of a pattern” of interest for the scientist among the virtual infinite number of possible patterns to be detected. This requires a previous selection of three contiguous levels of interest within the cascade of hierarchical levels through which Self-organizing Adaptive Holarchies operate. We can think of it also as a process of “epistemic filtering.”

That is, when describing a particular phenomenon occurring within a SAH we have to define a group of three contiguous levels starting with:

- **Focal level** – this implies the choice of a space-time window of observation at which system qualities of interest can be defined and studied using a set of “observable” qualities (that can be translated into numerical encoding variables). After this choice we can look for measurement schemes able to assign numerical values to the selected variables supposed to catch changes in the relevant qualities of our system;
- **Higher level** – the choice of a time and space differential for the dynamics on the focal level (= “the smallest duration that can be used to perceive, as separated in time, two events” and “the smallest element that can be detected”) implies that changes of the characteristics of the higher level are so slow when described on the space-time window of the Focal level that they can be assumed to be negligible. In this case, the higher level can be accounted for – in the scientific description – as a set of external constraints imposed on the dynamics of the focal level (= the given set of boundary conditions);
- **Lower level** – the gradient in time differentials across levels implies also that perturbations generated by the changing behavior of lower level components is not affecting in a relevant way the main dynamic defined on the space-time window of the focal level description. In fact, lower level activity can be accounted for in terms of a statistical description of events occurring there. That is, we can “average out” heterogeneity in the behavior of lower level individuals. Put in another way, we can deal with lower level perturbations in the form of ‘noise.’ Due to the differences in scale, the identity of lower level processes is accounted for in the “focal description” in terms of a set of initiating conditions.

For example, economic analyses describe the economic process in terms of prices determined by curves of demand and supply. This implies adopting a focal level which has a time window: (i) small enough to assume that changes in ecological processes such as climatic changes or changes in institutional settings (the higher level) are negligible; and (ii) large enough to average out 'noise' from processes occurring at the lower level – e.g., ''non-rational'' consumer behavior of artists, terrorists, or Amish is averaged out by a statistical description of the preferences of population [12].

2.4. The Epistemological Predicaments Implied by the Ambiguous Identity of Holarchies

As noted earlier, the concept of ''holon'' implies two major epistemological problems:

1. ''Functions'' (or ''roles'') and ''organized structures'' (or ''incumbents'') overlap in the real systems when coming to specific actions (e.g., Mr. Clinton and the President of the USA decide as a whole). However the two parts have different histories, different mechanisms of control and diverging local goals (e.g., the wants of Mr. Clinton as a human being in a particular moment of his life can diverge from those of US presidency as an institutional role and vice-versa). For example, the recent case of Monica Lewinsky has been about legitimate contrasting interests expressed by the dual nature of that specific holon. Unfortunately, scientific analyses trying to model holons operating within holarchies, have no other option but that of assuming a single goal and identity for the acting holon, within the particular descriptive domain associated to the selected model. The existence of multiplicity of roles for holons operating within holarchies shows the inadequacy of the traditional reductionist scientific paradigm for modeling them. For the assumption of a single goal and identity for the acting holon, necessary in this mode of analysis, restricts it to a particular model (descriptive domain), to the exclusion of all others.
2. To get a quantitative characterization of a particular identity of a holon one has to assume the holarchy is in steady-state (or at least in quasi-steady-state). That is, one has to choose a space-time window at which it is possible to define a clear identity for the system of interest (the triadic reading, which is often expressed in the more familiar ''ceteris paribus'' assumption). However, as soon as one obtains the possibility to quantify characteristics of the system after ''freezing it'' on a given space-time window, one loses, as a consequence of this choice, any ability to see and detect existing evolutionary trends. Evolutionary trajectories are detectable only using a much larger space-time scale than that of the dynamic of interest [26]. This implies admitting that sooner or later the usefulness of current descriptive domain and the validity of the selected modeling relation will expire. For example, an exact definition of the ecological footprint of a country in a particular year depends on the adoption of a lot of space-time specific assumptions (definition of existing technical coefficients, the mix of inputs adopted in the process of production, etc.). Due to this extreme location specificity (in space and time) such an assessment ''per se'' does not say anything about the ''performance'' of the society in relation to sustainability. How does such an assessment fit with current trends? It has been generated by a temporary perturbation or it is reflecting long term changes? What is the effect of this value on the various trade-offs linked to sustainability? Put in another way, an excessive ''location specific scale,'' which is needed to obtain ''determinacy'' in the numerical assessments is often not good to obtain ''meaning'' for the assessments. On the other hand, if one wants to look at evolutionary trends in holarchies, one has to accept the consequent loss of accuracy in the assessments of their details. Discussing of ''meanings'' has always to do with dealing with the big picture (the use of metaphors rather than models), that is losing the ability of using formal definitions based on accurate mappings. This implies accepting indeterminacy.

This discussion is reminiscent of the principles of quantum mechanics articulated in the 1920s, those of indeterminacy and complementarity. The relation is clearer when we recall that the term ''measurement'' is critical in that analysis. In fact, previously measurement was taken for granted as not interfering, in principle, with the physical system being measured. Using a ''holarchic thinking'' we can understand that the measuring apparatus belongs to a larger scale holon (the scientist providing the experimental setting), so that energy losses which are insignificant on that scale can become very significant at the micro level.

Complementarity refers to the fact that holons, due to their peculiar functioning on parallel scales, always require a dual description. The relational functional nature of the holon (focal-higher level interface) provides the context for the structural part of the holon (focal-lower level interface), which generates the behavior of interest on the focal level. Therefore, an holarchy can be seen as a chain of contexts and relevant behaviors in cascade. The niche occupied by the dog is the context for the actions of individual organisms, but at the same time any particular organism is the context for the activity of its lower level components (organs and cells dealing with viruses and enzymes).

Established scientific disciplines rarely acknowledge that the unavoidable and prior choice of 'perspective' determining what should be considered the relevant action and what its context – which is implied by the adoption of a single model (no matter how complicated) – implies a bias in the consequent description of complex systems' behavior [12].

For example, analyzing complex systems in terms of organized structures – or incumbents (e.g., a given doctor in a hospital) – implicitly requires assuming for the validity of the model: (1) a given set of initiating conditions (a history of the system that affects its present behavior); and (2) a stable higher level on which functions – or roles – are defined for these structures in order to make them "meaningful," useful and, thus, stable in time [10]. That is, the very use of the category "doctors" implies, at the societal level, the existence of a job position for a doctor in that hospital together with enough funding for running the hospital.

Similarly, to have "functions" at a certain level, one needs to assume the stability at the lower levels where the structural support is provided for the function. That is, the use of the category "hospital" implies that something (or rather someone) must be there to perform the required function [10]. In our example the existence of a modern hospital – at the societal level – implies also the existence of a supply of trained doctors – potential incumbents – able to fill the required roles (an educational system working properly). All these considerations become quite practical when systems run imperfectly, as when doctors are in short supply, have bogus qualifications, are inadequately supported, etc.

Hence, no description of the dynamics of a focus level, such as society as a whole, can escape the issue of **structural constraints** (*what/how*, explanations of structure and operations going on at lower levels) and at the same time the issue of **functional constraints** (*why/how*, explanations of finalized functions and purposes, in relation to the higher level). The key for dealing with holarchic systems is to deal with the difference in space-time domain which has to be adopted for getting the right pattern recognition. Questions related to the why/how questions (to study the niche occupied by the "*canis familiaris*" species or the characteristics of US Presidency) are different from those required for the what/how questions (to study the particular conditions of our neighbor's dog related to her age and past, or the personal conditions of Mr. Clinton this week). They cannot be discussed and analyzed by adopting the same descriptive domain. Again, even if the two natures of the holon act as a whole, when attempting to represent and explain both the "why/how questions" and the "how/what questions" we must rely on complementary non-equivalent descriptions, using a set of non-reducible and non-comparable representations.

As observed by O'Neill et al. [31] biological systems have the peculiar ability of being both in 'quasi-steady-state' and 'becoming' at the same time. Their hierarchical nature makes possible this remarkable achievement. They can be described as stable categories, when analyzed (as organized structure guaranteeing relational functions within a stable associative context) on the bottom of the holarchy. They should be considered as becoming systems in evolution (when considering the continuous introduction of new functions) on the top of the holarchy. This applies also to societal systems [26]. Both classes of systems are well describable as in quasi-steady-state on small space-time windows (when dealing with the identity of cells, individuals, species, jobs, institutions) and as entities which are becoming, when we use a much large space-time window that forces us to deal with the process of evolution. For example: (1) the process of biological evolution (e.g., the becoming of ecological holons) requires the use of "relevant time differentials" of thousands of years. (2) the process of evolution of institutional settings of human societies requires the use of "relevant time differentials" of centuries. (3) the process of evolution of human technology requires the use of "relevant time differentials" of decades. (4) when dealing with price formation we are dealing with a time differential of one year or less. (5) preferences and feelings of individuals can change in a second. Obviously the epistemological categories required for representing changes over these different time windows are distinct.

To make things more complicated, complex adaptive systems tend to pulse and operate in cyclic attractors, so that we have an additional problem. Scientific analyses should be able to avoid confusing movements of the system over predictable trajectories in a given state space, with changes due to the genuine emergence of new evolutionary patterns. Genuine emergence requires, in fact, an updating of the set of tools used to represent system's behavior (e.g., a continuous change in the identity of the state space used in the analysis – the introduction of new epistemological categories and different modeling relations).

In conclusion, by choosing an appropriate window of observation we can isolate and describe, in simplified terms, a domain of the reality -the one we are interested in. In this way it is possible to define boundaries for specific systems, which can be considered, then, as independent entities from the rest of the holarchy to which they belong. The side effect of this obliged procedure, however, is the neglect, either aware or unaware, of: (1) dynamics and other relevant features which are occurring outside the space-time differential selected in the focal descriptive domain; (2) changes in other system's qualities which were not included in the original set of observable qualities and encoding variables used in the model. When dealing with becoming systems, the evolution of the system requires a parallel evolution in the identity of its descriptive domains (requiring different definitions of state spaces) to be usefully described. Put in another way, we must be aware that when applying a triadic filtering to the reality we are choosing just one of the possible non-equivalent descriptive domains for our system. Modeling means a "heroic simplification of reality" [33] based on a previous definition of a "time duration" for the analytical representation. This explains why there can be no complete, neutral, objective study of a holarchic system, and why these systems are "complex" in the sense of having multiple legitimate perspectives.

2.5. Bifurcation, Emergence and Scientific Ignorance

2.5.1. "Bifurcation" in a Modeling Relation and Emergence

Rosen [23] suggests the term "bifurcation" to indicate the existence of two different representations of the same Natural System, which are logically independent of each other. The concept of bifurcation entails the possibility of having two (or more than two) distinct formal systems of inferences, which are used on the basis of different selection of encoding variables (or focal level of analysis) to establish different modeling relations for the same "natural system." As noted earlier bifurcations are therefore entailed by different goals for the mapping.

The concept of bifurcation implies the possibility of a total loss of 'usefulness' of a given mapping. For example, imagine that we have to select an encoding variable to compare the "size" of London (U.K.) and Reykjavik (Iceland). London would result larger than Reykjavik, if the selected encoding for the quality "size" is the variable population. However, by changing the choice of encoding variable, London would result smaller than Reykjavik if the perception of its "size" is encoded by the variable: 'number of letters making up the name' (= a new definition of the relevant quality to be considered when defining the size of London and Reykjavik). Such a choice of encoding could be performed by a company which makes road signs.

In this trivial example the bifurcation is generated by a change in the set of goals and context (in the logic) related to the use of such a mapping. Two non-equivalent observers. (1) Someone willing to characterize "London" perceiving this name as a proxy for a city will adopt an identity which includes an epistemological category for its size that can have as a proxy – population size. (2) Someone working in a company making road-signs, perceiving this name as a string of letters to be written in its product, will adopt an identity which includes an epistemological category for its size based on the "demand of space on road-sign." The proxy for this system quality will be the number of letters making up the name. Clearly, the existence of a different "logic" in selecting the "category" and the "proxy" used to encode what is relevant in the quality "size" is related to a different meaning given to the perception of the natural system "London" (its identity to be adopted in the modeling process).

Obviously this is then reflected into numerical assessments which are no longer necessarily supposed to be neither reducible into each-other or directly comparable by the application of an algorithm. A bifurcation in the system of mapping can be seen as – as stated by Rosen [23: p. 302]- "the appearance of a logical independence between two descriptions." Clearly such a bifurcation depends on the intrinsic initial ambiguity in the definition of the natural system when using symbols or codes. The same label "London" can be perceived as a name of a city made up of people or "London" as a 6-letter-word. As observed by Schumpeter [34: p. 42] – "Analytical work begins with material provided by our vision of things, and this vision is ideological almost by definition."

Obviously, bifurcations in systems of mappings (reflecting differences in logic) can entail bifurcations also in the use of mathematical systems of inference. For example, a statistical office of a city recording the effect of the marriage of two "singles" already living in that city and expecting a child would map the consequent changes implied by these events in different ways according to the encoding used for assess changes in the quality "population." The event can be described either as: $1 + 1 \rightarrow 1$ (both before and after the birth of the child) if the mapping of population is done using the variable "number households." In alternative as: $1 + 1 \rightarrow 3$ (after the birth of the child) if the mapping is done in terms of "number of people" living in the city. In this simple example, it is the definition of the mechanism of encoding (implied by the choice of the identity of the system to be described – i.e., "households" versus "people" – which entails different mathematical descriptions of the same phenomenon).

The concept of bifurcation has also a positive connotation, in relation to the possibility of increasing the repertoire of models and metaphors available to our knowledge. In fact, a direct link can be established between the concept of "bifurcation" and the concept of "emergence." Using again the wording of Koestler [17] we have a "discovery" – Rosen [23] suggests to use for this concept the term "emergence" – when two previously unrelated frames of reference are linked together. Using the concept of equivalence classes both for organized structures and relational functions, we can say that "emergence" or "discovery" is obtained: (1) when assigning a new class of relational functions (which implies a better performance of the holon on the focal/higher level interface) to an old class of organized structures or (2) when using a new class of organized structures (which implies a better performance of the holon on the focal/lower level interface) to an existing class of relational functions.

An emergence can be easily detected by the fact that **it requires changing the identity of the state space used to describe the new holon**.

A simple and well-known example of "emergence" in dissipative systems is the formation of "Bénard cells" (a special pattern appearing in a heated fluid when switching from a linear molecular movement to a turbulent regime – for a detailed analysis from this perspective see Schneider and Kay [35]). The emergence (the formation of a vortex) requires the need of using in parallel 2 non-equivalent descriptive domains to properly represent such a phenomenon, since the process of self-organization of a vortex is generating both "an individual organized structure" and "the establishment of a type." We can use models of dynamic of fluids to study, simulate and even predict this transition. But no matter how sophisticated these models are they can only guess the insurgence of a type (= under which conditions you will get the vortex). From a description based on the molecular level it is not possible to guess the direction of rotation that will be taken by a particular vortex (if clockwise or anti-clockwise). Whereas, at a larger scale, any particular Bénard cell, because of its personal story, will have a specific identity, that will be kept until it remains alive (so to speak). The new scale of operation of a vortex (above the molecular one), that at which we can detect the direction of rotation, implies the use of a new epistemological category (i.e., clockwise or anti-clockwise) to properly represent such a phenomenon. Put in another way, the information required to describe the transition on two levels (characterizing both the individual and the type) can not be all retrieved describing events at the lower level.

In conclusion, whereas it is debatable whether or not the concept of emergence implies something ‘‘special’’ in ontological terms, it is clear that it implies something ‘‘special’’ in epistemological terms. **Every time we deal with something which is “more than” and “different from” the sum of its parts, we have to use in parallel non-equivalent descriptive domains to represent and model different relevant aspects of its behavior**. The implications of this fact are huge. When dealing with the evolution of complex adaptive systems (real emergence) the information space that has to be used for describing how they change in time is not closed and knowable ‘‘a priori.’’ This implies that models, even if validated in previous occasions, not necessarily will result good in predicting future scenarios. This is especially true when dealing with human systems (adaptive reflexive systems).

2.5.2. The Crucial Difference Between Risk, Uncertainty and Ignorance

The distinction proposed below is based on the work of Knight [36] and Rosen [23]. Knight [36] distinguishes between cases in which it is possible to use previous experience (e.g., record of frequencies) to infer future events (e.g., guess probability distributions) and cases in which such an inference is not possible. Rosen [23], in more general terms, alerts on the need of being always aware of the clear distinction between a ‘‘natural system,’’ which is operating in the complex reality and ‘‘the representation of a natural system’’ which is scientist-made. Any scientific representation requires a previous ‘‘mapping,’’ within a structured information space, of some of the relevant qualities of the natural system with encoding variables. Since scientists can handle only a finite information space, such a mapping implies the unavoidable missing of some of the other qualities of the natural system (those not included in the selected set of relevant qualities).

Using these concepts it is possible to make the following distinction between Risk and Uncertainty.

Risk (= situation in which it is possible to assign a distribution of probabilities to a given set of possible outcomes – e.g., the risk of losing when playing the ‘‘roulette’’). That is, RISK implies an information space used to represent the behavior of the investigated system which is: (i) closed; (ii) known; and (iii) useful (= it includes all the relevant qualities to be considered for a sound problem structuring). In this situation, there are cases in which we can even calculate with accuracy the probabilities of states included in the accessible state space (e.g., classic mechanics). That is, we can make reliable predictions.

The concept of risk is useful when dealing with problems: (i) easily classifiable (about which we have a valid and exhaustive set of epistemological categories for the problem structuring). (ii) easily measurable (the encoding variables used to describe the system are ‘‘observable’’ and measurable, adopting a measurement scheme compatible in terms of Space-Time domain with the dynamics simulated in the modeling relation). Under these assumptions, when we have available a set of valid models, we can forecast and usefully represent what will happen (at a particular point in space and time). When all these hypotheses are applicable, the expected errors in predicting the future outcomes are negligible.

Uncertainty (= situation in which it is not possible to predict what will happen). That is, UNCERTAINTY implies that we are using to make our prediction an information space, which is: (i) closed; (ii) finite; and (iii) partially useful, according to previous experience, but, at the same time, there is awareness that this is just an assumption that can fail.

The concept of uncertainty entails that the structure of entailments in the natural system simulated by the given model can change and/or that our selection of the set of relevant qualities to be used to describe the problem can become no longer valid.

Therefore, within the concept of UNCERTAINTY we can distinguish between:

- **Uncertainty due to indeterminacy** (= there is a reliable knowledge about possible outcomes and their relevance, but it is not possible to predict, with the required accuracy, the movement of the system in its accessible state space. – for example, the impossibility of predict the weather in 60 days from now in New York City). Indeterminacy is unavoidable when dealing with nested hierarchical systems or with ‘‘reflexivity’’ of humans. The simultaneous relevance of characteristics of elements operating on different scales (= the need of considering more than one relevant dynamic in parallel on different space-time scales) and non-linearity in the mechanisms of controls (the existence of cross-scale feed-backs) entail that expected errors in predicting future outcomes can become high (butterfly effect, sudden changes in the structure of entailments in human societies – laws, rules, opinions). Uncertainty due to indeterminacy implies that we are dealing with problems which are **classifiable** (we have valid categories for the problem structuring), but that they are not fully measurable and predictable.

- **Uncertainty due to ignorance** (= situation in which it is not even possible to predict what will be the set of attributes that will result relevant for a sound problem structuring). That is, IGNORANCE implies the awareness that the information space used for representing the problem is: (i) finite and bounded, whereas the information space, that would be required to catch the relevant behavior of the observed system, is open and expanding; and (ii) our model is missing relevant system qualities. The worst aspect of scientific ignorance is that it is possible to know about it, only through experience. That is, when the importance of events (attributes) neglected in a first analysis becomes painfully evident. For example, Madame Curie, who won two Nobel Prizes for her outstanding knowledge of radioactive materials, died of leukemia. Some of the characteristics of the object of her investigations, known nowadays by everybody, were not fully understood at the beginning of this new scientific field.

There are typologies of situations in which we can expect to be confronted in the future with problems that we cannot either guess or classify at the moment. For example, when facing fast changes in existing boundary conditions. In a situation of rapid transition we can expect that we will have to learn soon new relevant qualities to consider, new criteria of performance to be included in our analyses, and new useful epistemological categories to be used in our models. That is, in order to be able to understand the nature of our future problems and how to deal with them we will have to use an information space different from the one used right now. Obviously, in this situation, we cannot even think of valid measurement schemes (how to check the quality of the data), since there is no chance of knowing what encoding variables (observable relevant qualities) will have to be measured.

Even admitting that ignorance means exactly that it is not possible to guess the nature of future problems and possible consequences of our ignorance, this does not mean that it is not possible to predict, at least, when such an ignorance can become more dangerous. For example, when studying complex adaptive systems it is possible to gain enough knowledge to identify basic features in their evolutionary trajectories (e.g., we can usefully rely on valid metaphors). In this case, in a rapid transitional period, we can easily guess that our knowledge will be affected by larger doses of scientific ignorance.

The main point to be driven home from this discussion over risk, uncertainty and ignorance is the following. In all cases in which there is a clear "awareness" of living in a fast transitional period in which the consequences of "scientific ignorance" can become very important, it is wise not to rely only on reductionist scientific knowledge. The information coming from scientific models should be mixed with that coming from metaphors and additional inputs coming from various systems of knowledge found among stakeholders. A new paradigm for science – Post-Normal Science – should aim at establishing a dialogue between science and society moving out from the idea of a one-way flow of information. The use of mathematical models, as the ultimate source of truth, should be regarded just as a sign of ignorance of the unavoidable existence of scientific ignorance.

2.6. Non-Reducibility (Multiple Causality) and Incommensurability

2.6.1. Non-Reducible Assessments

In this section I discuss an example of legitimate non reducible assessments. The example is based again on the 4 views presented in Figure 1. The metaphor this time is applied to the process generating a concrete assessment. For example: "kg of cereal consumed per capita by US citizen in 1997." Let us imagine that a very expensive and sophisticate survey is performed, at the household level, to get an "accurate" assessment of food consumption. By recording events in this way we can learn that each US citizen consumed, in 1997, 116 kg of cereals per person per year. On the other hand, by looking at the FAO Food Balance Sheet [37] – which provides for each FAO-member country a picture of the flow of food consumed in the food system – we can derive other possible assessments for the "kg of cereals consumed per capita by US citizen in 1997." For example:

1. **cereals consumed as food, at the household level.** This is the figure of 116 kg per year per capita for US citizen, in 1997, discussed before. This can also be obtained by dividing the total amount of cereals directly consumed as food by the population of USA in that year.
2. **consumption of cereals per capita in 1997 as food, at the food system level.** This value is obtained by dividing the total consumption of cereals in the US food system by the size of US population. This assessment is more than 1,015 kg (116 kg directly consumed, 615 kg fed to animals, plus almost 100 kg of barely for making beer, plus other items related to industrial processing and post-harvest losses).
3. **amount of cereals produced in US per capita, in 1997, at the national level, to obtain an economic viability of the agricultural sector.** This amount is obtained by dividing total internal production of cereals by population size. Such a calculation provides yet another assessment: 1,330 kg/year per capita. This is the amount of cereal used per capita by US economy.
4. **total amount of cereals produced in the world per capita, in 1997, applied to the humans living within**

> **the geographic border of the USA in that year.** This amount is obtained by dividing total internal consumption of cereal at the World level in 1997 (which was 2×10^{12} kg), by world population size (5,800 millions). Clearly, such a calculation provides yet another assessment: 345 kg/year per capita (160 kg/year direct, 185 kg/year indirect). This is the amount of cereal used per capita by each human being in 1997 on this planet. Therefore this would represent the share assigned to US people when ignoring heterogeneity of pattern of consumption among countries.

We can use again Figure 1 to discuss the mechanisms in the process of generation of the assessment generating these numerical differences. In the first two cases, we are considering only the direct consumption of cereals as food. On a small scale – assessment (1) reflecting Figure 1A in the metaphor – and on a larger scale – assessment (2) would refer to Figure 1B in the metaphor. The logic of these two mappings is the same. We are mapping flows of matter, with a clear identification in relation to their role: food as a carrier of energy and nutrients, which is used to guarantee the physiological metabolism of citizens. This very definition of consumption of "kg of cereals" implies a clear definition of compatibility with physiological processes of conversion of food into metabolic energy (both within fed animals and human bodies). This implies that since the mechanism of mapping is the same (in the metaphor of Figures 1A and 1B, we are looking for pattern recognition using the same visible wave-length of the light) we can bridge the two assessments by an appropriate scaling (e.g., Life Cycle Assessment). This will require, in any case, different sources of information related to process occurring at different scales (e.g., household survey + statistical data on consumption and technical coefficients in the food systems). When considering assessment (3) we are including in such an assessment "kg of cereals" which are not "consumed" either directly or indirectly by US households in relation to their diet. The additional 315 kg of cereals produced by US agriculture per US citizen for export (assessment (3) – assessment (2)), are brought into existence only for economic reasons. But exactly because of that, they should be considered as "used" by the agricultural sector and the farmers of that country to stabilize its own economic viability. The US food system would not have worked the way it did, in 1997, without the extra income provided to farmers by export. Put it in another way, US households "indirectly used" this export (= took advantage of the production of these kg of cereals) for getting the food supply they got, in the way they did. This could be in the metaphor the pattern presented in Figure 1D. We are looking at the same head (the US food system in the analogy) but using a different mechanism of pattern recognition (using X-rays rather than visible light). The difference in numerical value between assessment (1) and (2) is generated by a difference in the hierarchical level of analysis. Whereas the difference between assessment (2) and (3) is generated by a "bifurcation" in the definition of indirect consumption of cereals per capita (a biophysical definition versus an economic definition). Finally, Figure 1C would represent the numerical assessment obtained in (4), when both the scale and the logic adopted for defining the system is different from the previous one (US citizen as members of humankind).

Table 1. Multiple scientific explanations for a given event.

Event to be explained: DEATH OF A PARTICULAR INDIVIDUAL

	Space-time scale:	Example of situation:	Explanation:	Implications for action:
Explanation 1 → (looking for the known HOW)	Very small	Emergency room	No oxygen supply to the brain	Apply known procedures
Strong entailment of the past on present action				
Explanation 2 → (looking for a better HOW)	Small	Medical treatment	Affected by lung cancer	Apply known procedure & explore new ones
Entailment of the past on present, room for exploring changes				
Explanation 3 → (considering HOW to WHY)	Medium	Meeting at the Ministry of Health	Individual was heavy smoker	Policy formulation mixing experience with aspirations for change
Mixed entailment of the past and "virtual future" on present				
Explanation 4 → (exploring the implications of WHY)	Very large	Discussion on sustainability	Humans must die	Dealing with the tragedy of change
Entailment of the "virtual future" (passions) on present				

Again it has to be noted, that these non reducible differences do not imply that any of these assessments is useless. Depending on the goal of the analysis, each one of these numerical assessments can carry useful information.

2.6.2. Multiple Causality for the Same Event

The next example deals with multiple causality: 4 non-equivalent scientific explanations for the same event are listed in Table 1 (the possible death of a particular individual). This example is particularly relevant in all cases in which the explanation provided is then used as an input for the process of decision making.

- Explanation 1 refers to a very small space-time scale at which the event is described. This is the type of explanation generally looked for when dealing with a very specific problem (= when we have to do something according to a given set of possibilities, perceived here and now = a given and fixed associative context for the event). Such an explanation tends to generate a search for maximum efficiency. According to this explanation we can do as good as we can, **assuming that we are adopting a valid, closed and reliable information space**. In political terms, these type of "scientific explanations" tend to reinforce current selection of goals and strategies of the system. For example, policies aimed at maximizing efficiency implies not questioning (in the first place) basic assumptions and the established information space used for problem structuring;

- Explanation 2 refers again to a small space-time scale at which the event is described. This is the type of explanation generally looked for when dealing with a class of problems that have been framed in terms of the WHAT/HOW question. We have an idea of the HOW (of the mechanisms generating the problem) and we want to both fix the problem and understand better (fine tuning) the mechanism according to our scientific understanding. Again we assume that the basic structuring of the available information space is a valid one, even though we would like to add a few improvements to it;
- Explanation 3 refers to a medium/large scale. The individual event here is seen through the screen of statistical descriptions. This type of explanation is no longer dealing only with the WHAT/HOW question but also, in an indirect way with the WHY/WHAT question. We want to solve the problem, but in order to do that we have to mediate between contrasting views found in the population of individuals to which we want to apply policies. In this particular example, dealing with the trade-offs between individual freedom of smoking and the burden of health-costs for the society generated by heavy smoking. We no longer have a closed information space and a simple mechanism to determine optimal solutions. Such a structuring of the problem requires an input from the stakeholders in terms of "value judgement" (= for politicians this could be the fear of losing the next elections);
- Explanation 4 refers to a very large scale. This explanation is often perceived as "a joke" within a scientific context. My personal experience is that whenever this slide is presented at conferences or lessons, usually the audience starts laughing when seeing the explanation "humans must die" listed among the possible scientific explanations for the death of an individual. Probably this reflects a deep conditioning to which scientists and students have been exposed for many decades. Obviously, such an explanation is perfectly legitimate in scientific terms when framing such an event within an evolutionary context. The question then becomes why it is that such an explanation tends to be systematically neglected when discussing of sustainability? The answer is already present in the comments given in Table 1. Such an explanation would force the scientists and other users of it to deal explicitly and mainly with "value judgements" (dealing with the "why" or "what for" question rather than with the "how" question). Probably this is why, this type of question seems to be perceived as not "scientifically correct" according to western academic rules.

Also in this second example we find the standard predicament implied by complexity: the validity of using a given scientific input depends on the compatibility of the simplification introduced by the "problem structuring" with the context within which such an information will be used. A discussion about pros and cons of various policies restricting smoking would be considered unacceptable by the relatives of a patient in critical conditions in an emergency room. In the same way, a physiological explanation on how to boost the supply of oxygen to the brain would be completely useless in a meeting discussing the opportunity of introducing a new tax on cigarettes.

2.6.3. Multicriteria Space – Dealing with Incommensurability

The last example of this paper deals with the problem of how to make use of the descriptive input obtained through a set of parallel, non-equivalent and reducible models. Let's imagine that one wishes to buy a new car and wants to decide among the existing alternatives on the market. Such a choice would depend on the analysis of various characteristics (e.g., economic, safety, aesthetic and driving characteristics) of the various models of car taken into considerations. Obviously, the set of characteristics considered in Figure 2 is just one of the possible sets of relevant attributes, since it is not possible to generalize all the sets of possible criteria used by the population of non-equivalent car buyers operating in this world. It is sure, however, that some of the criteria (and related indicators) measuring the relevant characteristics determining such a choice will result incommensurable (e.g., price in dollars, speed in Km/h, status symbol, aesthetic preferences) and conflicting in nature (e.g., the higher the speed the higher the economic cost). Given a set of indicators we can represent the performance of any given alternative, according to the set of relevant criteria through a multicriteria impact profile, which can be represented either in a graphic form, as shown in Figure 2, or in a matrix form, as shown in Table 2. These multicriteria impact profiles can be based on quantitative, qualitative or both types of information.

The way humans represent and structure the problem to be solved, in scientific terms, necessarily reflects the values and interests of those that will use the information. This is perfectly OK as long as this obvious fact is acknowledged and its related implications are taken into account. The same applies to the mechanism used to compare and rank possible alternative actions. From a philosophical perspective, it is possible to distinguish between two key concepts [38, 39]. (1) *strong comparability* (= it is possible to find a single

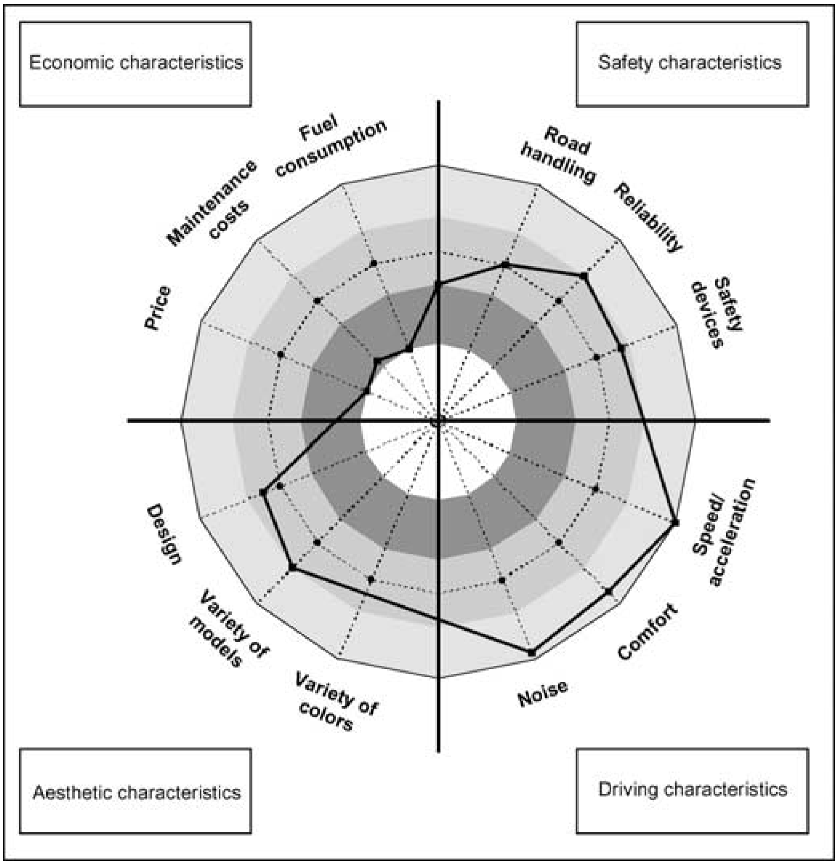


Fig. 2. Multi-objective integrated representation of the performance of a car.

Table 2. Example of an impact matrix.

Criteria	Units	Alternatives			
		a_1 – car A	a_2 – car B	a_3 – car C	a_4 – car D
g_1 Price	US$ (1997)	$g_1(a_1)$	$g_1(a_2)$	·	$g_1(a_4)$
g_2 Maintenance costs	US$/year	·	·	·	·
g_3 Fuel consumption	Liter/km	·	·	·	·
g_4 Road handling	Qualitative	·	·	·	·
. . .	. . .	·	·	·	·
g_{12} Design	Qualitative	$g_{12}(a_1)$	$g_{12}(a_2)$	·	$g_{12}(a_4)$

comparative term by which all different actions can be ranked). This implies strong commensurability (= it is possible to obtain a common measure of the different consequences of an action based on a cardinal scale). According to this hypothesis the ''value'' of ''everything'' (including your mother) can be compared to the value of ''everything else'' (including someone else mother) by using a single numerical variable (e.g., monetary or energy assessments). (2) *weak comparability* (= there is an irreducible value conflict when deciding what term should be used to rank alternative actions). This translates into the assumption that different stakeholders can exhibit different ''rational choices'' when facing the same specific situation. Weak comparability, however, does not imply that it is not possible to use ''rationality'' when deciding or that ''everything goes'' when coming to scientific analyses. As discussed in the second part, procedural rationality is based on the acknowledgement of ignorance, uncertainty and the existence of legitimate non-equivalent views of different stakeholders. That is, this requires, when ranking options, to agree on **what is important** for the stakeholder as well as to agree on **what is relevant** for the stability of the process described in the model. As a consequence of this fact, the validity of a given approach used to evaluate and rank possible options depends on its ability to: (1) include **several legitimate perspectives** (acknowledging the reflexive properties of the system) and (2) provide a reliable check on the viability of the system in relation **to different dimensions of viability** (technical, economic, ecological, social).

This, in turn, requires ''transparency'' in relation to two main points: (1) quality of the participatory process (a quality check on the process of decision making): e.g., how fair and open was the discussion about problem structuring; about the choice of models used to characterize scenarios; about the choice of alternatives to be considered. How fair was the mechanism used for the final decision? (2) quality of the scientific process (a quality check on the representative tools which make the set of models used conform to given requirements): e.g., how credible are the assumptions, what are the implications of these assumptions, how good are the data; how competent are the modelers? A quality control on the available information to be used for decision making is obviously crucial: how reliable are the data used to prepare either the characterization given in Figure 2 or the impact matrix given in Table 2?

This last question points at an additional problem: whenever it is impossible to establish exactly the future state of the problem faced, one can decide to deal with such a problem either in terms of stochastic uncertainty (thoroughly studied in probability theory and statistics) or in terms of fuzzy uncertainty (focusing on the ambiguity of the description of the event itself) [40]. However, as noted earlier, one should always be aware that genuine ignorance is always there too. This predicament is particularly relevant when facing sustainability issues, because of large differences in scales of relevant descriptive domains (e.g., between ecological and economic processes) and the peculiar characteristics of reflexive systems. In these case it is unavoidable that the information used to characterize the problem is affected by subjectivity, incompleteness and imprecision (e.g., ecological processes are quite uncertain and little is known about their sensitivity to stress factors such as various types of pollution). A great advantage of multicriteria evaluation (compared with conventional ‘‘monocriteria’’ Cost Benefit Analysis) is the possibility to take these different factors into account.

3. PART 2 – IMPLICATIONS OF COMPLEXITY AND SCALES ON INTEGRATED ASSESSMENT

3.1. The Epistemological Predicament of Sustainability Analysis

In Part 1 the concept of ‘‘complexity’’ has been presented according to the theoretical framework proposed by Robert Rosen [1, 23, 41]. In Rosen’s view complexity implies the impossibility to fully describe the behavior of a given natural system by using a single model (or a finite set of reducible models) of it. This impossibility derives from the unavoidable epistemological dimension of the very perception and definition of ‘‘a system’’ in the first place and the consequent existence of legitimate and logically independent ways of modeling the behavior of any adaptive nested hierarchical system. Put in another way, the usefulness of any scientific representation of a complex system cannot be defined ‘a priori,’ without considering the goal for which this representation has been generated.

As a general principle we can say that by increasing the number of reciprocally irreducible models used in parallel for mapping systems’ behavior (this is what integrated assessment is all about) we can increase the richness and usefulness of any scientific representation. The good news implied by this concept is that: (1) it is often possible to catch and simulate relevant aspects of the behavior of a complex system even when having an incomplete knowledge of it. The bad news is that: (2) any ‘‘perspective’’ on a complex system (comprehensive and consistent knowledge – interpretation of the system including modeling relations) will necessary miss some of the elements and/or relevant relations in the system. Scientific models of complex systems (even if extremely complicated) imply the generation of errors (due to the unavoidable neglecting of some relevant relations referring to events – or patterns – detectable only on distinct space-time scales or in different systems of encoding). In more technical jargon Rosen [23, 41] refers to this fact as the unavoidable existence of ‘‘bifurcations’’ in any mapping of complex systems.

We can reduce the effect of these errors by using in parallel various mutually irreducible ‘‘perspectives’’ (by generating ‘‘mosaic effects’’ in our scientific representation [32]). However, this solution: (i) does not solve completely the problem; (ii) introduces another source of arbitrariness in the resulting analysis. In fact, the very concept of complexity implies that a virtually infinite number of mutually irreducible ‘‘perspectives’’ (modeling relations) **can** and (depending on the objective of the analysis) **should** be considered to fully describe the behavior of a ‘‘real’’ natural system.

Therefore, any selection of a limited set of mutually irreducible perspectives to be used in an integrated assessment (= a multicriteria description able to generate a mosaic effect and based on a finite set of relevant criteria or attributes) can only be based on a subjective decision about the relative relevance of the selected set of perspectives (why should we limit the analysis only to the selected set of criteria?). For example, when selecting an airplane pilot, is her/his zodiacal sign (or her/his religious belief) one of the relevant criteria to be considered? Probably a commercial airline would definitely exclude these two criteria from its screening process. On the other hand, it could very well be that an eccentric millionaire (or an integralist religious group) when looking for a pilot for her/his/their private jet could decide to include one (or both) of these criteria among the relevant pieces of information to be considered in the process of pilot selection.

Every time we are dealing with a decision about the relevance or irrelevance of the set of criteria to be considered in the integrated assessment we cannot expect to find general algorithms which will make possible to escape ‘‘value judgements.’’ The irreducibility of possible perspectives that should be considered as relevant when structuring the description of a natural system (= determining the selection of variables used in the modeling relation) implies that there is always a ‘‘logical independence’’ in the various selections of relevant ‘‘qualities’’ of the system. That is, it is only after deciding (how?) the set of relevant qualities to be considered in the scientific analysis which it becomes possible to discuss about encoding variables and consequently about models to be developed. On the other hand, scientific information already available – based on the selection of models done in the past – can affect the ‘‘feelings’’ of stakeholders about which are the most relevant qualities to be considered. This is a typical problem of ‘‘reflexive systems’’ which is at the core of the new paradigm for science for sustainability proposed under the name of Post-Normal Science [42–47].

This fact has also another important consequence for scientific analyses. When dealing with non-equivalent, alternative models which can be used to represent the behavior of a given complex system, we cannot check or compare their ‘‘validity’’ by focusing only on a single aspect of system behavior at the time. The ‘‘validity’’ of a given model is not simply related to its ability to make good simulations and consequently predictions on changes that will occur for a particular system quality. Even when the predictions of a model are supported by experimental evidence, this does not guarantee that:

- such a quality is relevant for a sound structuring of the problem. This is related to the well-known trade-off between ‘‘accuracy’’ and ‘‘relevance’’ of scientific models. We can increase the accuracy of modeling relations by adding assumptions that make the model less and less credible and applicable to real situations. We can remember here the example of the broken clock that happens to indicate the right time twice a day versus a clock, which loses 5 seconds every day. This second clock will never indicate the right time in the next year, but still result much more useful than the first one in the next month. In this example, the ability of being perfectly right twice a day does not coincide with the ability of being useful.
- the modeling relation valid at the moment under a given ‘‘ceteris paribus’’ hypothesis will retain its ability to model the same system again in the future when some conditions and characteristics (external and/or internal to the system) will change. The validity of useful models of real systems expires. This is due to the fact that real systems evolve in time, whereas formal systems of inference are out of time.
- nobody ‘‘cheated’’ in collecting the data used to validate the model. This observation carries a completely new domain of ‘‘quality control’’ to be added to the evaluation process. Without social trust in the process generating the integrated assessment, technical aspects of the models can become totally irrelevant.

3.2. A New Conceptualization of ‘‘Sustainable Development’’: Moving from ‘‘Substantial’’ to ‘‘Procedural’’ Rationality

It is often stated that Sustainable Development is something that can only be grasped as a ‘‘fuzzy concept’’ rather than expressed in terms of an exact definition. This is due to the fact that sustainable development is often imagined as a formal, static concept that could be defined in general terms without the need of using, any time we are applying it to a specific situation, several internal and external semantic checks. The only way to avoid the ‘‘fuzzy trap’’ implied by such a substantive concept of sustainability is to move away from a definition, which is of general application (= it is related to some predefined optimizing function related to a standard associative context). We should rather look for a definition which is based on (and implies the ability of performing) internal and external semantic ‘‘quality checks’’ on the correct use of adjectives and terms under a given set of special conditions (at a given point in space and time). These ‘‘quality checks’’ should be able to reflect the various perceptions of the stakeholders found within a defined context. Clearly, these perceptions depend on the particular point in space and time at which the application of general principles occurs (this implies also a strong dependency on the history of the local system – e.g., cultural identity of various social groups, existing institutions and power structure, existence of shared goals and trust among stakeholders).

The main point here is that a definition of Sustainable Development can be given (see below) but only after assuming that within a given society it is possible to obtain these semantic and quality checks. In this case we can say that the concept of Sustainable Development should be defined in a different way. What I propose is: ‘‘**the ability of a given society to move, in a finite time, between satisficing, adaptable, and viable states**.’’

Such a definition implies that sustainable development has to do with a process (procedural sustainability) rather than with a set of once-and-for-all definable system-qualities (substantive sustainability) (note: I am using the distinction between substantive and procedural rationality proposed by Simon [3, 4]). Put in another way, sustainability implies the following points:

1. ***governance and adequate understanding of present predicaments*** – as indicated by the expression: ‘‘the ability to move, in a finite time,’’;
2. ***recognition of legitimate contrasting perspective related to the existence of different identities for stakeholders*** (implying the need of: (i) an adequate integrated scientific representation reflecting different views; and the possibility of having: (ii) institutionally organized processes for negotiation within the process of decision making) – as indicated by the expression: ‘‘satisficing’’ (again a term suggested by Simon [3]) as opposed to ‘‘optimizing’’;
3. ***recognition of the unavoidable existence of uncertainty and indeterminacy in our understanding, representation and forecasting of future events*** – as indicated by the expression: ‘‘adaptable.’’ When discussing of adaptability (= the usefulness of a larger option space in the future):

(i) reductionist analyses based on ‘‘ceteris paribus’’ hypothesis have little to say; and (ii) incommensurability implies that ‘‘optimal solutions’’ cannot be detected applying algorithmic protocols (the information space needed to describe the performance of the system is expanding and therefore cannot be mapped by any closed formal inferential systems);

4. ***availability of sound reductionist analyses*** able to verify within different scientific disciplines the ‘‘viability’’ of possible solutions in terms of existing technical, economic, ecological and social constraints – as indicated by the expression: ‘‘viable.’’

I personally believe that reaching a societal agreement on a procedural definition of sustainable development is a possible task. However, this would require a paradigm shift in the way scientific information is generated and organized when providing inputs to the process of decision making.

To conclude this section I would like to quote Herbert Simon [4] in relation to the concept of ‘‘satisficing’’ solutions. When there is indeterminacy or complexity it is no longer possible to get rid of deliberation. The formation of human perceptions and preferences should be considered as part of the problem of decision [48]. In fact, decision making is influenced by the decision-maker’s mind: ‘‘A body of theory for procedural rationality is consistent with a world in which human beings continue to think and continue to invent: a theory of substantive rationality is not’’[4].

4. CONCLUSION

In this paper, I tried to convince the reader that there is nothing transcendent about complexity, something, which implies the impossibility of using sound scientific analyses (including reductionist ones). For sure, in the process of decision making about sustainability we need more and more rigorous scientific input to deal with the predicament of sustainability faced by humankind in this new millennium.

On the other hand, complexity theory can be used to show clearly the impossibility to deal with decision making related to sustainability in terms of ‘‘optimal solutions’’ determined by applying algorithmic protocols to a closed information space. When dealing with complex behaviors we are forced to look for different causal relationships among events. However, the various causal relations found by scientific analyses will depend on decisions made in the pre-analytical structuring of the problem. We can only deal with the scientific representation of a nested hierarchical system by using a strategy of stratification (= by using a triadic reading based on the arbitrary selection of a focal space-time differential able to catch one dynamic of interest at the time).

In order to be able to use fruitfully science, when discussing of sustainability, humans should just stop pretending that their processes of decision making are based on the ability to detect the ‘‘best’’ of the possible courses of action, after applying standard protocols based on reductionist analyses. This has never been done in the past, it is not done at the present, and it will never be done in the future. Any ‘‘decision’’ always implies a political dimension, since it is based on imperfect information and a given set of goals. Otherwise it should be called ‘‘computation’’ (R. Fesce; personal communication).

The confusion on this point is often generated by the fact that, in the last decades, in Western countries the ‘‘elite’’ in power, for various reasons, decided to pretend that they were taking decisions based on ‘‘substantive rationality.’’ Clearly, this was simply not true, and the clash of reductionist analyses against the issue of sustainability in these decades is clearly exposing such a faulty claim. Complex systems theory can help in explaining the reasons of such a clash. Any definition of priorities among contrasting indicators of performance (reflecting legitimate non-equivalent criteria) is affected by a bias determined by the previous choice of how to describe events (the ideological choices in the pre-analytical step . . .). That is, such a choice reflects the priorities and the system of values of some agent in the holarchy.

When dealing with the problem of how to do a sound problem structuring, we are in a classic example of a chicken-egg situation. The results of scientific analyses will affect the selection of what is considered relevant (how to do the next pre-analytical step) and what is considered relevant will affect the results of scientific analyses. This chicken-egg pattern simply explains the co-existence of alternative, non-equivalent and legitimate ‘‘structuring’’ of sustainability problems in different human groups separated by geographic and social distances. After acknowledging this fact, we cannot expect that scientists operating within the given set of assumptions of an established disciplinary field can be able to boost the ‘‘quality’’ of any process of problem structuring on their own. In order to do that, they need to work with the rest of the society. Therefore, the only viable way out of this epistemological predicament is an integrated assessment based on transdiciplinary analyses and participatory techniques. That is, by establishing an iterative interaction between scientists and stakeholders as implied by the concept of ‘‘procedural rationality.’’

The unavoidable existence of reciprocally irreducible models and the goal of increasing the richness of scientific representation, however, should not be misunderstood as an invitation to avoid decisions on how to compress in a useful way the set of analytical tools used to represent and structure our problems. On the contrary, the innate complexity of sustainability issues requires a rigorous filter on sloppy scientific analyses, poor data, inadequate discussion of basic assumptions.

Reciprocally irreducible models may have significant overlap in their descriptive domains. In this case, the parallel use of non-equivalent models dealing with the same system can be used not only to increase the richness of scientific representation, but also help to uncover inconsistencies in the basic hypotheses of the different models, numerical assessments, and predicted scenarios. An application of this rationale in terms of biophysical analyses of sustainability is provided in Giampietro and Mayumi [49, 50]. This is another important application of complexity and multiple scales for integrated assessment.

The problem of ‘‘how to improve the quality of a decision process’’ has not been considered as relevant by ‘‘hard scientists’’ in the past. However, the new nature of the problems faced by humankind in this third millennium implies a new challenge for science. This new terms of reference is especially important for those working in integrated assessment.

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