MATHEMATICAL MODELS OF SOCIETY AND DEVELOPMENT: DEALING WITH THE COMPLEXITY OF MULTIPLE-SCALES AND THE SEMIOTIC PROCESS ASSOCIATED WITH DEVELOPMENT

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Summary

This chapter is organized in three sections. Section 1 provides an overview of the various underlying chapters and an introduction to the theme of this chapter. The other two

sections discuss key epistemological issues associated with the use of mathematical models to study the evolutionary process of social systems. In particular, Section 2 introduces several concepts which can be associated with complexity: (1) *Jevons' paradox* - when dealing with the perception/representation of the evolution of adaptive systems, "ceteris" are never "paribus"; (2) *Hierarchy Theory* - there are multiple legitimate formalizations that can be adopted for perceiving and representing a given relevant reality; (3) *Holons and Holarchies* - any perception and representation of an evolving system organized on multiple levels and scales must hinge on a pre-analytical coupling of a functional and a structural type. That is, the perception and representation of a holon is based on a given semiotic coupling of two identities (structural and functional types) both required to characterize it. Therefore, holons are not formalizable in substantive terms. Section 3 explores concepts useful for explaining the epistemological roots of these predicaments: (1) the semiotic nature of the concept of identity; (2) the modeling relation theory developed by Robert Rosen; (3) the implications of the two-step process entailed by a modeling relation: (i) the semiotic framing of the relevant issue to be modeled is made by a story-teller; whereas (ii) the formalization of the relative analysis is made by an analyst. The definition of quality for a model given by the story-teller does not coincide with that given by the analyst. (4) the difference between *models* and *similes* is related to the possibility of generating an uncontested agreement on the set of narratives, modeling choices, calibration and validation procedures selected in a given modeling relation.

1. Introduction and Overview of the Underlying Chapters

The use of mathematical models for dealing with human affairs received a major boost during World War II. Subsequent decades saw the generation of new academic fields associated with the development of their theoretical foundations. In particular, two fields were: (i) Cybernetics dealing with a sort of "theory of controls"; and (ii) "operations research" dealing with all types of optimization problems. As a result of this sudden acceleration in the ability to make useful models, the number of fields of possible application exploded. A large scale attempt to apply mathematical models to the fields of anthropology and sociology was experienced in the 1960s, but the momentum and the enthusiasm in these two fields disappeared quite soon in the 1970s. Whereas, in the field of ecology and, more in general, of sustainability of human development, the pioneering work of Oak Ridge National Lab on environmental models of the 1960s and *The Limits to Growth* of Meadows, et al. , despite simple linear structure, opened the way to further elaboration. Nowadays, Integrated Environmental Modeling is the field in which mathematical modeling is becoming a key element of the process of discussion, selection and enforcement of environmental policies (see for example EPA announcement about Models Knowledge Base www.epa.gov/crem - where CREM stands for Council for Regulatory Environmental Models). The original legacy of operations research led to the development of mathematical tools for decision support that are often associated with Integrated Environmental Modeling.

In the era of powerful supercomputers and more challenging global environmental and economic problems there is an increasing amount of funds invested on modeling problems related to the sustainability of human development. Socioeconomic and environmental variables are often mixed together within simulations designed to address different dimensions of sustainability at different scales. To make things more challenging alfa-numeric data are more and more integrated with graphic analysis (e.g. in GIS applications).

There are, at least, two merits of mathematical models as applied to society or economy. The first is that of bringing to light important errors in the works of literary researchers who reasoned only dialectically. In a certain sense, mathematical models can show what is wrong in a given reasoning rather than what is right. The second merit of mathematical models is that of providing additional insights on critical points of dialectical argument in order to make them more understandable and effective. That is, one may use, in the case of economics, a utility function containing a special parameter in order to discuss didactically the problem of change in tastes or, in alternative, a probability distribution to illustrate the situation of an individual confronted with risk.

The contributions underlying this overview: *Mathematical Models in Demography and Actuarial Mathematics, Ecological and Socio-Ecological Economic Models, Ecological and Socio-Ecological Economic Models, Mathematical Modeling in Social and Behavioral Sciences, Mathematical Models of Management of the Environment and its Natural Resources* indeed show these two merits.

In fact, Robert Schoen (see *Mathematical Models in Demography and Actuarial Mathematics*) provides an overview of how population models typically describe patterns of mortality, fertility, marriage and/or migration, and depict how those demographic behaviors change the size and age structure of populations over time. Intensive research on demographic behavior had been accomplished based on models with fixed rate and one-sex populations. Prof. Schoen argues that a variety of new population models have been created that accommodate changing vital rates within two-sex marriage and a fertility population model. The greatest progress has been made in understanding how population structure responds at the margin to changing rates.

The contribution of Alfredo Medio (Mathematical models in economics) focuses on a small number of critical issues concerning the relation between mathematical models and basic theoretical assumptions in economics. In particular he deals with the theory of general equilibrium, and dynamic systems theory, a broad, diverse and rapidly growing area of mathematical research. The development of new tools of analysis, particularly in dynamical systems theory, may open new vistas for economic theory to cope with several issues such as indeterminacy, non-linearity and the behavior of learning agents.

The aim of the contribution by Jacek Krawczyk and Jacques Poot (see *Ecological and Socio-Ecological Economic Models*) is to review common foundations and recent developments in the area of socio-ecological economic modeling. The focus is on dynamical mathematical systems for the purpose of policy experiments, scenario formulation and forecasting. At the theoretical level, there is an increasing emphasis on nonlinear dynamical systems that can mimic complex patterns in ecological economic systems, such as cycles, turbulence, resilience, chaos, and catastrophic discontinuities. Nonlinear dynamical systems can provide an effective perspective for achieving sustainability of natural resource exploitation and preservation of environmental quality.

Wei-bin Zhang's contribution (see *Mathematical Modeling in Social and Behavioral Sciences*) provides a general overview of mathematical approaches to different social and behavioral sciences: (1) application of optimization theory and comparative statistics analysis---the optimal behavior of workers with multiple interests and the impact of job amenity on moonlighting; (2) application of operations research—the job assignment problem; (3) application of game theory— political competition; (4) application of differential equations—investigation of long-run socioeconomic consequences of altruism; (5) application of chaos theory—identification of socioeconomic chaos from a simple population model based on Malthus' ideas.

Carlos Romero's contribution (see *Mathematical Models of Management of the Environment and its Natural Resources*) presents a set of models having the goal to form a fundamental underpinning for a rational understanding and management of current environmental problems such as: (1) the excessive generation of adverse environmental effects in modern industrialized countries; (2) the clear insufficiency of the market mechanism to generate a socially optimal supply of environmental public goods; (3) the risk of exhaustion of many natural resources.

In contrast with the chapters listed above, we want to focus, in this chapter, on a few key epistemological issues associated with the use of mathematical models to study the evolutionary process of social systems. In the past, these epistemological issues used to be considered relevant only in philosophical discussions. However, the increasing use of mathematical models in sustainability science is putting back these issues on the front burners. As a matter of fact, in the last decades, the scientific world had to face a new type of challenge associated with the issue of governance. Whenever science is used for dealing with controversial political issues *the quality* of the input provided to the process of decision making is no longer uncontested. That is, whenever an indication given by a mathematical model is not welcome by either a given social group or by a powerful stakeholder, the most likely reaction is an open questioning of the quality of the process that generated the unwanted scientific result. A clear example of this phenomenon is represented by the denial of the scientific evidence warning against global warming.

Therefore, any process of decision making which is based on the use of mathematical models entails the twin procedural problems of who should define their relevance, pertinence, usefulness, robustness, accuracy, and how these should be defined. Obviously, there is a danger that legitimate concerns about the use of mathematical models in decision making may bring about disregard for valid findings of well designed mathematical models that are properly used within their limitations. However, without an agreed upon procedure for validation, it becomes possible that politicians and other decision makers may find it convenient to ignore findings that they should heed. Neglected findings could be about climate change, or levees breaking, or an epidemic spreading, or economic consequences of clearing forests.

In relation to this problem, it is crucial to make a distinction between: (1) models that are used for descriptive purposes – for instance, to characterize, represent, understand, simulate possible outcomes; and (2) models that are used for normative purposes – for instance, to identify and prescribe the best course of action in relation to the welfare of the social actors affected by the decision. This second use of mathematical models is the one, which, in our view, poses more problems. In fact, very often this second use may represent a strategy to avoid negotiating with social actors carriers of legitimate but contrasting views about what "an improvement in welfare" means. A mathematical model that is supposed to identify "the best" course of action can be used to obtain a sort of legitimization - because of the association with a technical analysis - to a given perspective about "how to improve the welfare" against alternative ones. In fact, the decision indicated by the model translates into an endorsement of just one of the possible interpretations of what "an improvement in welfare" means.

To make things more difficult, the existence of legitimate but contrasting interpretations of concepts such as welfare, equity, freedom is not the only problem faced by mathematical models. When dealing with sustainability, another huge problem is represented by the evolutionary nature of socioeconomic systems. Here we can recall Georgescu-Roegen's argument concerning mathematical models and their proper use in economic science. According to him, the essential object of economics is very often defined as the determination of the allocation of a set of *given* means towards the optimal satisfaction of a set of *given* ends. Within this framework economics is reduced to "the mechanics of utility and self-interest". Indeed, any system that involves a conservation principle (a given and finite set of means) and a maximization rule (optimal satisfaction of a given and finite set of goals) is a mechanistic one. This framework seems to contrast with the idea that economic activity and sustainability should be associated with complexity and learning. That is, the sustainability of living systems is associated with their ability of expanding and updating their original definition of their universe of discourse. The same applies to economic systems. In spite of the basic assumptions of the invariance of both means and options, in all human societies "the typical individual" is continuously updating and expanding the definition of the available sets of means and ends. Individuals are continuously trying to improve their social status, from their current position and in relation to existing distributive norms. New means are continuously invented, new economic wants created, and new distributive rules introduced in any real economic process. These evolutionary aspects of the economic process require a continuous update in the current definition of both the universe of economic activities within the economic process and the meaning to be assigned to the concept of income and welfare. New and more appropriate choices of formalization of these concepts in the relative models must be introduced to cope with the evolutionary process of economic systems.

For these reasons, various authors claim that modern economics needs to expand its empirical relevance by introducing more and more realistic (and of course more complex) assumptions in its models. For instance, the issue of "distributional coalitions" has been recently considered as of a key importance to determine growth factors. One of the most interesting research directions in the field of public economics is the attempt to explicitly introduce political constraints, interest groups and collusion effects. In practical terms, especially when dealing with models used for normative purposes, this translates into an attempt to moving away from mono-criterion type of analysis - for instance Cost Benefit Analysis (CBA). Cost Benefit Analysis is based on the assumption that different typologies of costs and benefits (originally defined in different disciplinary fields - economics, ecology, sociology, anthropology) can be compared and weighted in an uncontested way. This entails assuming that it is possible to: (1) reach an agreement, among all those that will be affected by the decision, on how to formalize “what an improvement in welfare” means; (2) reduce the heterogeneous assessments of non-equivalent costs and benefits to a single proxy variable mapping onto such a formalization of welfare; and (3) reduce the level of uncertainty about the future to an acceptable level for prediction, by using bigger computers and more complicated inferential systems. Whenever the analysts acknowledge that these three assumptions are untenable CBA has to be replaced by Multi-Criteria Analysis (MCA).

Historically, the first stage of the development of multi-criteria decision theory was characterized by the so-called methodological principle of Multi-Criteria Decision Making (MCDM). The main aim of MCDM is to elicit clear subjective preferences from a “mythical decision-maker” (seen as the ultimate and uncontested story-teller), and then try to solve a well-structured mathematical decision problem thanks to a more or less sophisticated algorithm. In this way a multi-criteria problem can be still presented in the form of a classical optimization problem. However, this attempt to avoid confronting the existence of: (i) legitimate but contrasting views about what “an improvement in welfare” means; and (ii) large doses of uncertainty about the future, did not solve the problem. This led Herbert Simon to propose a distinction between the general notion of rationality as an adaptation of available means to ends, and the various theories and models based on a rationality which can be either substantive or procedural. In turn, this makes it possible to distinguish between: (a) substantive rationality, in which the rationality of a decision is considered independently of the manner in which it is made (the rationality of evaluation refers exclusively to the results of the choice); and (b) procedural rationality, in which the rationality of a decision depends on the manner in which it is made (the rationality of evaluation refers to the decision-making process itself). According to Simon: “*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.*” Within this line of reasoning B. Roy states that it is impossible to say that a decision is a good one or a bad one by referring only to the formalization captured in a mathematical model. All aspects of the whole decision process which leads to a given decision also contribute to its quality and success. Thus, it becomes impossible to find the validity of a procedure either on a notion of approximation (that is, discovering pre-existing truths) or on a mathematical property of convergence (that is, does the decision automatically lead, in a finite number of steps, to the optimum a*?). According to these two authors, the most “satisficing solution” (a term introduced by Simon) for a group of social actors, carriers of legitimate but contrasting narratives and goals, is more like a "creation" than a discovery.

These new concepts call for a different framework, which recognizes the need of public participation in science for governance. This framework is generally called Multi-Criteria Decision-Aid (MCDA). In particular, G. Munda has proposed the concept of Social-Multi-Criteria Evaluation (SMCE) as a step forward in this direction. SMCE agrees on the need of extending MCDA by incorporating the notion of stakeholder. That is, it acknowledges explicitly that the quality of the overall process of issue definition and formalization depends not only on the quality of the analytical tools but also on the procedure adopted to select the narratives about a relevant reality. Therefore, a SMCE process must be as participative and as transparent as possible; although, it is obvious that participation is a necessary condition but not a sufficient one. In particular, SMCE reflects the call for a new paradigm in science for governance, which Silvio Funtowicz and

Jerome Ravetz called *Post-Normal Science*, claiming that any process producing information used for policy, requires the participation of extended peer-communities for its quality assurance.

In conclusion, when using mathematical models for normative reasons it is essential to have a quality check both on the semantic side of the process leading to a given formalization and on the pragmatic side of the process where the results of the model are used for guiding action. In fact, an inferential system (the formal part of the model) not properly combined with semiotic activity can generate meaningless mathematical patterns. By semiotic activity we mean the association of the patterns generated by an inferential system with an external referent providing a meaning to them.

This does not imply that syntactic representation is not important or powerful. No matter how complex the issues to be dealt with are, it is always possible to develop complicated mathematical models which can be fitted to past available data by relying on over-parameterization. However, when dealing with multiple scales and multiple dimensions of analysis, increasing the level of complexity of the formal system of inference is a strategy that can only be used for simulating what already happened and according to the given choice of formalization. It may not generate more reliable predictions about future scenarios or identify new relevant variables to be included in the model to deal with the emergence of new relevant attributes to be analyzed. This explains why, according to Georgescu-Roegen, the evolutionary nature of the economic process and all its relevant aspects cannot be grasped by mathematical models including dynamic ones.

When dealing with the issue of sustainability, it is important not to confuse "what is complicated" – for instance, large data set handled by elaborated formal systems of inference - with "what is complex" – for instance, what cannot be compressed in a simplified model without losing relevant information. This definition of complexity resonates with that given by Chaitin for mathematical objects, and it entails that the decision of "what is complex" depends on a preliminary definition of "what is relevant". In turn, this implies that this is an issue which can only be decided by those who will use the model for guiding action. In the same line of reasoning Rosen claims that complexity is not a property of the observed system, but rather of the process of observation. That is, it depends on why and how one decides to observe the observed system. If we forget this important distinction and apply complicated mathematical models to complex problems without a procedure capable of guaranteeing a semiotic check, we face a situation in which analytical tools are used outside their domain of applicability. This error can be explained by lack of knowledge (or careful reasoning) of basic epistemological issues. There are clear limits of the assumptions required to apply the various classes of mathematical models to the issue of evolution and sustainability.

This is why, we decided, in this chapter, to focus, rather than on technical aspects of mathematical models, on a few key epistemological challenges associated with the use of mathematical model to capture and simulate the process of evolution of social systems.

The basic problem faced by a modeler when dealing with evolution is quite easy to explain. By definition, *a given mathematical model itself* cannot learn how to add new external referents (meanings) to the representation it is providing. As proved by Gödel formal systems of inference alone cannot express semiotic activity. On the contrary, as suggested by the seminal work of Peirce, the very concept of evolution for human and biological systems is based on a continuous addition of meanings and beliefs to their semiotic universe. Using the expression suggested by Prigogine both ecosystems and human societies "are becoming" something else during their evolution. To be more precise both ecosystems and human societies are "autopoietic systems".

That is they belong to a class of systems capable of producing themselves conceptualized by Maturana and Varela. An autopoietic system must continuously re-define in time the set of formalizations adopted when storing experience, making anticipatory models and developing mechanisms of controls, aimed at preserving its own identity. Therefore, capturing the meaning and the implications of these changes requires a continuous update of the set of relevant perceptions of "what" the system is becoming. At the same time updating the set of relevant perceptions must be accompanied by a turn-over in the relative useful representations. This implies that any process of perception and representation is based on a pre-analytical decision (to be updated in time) which will be crucial in determining the choice of the proxy variables and the inferential systems used in the models.

In the rest of this chapter we will explore this conundrum by touching first (Section 2) on classical typologies of impasse found by those attempting to model the evolution of complex systems such as human societies and ecological systems. Then (Section 3) on the epistemological roots of these impasses, which are very relevant for those developing models related to the issue of sustainability.

In particular, Section 2 illustrates: (1) ***Jevons' paradox*** - when dealing with the perception/representation of the evolution of adaptive systems, "ceteris" are never "paribus". This implies acknowledging that ignorance about the future is unavoidable. (2) ***Hierarchy Theory*** - there are multiple legitimate formalizations that can be adopted for perceiving and representing a given relevant reality. These multiple legitimate formalizations reflect the existence of legitimate non-equivalent narratives about a relevant reality. When dealing with issues characterized by multiple relevant dimensions of analysis and multiple relevant scales, models developed within non-equivalent descriptive domains are not reducible to each other.

In this case, rigor and accuracy are only a part of the story: the usefulness of the model is more important and it depends first of all on the relevance of the narrative, in which the model is embedded. (3) ***Holons and Holarchies*** - any perception and representation of an evolving system organized on multiple levels and scales must hinge on a pre-analytical coupling of a functional and a structural type (the holon). The perception and representation of a holon is based on a given semiotic coupling of two identities required to characterize: (i) the relative structural type and (ii) the relative functional type. Unfortunately, these two formal identities do not map 1:1 onto each other, since the semiotic identity obtained by such a coupling is determined by special situations and continuously changing in time. Thus, it is impossible to formalize "once and for all" perceptions and representations of the evolution of holarchies which are organized across different scales.

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Biographical Sketches

Mario Giampietro, is Director of the Unit of Technological Assessment at the Istituto Nazionale di Ricerca sugli Alimenti e la Nutrizione. Dr. Giampietro has worked as visiting scholar in several prestigious institutions: Cornell University, Wageningen University; Joint Research Center of the European Commission of Ispra; Universitat Autonoma Barcelona; University of Wisconsin-Madison; and Penn State University. His expertise covers the fields of Ecological Economics, Energy Analysis, Sustainable Agriculture, Population and Development, Complex Systems Theory applied to the process of Decision Making in view of Sustainability. In 2003 he wrote a book published by CRC Press entitled "*Multi-Scale Integrated Analysis of Agro-ecosystems*".

Kozo Mayumi, is a Professor of economics at the University of Tokushima. Prof. Mayumi graduated from the Graduate School of Engineering at the Department of Applied Mathematics and Physics of Kyoto University. Between 1984 and 1988, he studied bioeconomics at the Department of Economics of Vanderbilt University under Prof. Nicholas Georgescu-Roegen. Since then, he has been working in the field of energy analysis, ecological economics and complex system-hierarchy theory. He is a member of the editorial board of *Ecological Economics* and *Organization and Environment*. In 2001, Mayumi published *The Origins of Ecological Economics: The Bioeconomics of Georgescu-Roegen* (Routledge).

David Pimentel, is a Professor in the Department of Entomology, Systematics and Ecology at Cornell University. He has a PhD from Cornell University. His research spans the fields of basic population ecology, genetics, ecological and economic aspects of pest control, biological control, energy use and conservation, genetic engineering, sustainable agriculture, soil and water conservation, and natural-resource management and environmental policy. He has over 500 scientific publications. He has served on many national and governmental committees including National Academy of Sciences, US Department of Agriculture, US Dept of Energy, US Department of Health, Education and Welfare, Office of Technological Assessment, and the US Congress.