Analysing the energy metabolism of economies from a complex-systems perspective

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CONTENTS

ABSTRACT

When analysing the compatibility of the evolution of economic systems with its surrounding environment, the insights of thermodynamics and complex systems theory are very useful. When considering those theories we might see economic systems as complex systems; that is, hierarchical, adaptive, self-reflexive and self-aware systems that evolve in a non-linear way. In this sense, economies evolve not only by adapting to changing boundary conditions, but also by responding to internal constraints. This fact means that once some paths are chosen, some others be closed forever; that is, there exists path dependency. All of these characteristics of economic systems makes them largely unpredictable, so a new epistemology to deal with them is needed; this is post-normal science. Due to their novelty and non-linear behaviour, extrapolations are no longer useful; this is why a phenomenological approach to empiricism is argued here to be better suited to describing and understanding such systems. The conclusion is therefore that a historical analysis is needed for analysing economic systems' evolution, in which we find historical regularities both spatial and temporal that will allow us to see the emergence of such systems' properties. From a policy perspective, however, the conclusion is that, due to the characteristics of complex systems, an adaptive management that focuses on flexibility and diversity of economic systems seems to be the proper response to changing boundary conditions, and to establishing compatibility between their evolution and their surrounding environment.

Dedicado a mis padres, Amalia y Antonio,
Con todo mi amor y agradecimiento

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1. INTRODUCTION

Economic development is a process, not a final state to be achieved by any society. It is related to the economic evolution of human systems as well as with their interaction with the environment. Therefore, a biophysical analysis is needed to fully understand the process. The main goals of this thesis are as follows:

i) To outline the relationship between energy and the environment for the different schools of economic thought that deal with it.

ii) To present human systems as complex open systems.

iii) To argue the need for a new epistemology to deal with such complex systems.

iv) To present and defend a new approach to empiricism for dealing with complex systems' evolution, regarding sustainability, under the framework of ecological economics.

This will require the presentation of some theoretical approaches that will help us to understand the working of economic systems through the analysis of energy dissipation. That is, the use of energy for economic development, or evolution of economic systems, will be analysed.

Among the concepts and approaches to be introduced, central are entropy and thermodynamic theory in general, as well as complex-systems theory, so they have specific chapters in this dissertation. While a full empirical analysis is not presented here, insights about what should be analysed, and how, will be given. In other words, some guidelines for empirical research on economic systems' evolution will be offered. This will include insights on the relationship between energy dissipation and environmental stress. It will be argued that the use of economic analysis should be complemented with the analysis of the energy metabolism of the societies, among other variables. This would try to explain the path of past developments (by finding some regularities that can be compared among countries) and trying to offer some keys for future developments. It can be said, therefore, that the dissertation is theoretical, but it has to be understood as a first step towards a deeper analysis of the exosomatic energy metabolism of societies (to analyse sustainability trade-offs), including empirical analysis using the approach presented here, to be undertaken in the future.

The structure of the dissertation is as follows. Chapter 2 presents energy analysis under the framework of the different schools of economic thought, stressing the fact that until recently economists have not gone back to their origins, to start looking again at the biophysical foundations of the economic process. This revival of the classical interest in production has been especially strong among those who call themselves 'ecological economists', who belong to a recent trans-discipline trying to understand the nature and causes of (un)sustainability. In fact, one of their major advances has been the incorporation of the insights of thermodynamics (that are also explained in the chapter) to economic analysis. They have mainly used the Second Law of thermodynamics and its major result, the irreversibility of processes.

Complexity and its relationship with environmental issues will be the subject of Chapter 3. After presenting the theory of 'far-from-equilibrium' thermodynamics, dealing with how open systems evolve over time, it will be argued that new environmental problems, such as global warming or biodiversity loss, can be considered as 'complex' problems. Their relationship with complex systems will then be highlighted, by using some concepts from the teleological approach to systems. The chapter will also argue that the main characteristics of complex systems, as well as their tendency towards self-organisation, can be understood as emergent properties of complexity.

Chapter 4 will use the concepts developed earlier to characterise human systems (i.e. economies) as open complex systems, far-from-(thermodynamic)-equilibrium. Their major characteristics will be presented, focusing on their hierarchical structure and their functioning via autocatalytic loops that link each level of the system. This fact induces, as will be argued, non-linear behaviour that is difficult to forecast. The evolution of economic systems will also be analysed from an evolutionary perspective, in which 'history counts'. It will focus especially on the relationship between economic development and exosomatic energy consumption, and will present non-linear explanations such as the 'punctuated equilibrium' hypothesis. It will also present a key characteristic of these kinds of systems, which is the fact that they show, in their evolution, two apparently contradictory features. One is the increase in the efficiency of processes (such as dissipative processes) to combat entropy generation. The other is the tendency to dissipate more energy and therefore increase entropy, to enhance their adaptability, and therefore their flexibility towards changing boundary conditions.

Due to all of those characteristics, Chapter 5 will present a new epistemology to deal with complex systems, in which the focus is on the quality of the process of knowledge generation and decision making, instead of on the final result of the decision. For this an interdisciplinary approach is better fitted to cope with the characteristics of complex systems. The chapter will also present a new way of understanding empiricism when dealing with the evolution of complex systems. It will be argued that an empirical integrated assessment of the exosomatic energy metabolism of economies is necessary in order to explain the evolution of their energy consumption over time. This would be done by finding some historical regularities, spatial and temporal, that could give insights about future development. This would be helpful to provide guidance to policy makers about the internal constraints of the system and about possible future scenarios of how the future might unfold.

Finally, Chapter 6 will offer an overview, summary and conclusions. As noted above, such empirical analysis will be object of future research by the author, as will be mentioned in Section 6.2., dedicated to further research.

2. ECONOMICS, ENERGY, AND THE ENVIRONMENT

2.1. Introduction

The relationship between energy, economy and the environment has a long history, and has been analysed in one way or another by all of the schools of economic thought. It is the intention in this chapter to review briefly the major views on this topic of the different schools of thought, and also to introduce some concepts from both economics and thermodynamics that will be useful when dealing with the energy metabolism of economic systems from a complex systems perspective. In order to do this, a review of the origins of the economy-environment debate will be offered, from the Physiocrats to the emergence of the discipline of ecological economics. Some issues will be the key points in the discourse, such as the different methodologies developed and used by the different schools, and also the role of time and the dialectics between explanation and understanding. Section 2.2 will offer an overview of the relationship between the environment and the economy for the different schools. Section 2.3 will introduce thermodynamic theory, while Section 2.4 will develop further what is ecological economics and Section 2.5 will summarise the conclusions of this chapter.

2.2. An historical overview of economy-environment relations

In this section, the main topic is economic thought regarding the environment (and particularly energy) from the early stages of economics, to the pessimistic forecasts of the Club of Rome in the 1970s. A comprehensive historical review of the concept of energy, as well as its applications and analysis by the different schools of economic thought, can be found in Mirowski (1989). Here, the object of the analysis will be only those elements of the debate that seem to be essential in understanding some concepts and methodologies developed below, when dealing with open complex systems.

2.2.1. Physiocratic and classical thought

As stated by Proops (1979: 125), economics has not taken into account energy in its different paradigms, apart from considering it a 'consumption good' or a 'factor of production'[1]. This lack of consideration has not been the case for the environment in general, and land in particular. Rather, during the history of economic thought, economists have shown an interest in three main topics:

(i) The production of goods and services and the generation of wealth through the transformation of inputs from nature.

(ii) The scarcity of resources.

(iii) The consequences of production, i.e. pollution.

The Physiocrats focused on production, considering land as the core producer of value. They regarded land as productive because a surplus could be taken from it once some inputs were used (Christensen, 1989). That is, they had in mind a kind of analogy between living systems and the provisioning of the economy[2]. It is in this way that we have to interpret Quesnay's *Tableau Economique*, in which he tried to apply his Cartesian[3] ideas to the analysis of wealth generation and value (see Mirowski, 1989 and Cleveland, 1987

[1] Mirowski (1989: chapters 3 and 4) has a different opinion and presents some analogies between physics and economics, mainly presenting 'value' as a conserved substance in motion (1989: 186), in a clear analogy with the concept of energy.

[2] As we shall see when dealing with ecological economics, this idea of economics as provisioning the *polis* comes from the Aristotelian distinction between *oikonomia* and *chrematistics*.

[3] Quesnay (1758) followed the French philosopher Decartes and his rationalism as a methodology of scientific research, leading to a deductive approach.

for more details). Quesnay concluded that the production of goods could be seen as a mere transformation of materials and food taken from the land (Christensen, 1989), in what is, clearly, a biophysical interpretation of the process. Indeed, "[agricultural] production is well defined as the locus of the increase of the value substance; trade or circulation as where the value substance is conserved, and finally, consumption as the locus of value destruction" (Mirowski, 1989: 159).

This focus on the production side of the economy is also what distinguished classical thought from the neo-classical approach. The focus, however, does not mean they *fully* understood the biophysical foundations of the economic process. Thus, even though Malthus and Ricardo acknowledged that all human-made production of material goods was based on materials from nature, they did not realise that the same logic could be applied to the products of nature. That is, in their explanations of the economic process they did not use completely the laws of thermodynamics developed in the 1840s and 1850s. More accurately, they did use the First Law of thermodynamics (conservation of matter and energy) to explain manufacturing but not production from land, which, for some of them had a *quasi-sacred* character. However, the introduction of the concept of the *steady state* by John Stuart Mill (1866) was an acknowledgement of the limits imposed by nature on economic development, something that would be explored later by the discipline of ecological economics[4]. On the other hand, Malthus (1778) was the first to point out the apparent contradiction between a growing population and the scarce resources available, as exemplified by limited arable land. This kind of analysis would later be developed by Jevons (1865) for the case of coal.

Despite writing after the laws of thermodynamics were formulated, Marx did not

[4] Daly (1990) has distinguished between growth (quantitative increase in physical scale) and development (qualitative improvement or unfolding of potentialities), allowing the existence of a qualitative development without growth.

integrate the work of Podolinsky, a Ukrainian socialist physicist, in his analysis, in what can be seen as a myopic error of the philosopher[5]. That is, he did not use terms from human ecology, such as energy and material flows, in his theory, as Podolinsky suggested. If he had, his analysis of both the theory of value and the evolution of economic systems might have been different[6]. In fact, Podolinsky's ideas were advanced for his time. He foreshadowed the idea of modelling labour productivity as a function of the quantity of energy used to subsidise it. He also developed the concept of energy return on energy input under the name of the 'economic coefficient', and he applied it to human beings, concluding that man has the capacity to transform one-fifth of the energy gained from food into muscular work. This result can be seen as a biophysical foundation of the theory of value. As Martinez-Alier (1987: 51) says, "in economics Podolinsky thought that he had reconciled the Physiocrats with the labour theory of value". His concepts, as Cleveland (1987) notes, have proved to be powerful and have been used later by some other biophysical analysts, such as Cleveland et al. (1984) and Odum (1971).

2.2.2. The neo-classical approach

The neo-classical approach represents a sharp change in the economic paradigm in the sense of Kuhn (1962). Neo-classical economics shifted the focus from production dynamics to an analysis of exchange value[7]. However, we can still find some interest in the natural world within the so-called neo-classical authors. Thus, it was as early as 1865 that

[5] For a deep analysis of Podolinsky and other fathers of 'energetics', as well as a review of the relevance of energy analysis as a foundation of ecological economics, see the seminal book by Martinez-Alier (1987).
[6] For instance, had he used Podolinsky's work, his conception of the crisis of capitalism due to the deterioration of the 'relations of production' might have changed towards the constraints on the further development of the 'productive forces', imposed by physical and ecological laws.
[7] For a deeper analysis on the influence of geometry and physics in neo-classical economics, see Mirowski (1989: chapters 5 and 6).

Jevons, in *The Coal Question,* addressed the issue of limited resources as a constraint on development, concluding that a parallel result to the increase in thermodynamic efficiency was that of the increase in the overall use of coal (Martinez-Alier, 1987)[8]. This line of argument was lost by Jevons himself, and by the other authors, when they ignored the biophysical foundations of capital in their analysis, concentrating on financial capital. The same lack of interest in raw materials can be found later in Marshall (1920), despite his saying "The Mecca of the economist lies in economic biology rather than in economic dynamics" (1920: xiv). The result was the focus of the neo-classical school on analysing exchange instead of production. This is important, since exchange can be analysed in an a-historical way, whereas production has a clear historical path, from resource exploration through the manufacturing of the good, to the disposal of waste.

For some economists, the discipline is "the science which studies human behaviour between ends and scarce means which have alternative uses" (Robbins, 1932: 15). As pointed out by Ruth (1993) the main characteristics of this approach are a concentration on market mechanisms, a focus on microeconomics instead of macroeconomics, static analysis (neglecting the history of processes), continuity[9] understood as smooth changes, and a consideration of the environment only as a given boundary. This means that the methodology developed by neo-classical economics, namely general equilibrium theory, *always* guarantees the achievement of a solution in the allocation of scarce resources (Faber et al., 1996).

To better understand neo-classical economics we might think that it follows classical mechanics in its description of the economic process. That is, either production,

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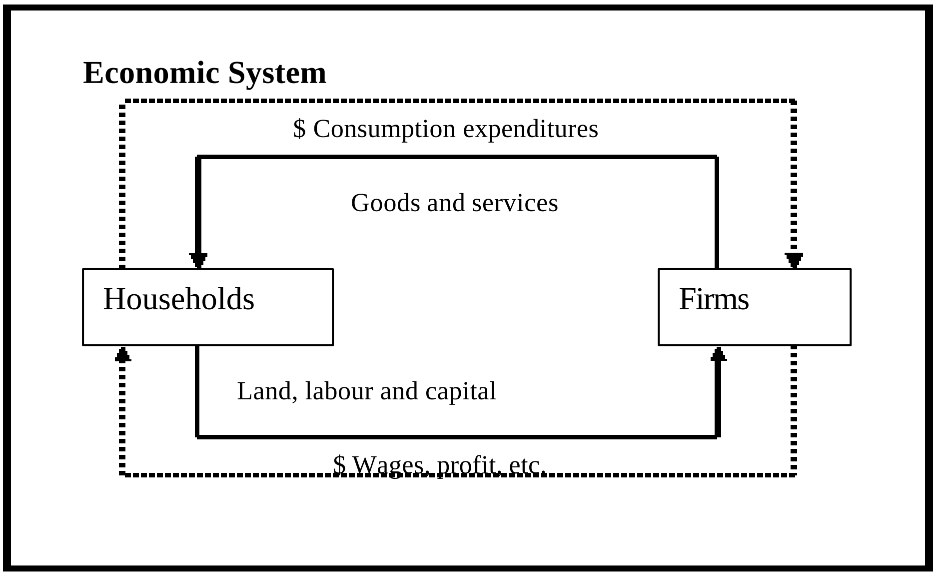
[8] Something called later Jevons' paradox is by a different scholar of the same name (Jevons, 1990).

[9] In this sense we have to remember Marshall's dictum *Natura non facit saltum*, that, as pointed out by Gould (1992), is appropriated from Linnaeus by way of Leibnitz and Darwin.

consumption or distribution are seen as single processes that can be analysed separately to achieve not only understanding of them, but also to make possible forecasting. In the words of Georgescu-Roegen (1971: 319), it "is a mechanical analogue". As in mechanics, economists are seeking 'universal laws' that can be applied everywhere and regardless of time. Once laws are defined, and basic principles or axioms are accepted, they proposed that economics must be a theoretical science, deductive, and deterministic, capable of finding *unique optimal solutions*.

Figure 1: The circular flow of exchange value



Source: Hall et al. (1986: 39)

In particular, neo-classical economists see the economic system as an *isolated system*[10], in which the factors of production (land, capital and labour) and goods and services are exchanged by firms and households, in what is called the circular flow of exchange value. Economics, therefore, analyses prices. This is *chrematistics*, and has a metaphysical conception of the economic system as working like a *perpetuum mobile*,

[10] An isolated system is one that exchanges neither matter nor energy with its environment. A fuller classification of systems in thermodynamic theory will be given in Section 2.3.

lubricated by money. For Aristotle, chrematistics was the analysis of price generation and exchange and therefore allocation, something that we, today, relate to what is called 'economics' in its traditional definition supplied by Robbins (1932). In more detail, firms rent or pay households for the factors of production (national income), whereas households pay firms for the finished good and services (national product). As Daly (1992: 195) suggested "although the physical embodiments differ, the exchange value in the two loops of the cycle is the same because of the principle that both sides of a transaction have equal exchange value (though different use value)". This cycle can be easily understood when looking at Figure 1.

When representing the economic process in this way, we are considering natural resources, technologies, preferences, etc, as being given. When doing so, we are not taking into account the biophysical foundations of the economic process, neither the need for resources nor the consequences of production and consumption in the form of wastes. That is, we are treating the economic system just as a kind of black box (Dyke, 1994).

The circular flow of exchange value implicitly considers natural resources as unlimited. This view, however, can be understood if we take into account that when the neo-classical theory was developed, although the laws of thermodynamics were already formulated, natural resources (both inputs and sinks) were not considered particularly scarce. This *social historical reality* might explain why these economists did not forecast the consequences of the economic process upon the environment beforehand. This is what led Georgescu-Roegen (1971) to state that we cannot blame either classical or neo-classical economists for not constructing a theory that can be applied in all circumstances. This is so because any economic theory is history-dependent, in the sense that it is based in the institutional setting of the moment.

In their challenge to classical theory, even the theory of value was changed radically by neo-classical thought. For the classicals, a good was given value either by its inputs (embodied labour for Ricardo and Marx) or by its purchasing power (purchasable labour or labour-command for Smith)[11]. Later, Sraffa (1960) tried to find the 'single numéraire' using input-output analysis and a mix of produced goods in a development of Marx's labour theory of value. Whatever the case, a clear link with the material world was established for the concept of value. For neo-classical economists, however, that idea was unacceptable, and they broke the biophysical link by stating that "economic values not only are but should be derived from individual preferences" (Christensen, 1989: 27), that is, subjective human wants[12].

When later 'natural resources economics' was developed within neo-classical economics (see Pearce and Turner, 1990; Scott, 1985) it dealt with the threats of scarcity and pollution using the traditional methodology:

(i) Optimisation in the case of managing natural resources (either renewable or exhaustible).

(ii) Assigning property rights to pollution (or more generally externalities) in order to incorporate them into the price system, and thus, into the decision process within the market mechanism.

This may be why supporters of this approach are usually optimistic when dealing with environmental problems. For example, in the case of exhaustible resources they propose substitution between production factors[13], neglecting two basic things. On the one

[11] The distinction made here between Smith's theory and Ricardo's and Marx's, is not usually found in the literature; see for example Judson (1989); Mirowski (1989). An exception is that of Dobb (1973) where the author, however, gives not much weight to that difference. I am in debt for this point to professor Barbé-Duran, whose lectures on "History of Economic Thought" I particularly enjoyed, and to Joan Martinez-Alier. For a development of the issue see Barbé-Duran (1996).

[12] See Mirowski (1989), mainly chapter 5, for more details.

[13] Leading to the concept of 'weak sustainability'. See Cabeza (1996) for more details.

hand, there are services provided by nature that are not substitutable at all (like the water and carbon cycles). On the other hand, energy, including that of labour, cannot be fully substituted, in physical terms, because each factor of production depends ultimately on an inflow of low entropy energy to support its own production and maintenance (Hall et al., 1986).

Since neo-classical economics follows mechanics, where all processes are reversible, its equations and models are also 'time symmetric', where time is treated just as a cardinal magnitude, susceptible of being added or subtracted (Beard and Lozada, 1999). This is the reason why they claim the theory to be valid in all societies, that is, to be a-historic. On the other hand, an evolutionary science deals with historical events, and the processes between the events; that is, it deals with the issue of time. At this point, although this topic will be developed in the next section, it is worth mentioning Georgescu-Roegen's distinction between 'time' and 'Time'. Using his own words (1971: 135), "*T* represents Time, conceived as the stream of consciousness or, if you wish, as a continuous succession of 'moments', but *t* represents the measure of an interval (*T', T''*) by a *mechanical clock*" (emphasis in the original). Using this distinction it can be said that an evolutionary science deals with 'Time', whereas neo-classical economics deals with 'time', so neo-classical economics cannot be considered as an evolutionary science[14].

All of these characteristics of neo-classical economics led to it being viewed as not suitable for dealing with new and complex problems. It also led to the proposing of new approaches, such as those developed by ecological economics.

Despite these limitations which, as will be argued later, apply to all mechanical deterministic models dealing with complex problems, such models can be applied for

[14] See Witt (1992), Ruth (1996), and Mesner and Gowdy (1999) for a development of evolutionary concepts in economics.

specific cases where both the variables and the relationships among them can be easily defined (i.e. analysing the behaviour of economic agents in the market, including markets for some environmental goods and services). In other words, the possible use of neo-classical analysis is not being denigrated here, but rather one should note the necessity of complementing it with new tools developed by other disciplines that might be better for analysing complex systems. Thus, the case for methodological pluralism (Norgaard, 1989) asks us to include also such alternative methodologies as part of our tool kit of analysis and understanding of the relationship between the economy and the environment.

2.3 Setting the boundaries: thermodynamics

There is a long history of concepts of physics being employed in economic theory. As Proops (1985) said, in his description of the use of physics in economic theory, it is clear that some kind of isomorphism exists between physical theory and economic theory. Here, however, only the First and Second Laws of thermodynamics, the issue of time irreversibility, and, incidentally, the importance of the discrepancy between human and ecological time scales (a brief criticism of Georgescu-Roegen's controversial Fourth Law of thermodynamics) will be considered. The interested reader can go to the cited sources for more details on thermodynamic theory.

Regarding thermodynamic theory, during the 1840s and 1850s the laws of thermodynamics were defined. The economic theory presented in the last section did not fully use the insights of those laws, although they have proved to be useful for analysing the relationship between the economy and the environment, more specifically, for energy[15].

[15] For an historical overview of the influence of thermodynamics principles on neo-classical thought, see Mirowski (1989).

2.3.1. The First Law of thermodynamics

As stated in the last section, both classical and neo-classical economists realised, although partially and in different ways, the limits set by the First Law of thermodynamics, the principle of the conservation of mass and energy. Before defining the principle, we need a classification of systems as defined in physics:

- *An isolated system* exchanges neither matter nor energy with its surroundings.
- *A closed system* exchanges energy but not matter with its surroundings.
- *An open system* exchanges both matter and energy with its surroundings.

Both isolated and closed systems are just idealisations, useful for developing the theory, but in reality there is always some exchange of energy *and* matter between a system and its environment (Hall et al., 1986).

The *First Law of Thermodynamics*, or the law of conservation of energy (and matter), was developed in the 1840s, and states that energy (and matter) can be neither created nor destroyed, but must be conserved. It has many interpretations; for example, it implies that the energy of an isolated system is constant. In the case of open systems (relevant when analysing economic systems, as we shall see in the next chapter), the First Law implies that "under non-steady flow conditions, the mass of matter in the system must also change by the amount that the mass of matter entering the system exceeds the mass of matter leaving the system" (Ruth, 1993: 51). This has clear implications for economic systems in the case of inputs and wastes. All processes, either natural or artificial, must satisfy this law, which sets physical constraints, since it "clearly dictate[s] that no agent can create the stuff on which it operates, i.e. manufactured capital cannot create the resources it transforms and the materials it is made from" (Cleveland and Ruth, 1997: 207).

Indeed, the First Law shows that all inputs used in every process will eventually be transformed into the same mass of a mix of products plus wastes (Buenstorf, 2000). This fact led Ayres (1998) to state that 'externalities' (the way neo-classical environmental economists deal with pollution, among other things) would tend to grow as the economy does. Whether these rising externalities would mean a constraint or not depends on the availability of natural resources (both inputs and sinks), substitution, etc.

Finally, an example of applying the First Law in economics is the use of input-output analysis, which, although it does not account for the *dynamic* interactions between the economy and the environment, does provide a *description* of the interactions among economic sectors and between the economic system and the environment[16].

2.3.2. The Second Law of thermodynamics

The Second Law of thermodynamics, or *the entropy principle*, is the piece of thermodynamic theory that has most influenced economic thought.

For this analysis, a definition of energy as the capacity to do work can be made. Work is, thus, a form of energy, as is heat. However, they are, in a sense, different. They have different *qualities*. While all work can be converted into heat, the reverse is not true. So, we need a measure of the quality of energy, and that measure is *entropy*.

As stated by Faber et al. (1996) all processes of change consume (or dissipate) energy. When dissipating energy, available or free energy[17] is transformed into work and heat. "That heat, however, cannot be completely converted back into mechanical energy

[16] See Duchin (1988, 1996), Duchin and Lange (1994), and Duchin and Szyld (1985) for the general use of input-output in environmental issues, and Proops et al. (1993) for an application to CO_2 emissions.

[17] In classical thermodynamics a distinction is made between free or available energy (which can be transformed into mechanical work) and unavailable or bound energy (which is not capable of doing mechanical work).

without addition of further energy" (Hall et al., 1986: 5). This is what is known as *the Second Law of thermodynamics*. More specifically, the law states that the entropy (the measure of the unavailable energy) of an *isolated* system tends to a maximum. As it is defined, entropy is an 'extensive' state variable that can be defined for every system (Ayres, 1998). By the term extensive is meant that it is proportional to the size of the system (this fact is relevant when analysing absolute versus relative variables, such as in the case of the dematerialisation debate). Entropy therefore defines quality differences between types of energy. Moreover, the Second Law implies that the efficiency of every transformation of heat energy into work is less than 100%. An alternative definition, in the same phenomenological tradition, is that "spontaneous exchanges of heat between two bodies can only take place in one direction, from hot to cold, in line with experience" (Faber et al., 1996: 99).

Theoretically, entropy is defined as follows (Georgescu-Roegen, 1971: 129, 130): $\Delta S = \Delta Q / T$ "where ΔS is the entropy increment, ΔQ the increment of the heat transferred from the hotter to the colder body, and T the absolute temperature at which the transfer is made".

The origins of the Second Law can be found in Sadi Carnot's study of energy efficiency, through his analysis of how much useful work could be obtained from an energy transformation. Indeed, Carnot (1824) analysed the efficiency of a heat engine, and found that it depends on the gradient of (absolute) temperature between the heat source (T_1) and the sink (T_2). Thus, the maximum efficiency was shown to be given by $E_{max} = (T_1 - T_2) / T_1$. That is, for any finite and positive heat sink temperature, E_{max} will always be less than 100%. This result can be considered as the first formulation of the entropy law. It was Clausius (1865), however, who gave the classical definition presented before: in an isolated system entropy always increases.

Since the Second Law concerns the irreversibility of the degradation of energy (in its change in quality, from available to unavailable), the law is not time symmetric. This fact led Georgescu-Roegen to state that "in thermodynamics there is *only one* truly temporal law, the Entropy Law" (1971: 139, emphasis in the original). This irreversibility and unidirectionality shown by entropy is what explains that for him it is an evolutionary law.

Josiah Willard Gibbs made a clarification that is useful for understanding better the scope of the entropy law. He distinguished between entropy and 'free' or available energy, later known as *exergy*. Available energy is that which is capable of doing mechanical work (i.e. what lay people usually mean when they talk about 'energy', whereas unavailable energy is not (Hall et al., 1986)). This means that, in an isolated system, when entropy reaches its maximum, exergy is zero (Funtowicz and Ravetz, 1997). Exergy is not, therefore, a conserved variable like energy. Exergy can be gained or can be lost in all physical processes (Ayres, 1998) in the form of low temperature heat. Exergy, unlike entropy, can be used to explain renewal and life in living systems, as we will see when dealing with far-from-equilibrium systems. This characteristic has led Ayres (1998) to suggest the use of exergy analysis when dealing with the economy-environment relationship; that is, considering exergy as a measure of resource/waste stocks and flows, and as the ultimate limiting factor of production. It is because of this scarcity that exergy can be considered as a subject for economic analysis.

Later analysis in the field of statistical mechanics helped to clarify the concept of entropy. As noted by Proops (1985), we can also see the entropy law as reflecting how the system becomes maximally 'mixed-up', by dispersing all energy and material concentrations. This later definition is owed to the work of Boltzmann[18] who related the entropy concept with that of likelihood. Thus, highly probable macrostates would have also high entropy (Faber et al., 1996). He also found that the tendency of the evolution of a system is from less probable to more probable. This result of statistical mechanics gave an alternative vision of the, until then, phenomenological definition of entropy, leading to an account of time and irreversibility. However, the identification of entropic irreversibility with the tendency of the system to maximum 'disorder' is not so obvious as authors like Khalil (1990) suggest. In fact, when the system is far-from-equilibrium, as we shall see, an increase in entropy *might be* related to an increase in the ordering and structuring of the system (O'Connor, 1991).

The fact that Georgescu-Roegen saw the entropy law as the only evolutionary law, led him to say that "the material universe, therefore, continuously undergoes a qualitative change, actually a qualitative degradation of energy. The final outcome is a state where all energy is latent, the Heat Death as it was called in the earliest thermodynamic theory" (1971: 129). In this assertion, however, he is implying that the universe is an isolated system, but he is not doing necessarily the same for the economic system, contrary to what Khalil (1990) seems to interpret from his words. In fact, as Georgescu-Roegen himself said (1971: 192), "the Entropy Law applies only to an isolated system as a whole". Thus we can only foresee a heat death of the universe if we consider it to be isolated, something that has yet to be proved. Actually, he considered the economic system as an open system, recognising the limitations of applying blindly the Entropy Law to the economic process (Mayumi, 1995).

[18] See Faber et al. (1996: 100-102); O' Connor (1991: 99-104) for a description of the relevance of statistical mechanics to the entropy concept.

2.3.3. Implications of the Second Law for the economic process

Having introduced the concept of entropy and the history behind it, what are the implications of the Second Law for the economic process? In the first place, the law excludes the reversibility of many processes (Faber, 1985). This is seen clearly from Clausius' formulation of the Second Law: "heat can never, of itself, flow from a lower to a higher temperature" (quoted in Proops, 1979: 35). As has been said before, this means that any spontaneous process in nature implies an increase in entropy. The environmental implication, thus, for the economic system is that any use of resources that implies forcing ecological cycles means that we are degrading the environment in an irreversible way, with the subsequent effects on economic development.

The second implication is that of efficiency. Indeed, the Second Law of thermodynamics sets limits to the efficiency at which energy and materials can be used (Ruth, 1993), as has been said when presenting Carnot's efficiency equation. This makes the goal of no-pollution physically impossible, especially if we take into account that recycling is exergy-intensive. That is, even with recycling, more entropy will be generated, since any actual conversion process is always less than 100% efficient. Despite this limitation, the concept of efficiency is very useful in practical terms, for instance, when choosing among processes, in which we might prefer those with higher efficiency (or less intensity of use of the resource).

These efficiency limits apply for individual processes, but they do not necessarily apply when analysing systems. At the macroeconomic level, we cannot define the constraints as easily as for individual processes (Cleveland and Ruth, 1997). That is, thermodynamic limits do not determine unique pathways, or unique structurings. They just place some boundaries on the ways systems unfold (Dyke, 1994). In the words of Faber et al. (1996: 125), "the nature of economic constraint imposed by the laws of thermodynamics is such that it tells us something about the maximal sustainable physical scale of the whole economy relative to the ecosystem”. Indeed, only exhaustible resources are bounded by the Second Law (Faber et al., 1996). On the other hand, when the economic system is working in a way that is not going beyond ecological cycles, renewable resources cannot be described with the insights of the Second Law. This result has led authors like Ayres (1998, 1999) to say that, provided a sufficient flux of exergy is available, total recycling of materials is compatible with the Second Law of thermodynamics, and thus there is no limit to the degree of dematerialisation of the economy. Despite the assertion of Ayres himself, this result is not in contradiction to Georgescu-Roegen’s thought, as we will discuss in Section 2.3.5.

Finally, interpretations of the laws of thermodynamics beyond the analysis of isolated systems should be avoided. So, Ruth’s notion, also found in Ayres (1998), that the Second Law “violates the evolution of life as a process leading to increasingly complex structures” (Ruth, 1993: 79) is untrue, because, by definition, a living system is an open system (see Chapter 3). In conclusion, entropy should not be seen as an analytical tool for economics (Faber et al., 1996). Rather, it should be seen only as a conceptual means to analyse economy-environment interactions (Binswanger, 1993) to better understand the physical constraints imposed upon the economic process by the environment. In particular it can be seen as a kind of ‘law of regularity’ which explains maintaining or increasing structures through importing low entropy from the environment.

2.3.4. Irreversibility: ‘the Arrow of Time’

The idea of life processes as irreversible is intuitive for every human being. However, we had to wait until classical thermodynamics to reconcile science with common sense, by showing that even in physics there are irreversible processes (Georgescu-Roegen, 1971).

The Second Law of thermodynamics led Eddington (1928) to talk about the 'Arrow of Time', in which the increase in entropy determines the direction of Time in the sense of Georgescu-Roegen. That is, the forward direction of time can be defined by the increase in entropy. After the statistical interpretation of Boltzmann, entropy can be seen as an image of disorder in the system (Faber et al., 1996). These interpretations led to seeing the universe as moving towards a 'Heat Death' of maximum disorder, as mentioned before.

The insights from thermodynamic theory allow, following Georgescu-Roegen[19] (1971), the distinguishing of two different kinds of time: 'Time' (T), and 'time' (t), as has been presented in Section 2.2.2. This distinction proves to be a powerful aid to understanding mechanics. As Georgescu-Roegen said, "mechanical laws are functions of t alone and, hence, are invariable with respect to Time" (1971: 136). This is what explains that they are reversible, or a-historical. On the other hand, this distinction is also useful for better understanding the economic process, which can also be seen as unidirectional in time and therefore irreversible (Faber et al., 1996). History is, thus, relevant for all processes, and should be analysed and taken into account.

2.3.5. Compatibility between ecological and human time scales: Georgescu-Roegen's Fourth Law of thermodynamics

Georgescu-Roegen (1977) proposed a controversial Fourth Law of Thermodynamics, which stated that in a closed system, such as the earth, material entropy would eventually reach a maximum value; that is, materials would become unavailable. This would imply that complete recycling would be impossible in that system. With this

[19] Georgescu-Roegen acknowledged that he was highly influenced by Schumpeter's distinction between 'historical' and 'dynamic' time, by which he understood 'Time' and 'time' respectively.

"law", Georgescu-Roegen tried to emphasise that, in the end materials and not energy, would be the crucial factor for the economic process, due to both material dissipation and declining quality. In noting this, he was reacting against the 'energetic theories of value' developed by Odum (1971) and later Costanza (1980), in which those authors argued that 'available energy' would be the ultimate limiting factor[20]. For Georgescu-Roegen (1971), entropy was a necessary but not sufficient condition for economic value; there must also be the concept of purposive human action – the enjoyment of life – to give a good value, as we shall see in Section 4.2.2. He was also criticising Daly's (1973) view of a steady-state, arguing that material dissipation would make even a steady-state unsustainable ultimately.

Odum's and Costanza's arguments are supported by Hall et al. (1986) and Ayres (1998, 1999), when they argue that "given enough exergy [available energy] any element can be recovered from any source where it exists, no matter how dilute or diffuse" (Ayres, 1998: 197). They argue, I think quite correctly, that Georgescu-Roegen's 'Fourth Law' is theoretically inconsistent with physics. Based on these grounds, however, Ayres (1999) proposed, in a way I disagree with, that 'imperfect recycling' on the earth is not a constraint provided that the 'wastebasket' of materials to be recycled is big enough. If so, it will compensate for the losses due to imperfect recycling (with an efficiency lower than 100% due to the entropy law), at the expense of an increase in the entropy of the universe.

The arguments of O'Connor (1994), Cleveland and Ruth (1997), Mayumi (1993, 1995), and Hall et al. (1986) seem more convincing. They argue that, even though it is true that from a theoretical point of view there is no Fourth Law as stated by Georgescu-Roegen, this might not be the case from a *practical* point of view, with reference to the

[20] Being the ultimate limiting factor, (free) energy would be the source of value, as well. The relative price of a good could be explained by the relative embodied energy cost. This theory neglects, however, that "no single factor, be it labor, utility, or energy, is both a necessary and sufficient condition for economic value" (Hall et al., 1986: 69).

human temporal scale. It is true that the biosphere can recycle all of the materials with enough energy *and time.* This would be appropriate for the economic system if we depended on the flow of solar energy only, but this is not the case. We depend on fossil fuels that have been created on a time scale irrelevant for human beings. A limiting factor is found. This is *'time'* in the sense of Georgescu-Roegen; i.e. an interval of 'Time'. We depend, also, on some exosomatic organs (physical capital like machines, etc.) and we do not have the devices necessary to recycle dissipated matter to be used by those exosomatic devices. We have, then, a problem of available technologies. Because of that latter problem, "some forms of low entropy lack instrumental value" (Kåberger and Månsson, 2001: 174). It is in this context that the Fourth Law has to be interpreted. It is not a physical law, but it acknowledges some constraints *for human beings, not for the biosphere.*

In summary, the position here can be better explained in the words of Binswanger (1993: 225): "as long as economic systems mainly used renewable resources and did not exploit them to exhaustion, entropy increases were not a specific problem of economics. Economic processes were part of ecocycles, and outputs of economic systems were recycled in terrestrial ecosystems. (…) Today economic systems mainly function outside the ecocycles and because of that, they need large amounts of additional inputs of negative entropy, which can only stem from nonrenewable resources. (…) This situation causes entropy increases in the environment where they lead to irreversible changes (deforestation, climate changes, extinction of species, etc.)". This is exactly what Georgescu-Roegen had in mind when arguing for a society based on renewable energy, a society which would use solar energy to manage and reduce the entropy of matter, just like ecosystems (Kåberger and Månsson, 2001).

From the debate about the Fourth Law it can be concluded, then, that the major constraint for economic systems is that of the compatibility of ecological processes and economic processes. That is, it is a question of time scales, a question of time.

2.4 Ecological Economics[21]: Economic system as a subsystem of the natural system

Ecological economics is a trans-discipline that has been developing during recent years. It takes production, or the transformation of energy and materials, as its focal point, as was done by classical economic thought, but it uses in its analysis the insights derived from thermodynamics. However, this does not mean that it does not address the issues studied by neo-classical analysis. It embraces them, but considers them within limits. This section offers a brief analysis of the origins of ecological economics, and its understanding of the economic process.

2.4.1. Introduction: 'Oikonomia'

Aristotle distinguished between 'chrematistics' and 'oikonomia'. In contrast to chrematistics (explained above in Section 2.2.2.), oikonomia would represent the analysis of the material provisioning of the 'oikos' (household) or the 'polis' (state-city). That is, oikonomia means a biophysical analysis of the economic process, something that can now be called 'human ecology' or 'ecological economics'. Classical economists later developed an interest in the biophysical foundations of the economic process, as we saw before, when

[21] It is not the intention in this section to describe fully this new field of knowledge, but only to point out some aspects that will be relevant for the rest of the analysis developed here. For a description of the history of the development of ecological economics, see Martínez-Alier (1987). For a presentation of main authors and topics see Costanza (1991). For a development of some relevant concepts see Faber et al. (1996). For the latest developments see the journal *Ecological Economics* (http://www.elsevier.com/inca/publications/store/5/0/3/3/0/5/index.htt), and for other information, visit the web page of the International Society for Ecological Economics (http://www.ecologicaleconomics.org).

the discipline was still called 'political economy'. It is precisely that interest in the biophysical foundation of economic processes, turning back to Aristotle and the classical economists, what distinguishes ecological economics from neo-classical economics.

2.4.2. Energy analysis

The revival of the interest in biophysical analysis owes a lot to the work of energy analysts such as Podolinsky (discussed above) and Lotka. Lotka's contributions to the debate was basically his statement that natural selection tends to:

(i) Increase energy flow through biological systems

(ii) Increase energy efficiency of biological processes.

More specifically, the original words of Lotka (1922: 148) were that "natural selection will operate so as to increase the total mass of the organic system, and to increase the rate of circulation of matter through the system, and to increase the total energy flux through the system so long as there is present an unutilized residue of matter and available energy". There are two approaches to Lotka's analysis. One is developed by Odum, arguing in favour of a universal law of evolution. The other sees Lotka's contribution without determinism (O'Connor, 1991; Buenstorf, 2000), but as a mere description of past regularities that can help to explain evolution, in a more phenomenological way.

Odum referred to Lotka's principle as the 'maximum power principle' (Odum and Pinkerton, 1955), and took it as an universal law that states that "any organism, or system, that invests energy very rapidly but inefficiently, or very efficiently but not at a high rate, will be less competitive in natural selection than that which works at some intermediate, but optimal, efficiency, so that the useful power output is maximum at an intermediate process rate" (Hall et al., 1986: 63). This principle, plus the energetic theory of value introduced by Odum (1971, 1996) and developed later by Costanza (1980) which introduced eMergy (embodied energy) as a measure of value, led some energy analysts to hypothesise that economic systems try to maximise power.

In sum, even though ecological economics is based also in part on the ideas of those energy analysts, Podolinsky's, Lotka's, or any energy analysis should not be considered from a literal point of view, but just as a metaphor or as a tool that may improve the understanding of economic processes. For example, the distinction first introduced by Lotka (1956), and later proposed as a working concept for the energetic analyses of bio-economics and sustainability by Georgescu-Roegen (1975), between exosomatic[22] and endosomatic[23] energy flows is helpful in the analysis, as will be developed later. In fact, exosomatic energy can express different things for both developed and developing countries. Thus, for the former, it is basically equivalent to 'commercial energy', whereas in the latter it is related to traditional sources of power such as animal power, wind, water falls, and fire (Giampietro et al., 2001).

2.4.3. Economic system as a unidirectional open system

"Ecological economics addresses the relationships between ecosystems and economic systems in the broadest sense" (Costanza, 1989: 1). However, I do not think that it is the "science and management of sustainability" (Costanza, 1991), but rather of (un)sustainability, since ecological economics focuses on what is not sustainable, and on sustainability trade-offs. Also, following Redclift (1986), one can see the concept of sustainability as a social construction, which evolves with society[24]. In any case, ecological

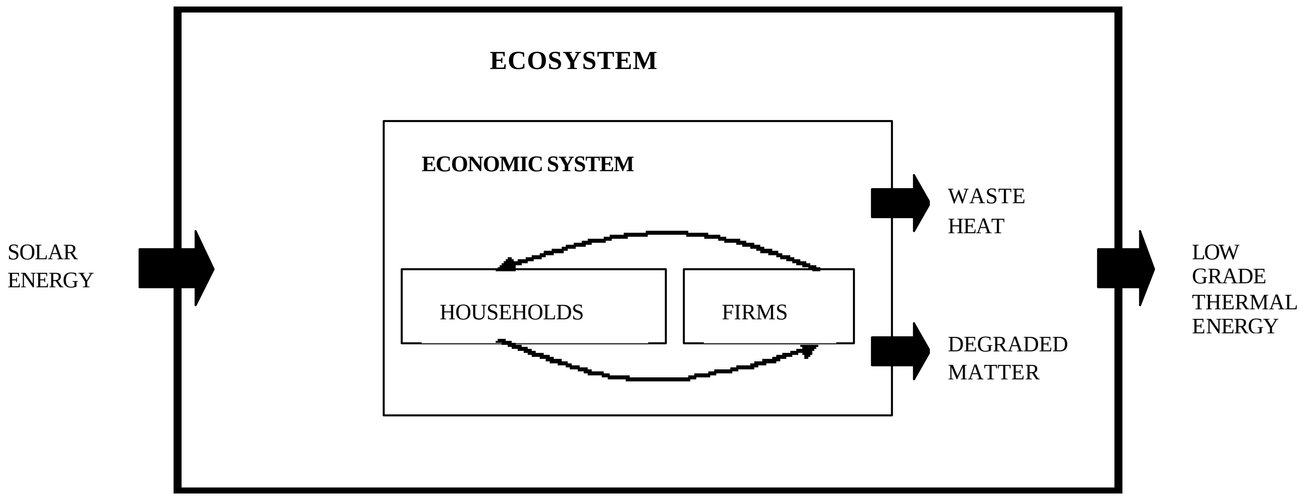
[22] Use of energy sources for energy conversions outside the human body, for societal metabolism, but which are still operated under human control.
[23] Use of energy needed to maintain the internal metabolism of a human being, that is, energy conversions linked to human physiological processes fuelled by food energy (Giampietro et al., 2001).
[24] As Daly (1996: 59) in footnote 5 said, "sustainability does not imply optimality – we may prefer another sustainable scale, one with more or less capital, but still sustainable".

economics uses concepts from ecology such as irreversibility, uncertainty and holism, to expand the scope of economic theory (Gowdy and Ferrer-i-Carbonell, 1999). The result of this is, as stated above, a revival of interest in the biophysical foundations of the economic process.

Central to ecological economics is the acknowledgement that economic systems not only affect the environment, but they depend on the life-support functions provided by the environment for their own survival. That is, there is a mutual relationship, a co-evolution (Norgaard, 1994; Gowdy, 1994). In fact, economic systems use matter and energy to be sustained and to grow, and it is this production and consumption that transforms matter and energy and that changes the environment.

The economic system can be seen as an open unidirectional system, a sub-system embedded in the larger natural system Earth, which can be approximated as a closed system.

Figure 2: Economic system as a unidirectional open sub-system of the natural system



Source: Hall et al. 1986: 39

Daly (1991: 36), following Boulding as he says, has called this transformation of energy and materials the 'throughput' (the entropic physical flow of matter-energy from nature's sources, through the human economy and back to nature's sinks). This can also be described as the 'metabolic flow' of society, following the ideas of Georgescu-Roegen.

As seen from Figure 2, the "economic process is sustained by the irreversible, unidirectional flow of low entropy energy and materials from the environment, through the economic system, and back to the environment in the form of high entropy, unavailable energy and materials" (Cleveland and Ruth, 1997: 205). Inside the economic system, the circular flow between households and firms can be seen, as described by neo-classical economics. However, the human economy, which is an open system, cannot be described as self-feeding, self-renewing, and circular, as neo-classical economists did. As Daly (1992: 196) said, both the unidirectional throughput and the circular flow are "different abstractions from the same reality, made for different purposes".

Solar energy drives the production of natural good and services, while industrial energy (fossil fuels or electricity) helps the economic system to transform or upgrade matter into produced goods for consumption. Ultimately, the consumption of these goods will represent the generation of waste in the form of degraded (high entropy) energy and matter. It can be seen, then, how both natural and domesticated environments support the economic system, as a fabricated system.

Figure 2 could be complemented with an additional arrow representing materials recycling (either by human means or by nature), but we have to bear in mind that material recycling is never 100 percent complete, and energy recycling is not feasible, which is why the throughput is ultimately unidirectional (from low entropy to high entropy). This is why, using the insights from the Second Law of thermodynamics, we talk about irreversibility. Actually, as stated by Daly (1996: 53), "we do not consume matter/energy, but we do consume (irrevocably use up) the capacity to rearrange matter/energy".

As stated, then, the economic system uses the throughput of matter and energy and other environmental services to maintain and develop its ordered structures, but at the expenses of generating entropy and exporting it to the ecosystem. Put in different words, "the production of wanted goods gives rise to additional *unwanted* outputs (bads), which may be harmful to the environment. The fundamental economic notion describing this relationship is that of *joint production*" (Baumgärtner et al., 2001: 365, emphasis in the original). It is this disorder, characterised by depletion of resources and pollution, and a consequence of the characteristic of the economic process as a joint production process, which "interferes with the life-support services rendered to the economy by other species and by natural biogeochemical cycles" (Daly, 1992: 226). This interference is not due to the absolute amount of entropy generated, which anyway is exported to the larger ecosystem, but due to the mismatch between the entropy generation rate and the capacity of absorption of the ecosystem. Here, an application of the importance of thermodynamics in setting the boundaries of the systems under analysis can be seen.

2.5. Conclusion

Summarising the arguments presented in this chapter, the Section 2.2 showed how the interest of economic science in environmental issues shifted over time. For the Physiocrats, the interest was in the production process, which by definition is biophysical, historical and evolutionary. The classical economists went beyond production to being also interested in scarcity. Acknowledging scarcity and its implications for the economic process might be interpreted as an interest in defining the boundaries of economic development. This tendency experienced a radical change with the emergence of neo-classical economics, which shifted the focus towards exchange and equilibrium instead of production, and developed a set of tools based on classical mechanics. Later, resource economists, armed with those tools, focused again on scarcity and pointed out the issue of waste. However, their response was in the form of finding 'optimal allocations' for the former and defining ‘property rights’ for the latter. These solutions, although very useful in certain contexts, are far from being a panacea when dealing with complex environmental problems. The second section ended by stating that the crucial problem may not be input scarcity but sink scarcity.

When analysing the relationship between the economy and the environment, thermodynamic theory provides useful insights. These were discussed in Section 2.3. Despite their importance, we should be careful when applying thermodynamic concepts and it should be done only for the appropriate systems.

From the First Law is derived that in every process, all inputs are converted, ultimately, into outputs. The Second Law, however, has more implications. It sets efficiency constraints (perfect recycling is impossible), and due to the irreversibility of the degradation of energy (from available to unavailable energy), defines the Arrow of Time in the evolution of the system, in the form of increasing entropy. Nevertheless, entropy cannot be considered a tool of analysis, but rather a basis for better understanding the relationship between the economy and the environment, pointing out the necessity of taking history into account when doing our analysis.

From thermodynamics it can be concluded that the major constraint imposed by the environment is that of making compatible economic time scales with ecological time scales, in order to guarantee sustainability by not disturbing the ecological processes that support life on earth.

Section 2.4 presented ecological economics, a trans-discipline that restores the interest of economic analysis in the provisioning of the ‘oikos’ or ‘polis’. That is, it is interested in the biophysical foundations of the economic process, meaning a revival of some aspects of classical economic thought. In its analysis, it used some concepts and tools developed by energy analysts or ecologists like Podolinsky, Lotka, and Odum. Ecological economics is the approach taken in this thesis for the biophysical analysis undertaken.

Ecological economics sees the economic system as an open sub-system of the larger closed natural system Earth, in which the economic process is seen as unidirectional and sustained by a continuous flow of low entropy energy and materials, that eventually will return to the environment degraded in the form of heat and waste materials. This fact imposes some constraints on the physical growth of the sub-system.

3. COMPLEXITY AND SELF-ORGANISATION

3.1. Introduction

Classical thermodynamic theory (dealing with systems in equilibrium) was presented in the previous chapter, in our attempt to understand better the relationship between the development of economies and their energy metabolism (i.e. energy dissipation), what Georgescu-Roegen (1971) called *exosomatic evolution*. In order to proceed with this presentation of the use of empirical analyses when considering the evolution of economies from a thermodynamic point of view, the main characteristics of human systems, and in particular, of economic systems, have to be defined in the framework of systems theory. Economies are, as has been stated before, open systems from a thermodynamic point of view (i.e. they are open to both energy and materials from the environment). Thus classical thermodynamics is not enough to describe economies since it focuses on isolated or closed systems. In particular, the Second Law cannot be directly applied to open systems in its classical interpretation[25]. This is why modern 'far-from-equilibrium thermodynamics' has to be used, as developed by Prigogine (1962) and his Brussels' school (Nicolis and Prigogine, 1977; Prigogine and Stengers, 1984). This theory seeks to explain the functioning of open systems in thermodynamic terms. Economic systems are also complex systems, so this chapter presents complex systems' main characteristics in order to proceed, in Chapter 4, to a characterisation of human systems as complex self-organising systems.

The structure of the rest of this chapter is as follows; Section 3.2 presents the thermodynamics of open systems, or 'far-from-equilibrium' thermodynamics. Section 3.3 relates the decrease in entropy within a system with its increase in structuring; this shows the compatibility of increased entropy in the environment and higher order in the particular

[25] See Schneider and Kay (1994) for a deep discussion on this.

system. Section 3.4 presents the main characteristics of complex systems. In particular, this section focuses on the fact that complex systems may be seen as teleological entities, which organise themselves in a hierarchical way, which show autocatalytic loops that stabilise the dissipation of energy, and which concentrate their behaviour around certain 'attractor points'. It also relates sustainability to complexity, by showing that present environmental problems that threaten sustainability are complex in their nature. Finally, self-organisation of open systems as a response (and also a cause) of energy dissipation will be described in Section 3.5, using the concepts developed in the previous sections. There, it will be argued that self-organisation might be viewed as an emergent property of complexity. Finally, Section 3.6 presents the concluding remarks for this chapter.

3.2. Far-from-equilibrium thermodynamics

Living systems, as well as social systems, are open systems from a thermodynamic point of view. As was said before, they are open to the entry and exit of energy and materials from the environment. For these systems, when talking of entropy generation, the insights provided by the Second Law are not enough, since for them two kinds of entropy generation can be distinguished. Following Nicolis and Prigogine (1977) it can be said that dS, or the entropy change in a defined system in an interval of time, can be divided into dS_e and dS_i ($dS = dS_e + dS_i$). Here, dS_e is the entropy change in the system due to exchanges of matter or energy with the <u>e</u>nvironment, while dS_i is the entropy change in the system due to the irreversible processes <u>i</u>nternal to the system. We know from the Second Law that $dS_i \geq 0$ (= 0 at equilibrium); that is, every process will lead to an increase in the internal entropy of the system, except when the system is at equilibrium (i.e. all the available energy is dissipated) where the entropy change must, by definition, be zero. We also know from the Second Law that $dS_e = 0$ for an isolated system; that is, since it is an isolated system (without exchange of energy or matter with the environment) there is no entropy generation derived from outside the system. When stated this way, we see that open systems are different from isolated systems, as they have a non-zero term, dS_e, which can be either positive or negative, depending on whether or not they are importing from or exporting entropy to the environment. This is the case of economies because they are open, as will be shown in the next chapter. If dS_e is negative, the export of entropy from the system to the environment might outweigh or equal the increase in the internal entropy, leading to a system with reducing or constant entropy. In other words, the entropy law ($dS_i \geq 0$) is compatible with a decrease of the overall entropy of the system ($dS < 0$), at the expense of an increase in the entropy of the environment. The interpretation of this, which is relevant in explaining the further structuring of systems, is presented in the next section. In sum, a far-from-equilibrium system will maintain and develop its state only by constant dissipation of energy and matter into the environment. This is relevant for living systems, as Schrödinger (1945) pointed out, suggesting that all organisms need to import low entropy from the environment and to export high entropy, or waste, in order to survive[26].

3.3. Decrease of entropy as increase in structuring: the Second Arrow of Time

The result, shown above, that the exchange of matter and energy with the environment (dS_e) may compensate the increase in entropy due to internal irreversible

[26] Spencer (1880) advanced a similar argument when he observed that human systems can reverse the increase in entropy by tapping energy flows in nature. Actually, as shown by Martinez-Alier (1987), this idea of "life against entropy" was in use already in the last years of the nineteenth century, by authors such as John Joly, Felix Auerbach, who coined the term 'ektropismus' to talk about it, Bernard Brunhes, and later by Henry Adams and Vladimir Vernadsky. Thus, as Martinez-Alier says, Auerbach's concept of 'ektropismus' might be considered as an antecedent of Systems Theory, anticipating Lotka, Von Bertalanffy, and Schrödinger. See Martinez-Alier (1987, chapter 7) for more details and for the references of those authors mentioned above.

processes, leading to a system with, eventually, reduced entropy, is related to the idea of ordering or structuring.

When dealing with this issue, Proops (1983: 358) made a clarification of concepts that is very useful. He said that “there seems to be a hierarchy of concepts. To say a system is ‘complex’ is to say that it is composed of distinguishable components. To assert that a system has ‘order’ is to say that these components are arranged in some recognizable pattern. The notion of ‘structure’ is stronger still, implying some unity to the arrangement of components. Finally, to say a system is ‘organized’ implies that the system’s ‘structure’ is some way an outcome of interrelations”.

Until the 1960s, scientists faced a ‘contradiction’ between the laws of thermodynamics and the appearance of life, as an expression of greater structuring of systems. In fact, following the Second Law, the tendency of systems should be towards increased disorder due to the irreversible increase in internal entropy (dS_i); thus has been called the Arrow of Time, as discussed above. However, the work of Prigogine (1962), and von Bertalanffy (1968) solved the apparent contradiction. Von Bertalanffy introduced General Systems Theory, in which he proposed that living systems are in a continuous exchange of inputs and outputs with the environment in a way that can be explained by feedback loops. They are thus open systems. This exchange of energy and matter with the environment and with other systems implies interdependence between systems, which are constrained by other systems’ feedback loops.

Prigogine (Nicolis and Prigogine, 1977; and Prigogine and Stengers, 1984, are the basis for what follows) said that the starting point for the work of the ‘Brussels School’ was Boltzmann’s order principle, in which he related low entropy with order, and high entropy with disorder. Thus, non-equilibrium (i.e. non-maximum entropy, $dS \neq 0$) can be seen as a source of order. That is, a system in non-equilibrium may, as a consequence, develop order at the expense of higher entropy in the environment. This order and the development of structures to metabolise energy and matter, was what he saw when analysing biological systems, as well as social systems, such as cities. That is, in biological systems, solar energy compensates for entropy generation, and induces ordering and the development of new structures, i.e. life. This is the so-called Second Arrow of time[27], "the tendency of certain systems to become more complex and more structured" (Proops, 1983: 357). Thus, systems may be maintained in far-from-equilibrium conditions by a continuous and sufficient flow of energy and matter, which provides inputs in the form of low entropy energy and expels waste in the form of high entropy waste heat. As a result, far-from-equilibrium systems would tend to higher organisation, as is further discussed in Section 3.5. In this way, the First and Second Arrows of Time are no longer separate, but 'two sides of the same coin'. The First Arrow applies for those systems at or near equilibrium, while the Second Arrow is operational for systems far-from-equilibrium (Faber and Proops, 1998).

Ulanowicz (1996: 229) expressed the same ideas in different words by saying that, "in the absence of major perturbations, *autonomous systems tend to evolve in a direction of increasing network ascendancy*" (emphasis in the original). By this he meant the same idea of increased structuring, but he was stressing the fact that the new structure links all of the compartments of the system (it is thus a network).

This approach resolves the apparent contradiction between biological order (i.e. the appearance of life) and the laws of physics. The problem was trying to apply the concepts of equilibrium thermodynamics to the wrong systems. Now, far-from-equilibrium thermodynamics allows us better to understand open systems.

[27] See Schneider and Kay (1994) for a deep analysis on the Second Arrow of Time. The title of their paper says much about it: "Life as a manifestation of the second law of thermodynamics".

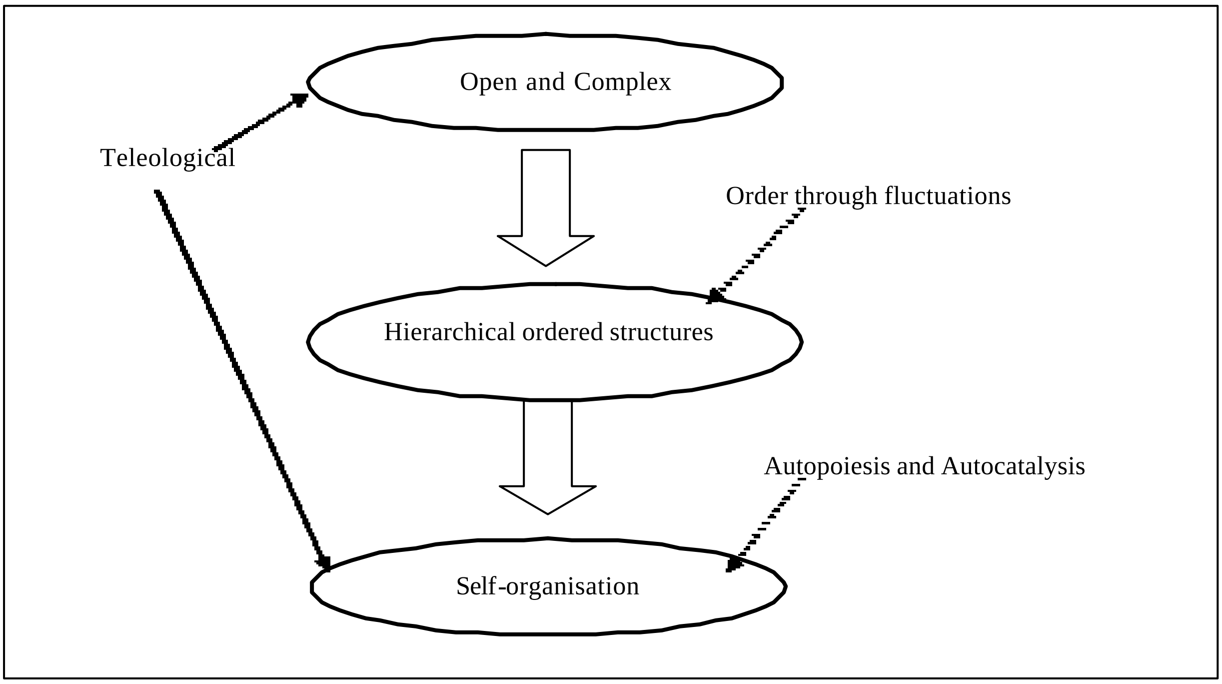
Based on the former arguments, Schneider and Kay (1994) explained the origin of life by suggesting that life on earth is just another means of dissipating the solar energy gradient; that is, their thesis is that due to the presence of a thermodynamic imperative by which gradients have to be dissipated, the logical response of systems is growth, development, and evolution.

In sum, at or near equilibrium, disorder (or 'mixed-upness') will prevail (there is only one steady state), while order prevails far-from-equilibrium (although, as we shall explain later, there is room for different stable states), provided there is the necessary flow of low entropy energy and materials from the surrounding environment. Thus, the low entropy flow can be seen as a metabolic flow that guarantees the maintenance of the structures of the system, and allows for further development. Prigogine called the kinds of systems showing this behaviour 'dissipative structures' (an example of non-equilibrium as a source of order), to distinguish them from equilibrium structures.

3.4. The characteristics of open complex systems

Dissipative structures are open systems (Prigogine and Stengers, 1984). They are open to a flow of energy and matter (throughput or metabolic flow); they also increase their complexity through increasing organisation. Thus, complexity can be seen as a necessary but not sufficient condition for organisation. Dissipative structures are thermodynamic systems whose behaviour is characterised by their boundary conditions, rather than by their initial conditions, in contrast to simpler dynamic systems. As long as they exist, they will dissipate energy. This fact is relevant from an environmental point of view, since when analysing the evolution of economic systems (towards more organisation, and thus more energy dissipation, depending on the net effect of efficiency gains), the balancing of economic time scales (i.e. of energy dissipation) with biological time scales (i.e. of waste assimilation), will be the key point for sustainability.

Figure 3: Map of concepts regarding complex systems



In Figure 3 a graphical presentation is made of the concepts used in this section, as well as the relationship between them. As we can see, there are three different kinds of concepts:

(i) Fundamental properties of dissipative structures (open, complex, and teleological).

(ii) Emergent properties derived from higher complexity (hierarchical ordered structures, and self-organisation).

(iii) The means by which these emergent properties arise (fluctuations, autopoiesis, and autocatalysis).

Although the concepts are explained throughout the section, a brief introductory explanation might be useful to link them all. Thermodynamically open systems can be maintained in far from equilibrium conditions by the throughput of energy and materials taken from the environment. These systems are complex; that is, they are composed of many elements that show interrelations among themselves. Moreover, they might be considered as teleological (i.e. they have an end) towards their maintenance and development.

In order to achieve that end, and because of the flow of low entropy within the systems, order appears in the system. This gives rise to structures that are hierarchical in nature; i.e., they are composed of different levels that interact with each other. When the flow of low entropy energy and matter reaches a certain level, the system becomes unstable. Then, random fluctuations act as trigger and lead the system in one direction or another, allowing the emergence of a new structure, which will evolve to cope with the different boundary conditions, which have been altered by the unidirectional flow of low entropy energy and matter[28]. This process of self-organisation (by reacting to the new boundary conditions and dissipating the available energy) is achieved through what is called autopoiesis. This is the capacity of the system to renew itself, to self-reproduce, through autocatalytic processes, in which the output of one process goes back to the beginning of the process as a particular kind of input (which will be no part of the final outcome of the process). It unleashes the reaction in the same process giving rise to the new outcome (i.e. human reproduction in which human beings are necessary to generate another human being that does not contain the former beings, genetic information apart). In sum, as we shall see in Section 3.4.2., we can say that the telos (or end) explains the further organisation from simpler components to complex organised systems. Thus, self-organisation is seen as an emergent property of complexity, triggered by random fluctuations.

[28] These new structures are novel in a chaotic sense (Faber and Proops, 1998) since they are originated by random fluctuations.

3.4.1. The definition of complex systems

A complex system is one in which both the number of components and their degree of interrelatedness increase. Complexity, however, can also be viewed in a different way, that of the multiple perspectives necessary to understand those physical and social complex systems.

In any case, "complex environmental systems are characterised as containing: feedback loops, many elements, multiplicity of inter-relations and non-linear, evolutionary behaviour. This makes systems unpredictable. There is no one, or any, optimal solution to the management of complex systems" (Munda, 2000: 16). They might be defined as hierarchical, energy dissipating systems in multiple space-time scales, showing properties like "anticipation, goal-seeking, historical uniqueness, adaptation, self-regeneration and evolution, and multiplicity of perspectives" (Funtowicz and Ravetz, 1997: 793). Foster et al. (2001: 2) put it in this way: "operationally, a complex system is one where understanding requires the insights of different disciplines operating at different scales; where there is irreducible uncertainty; and, where there are multiple likely future states". Rosen (1987: 133) also said that complex systems "should be able to manifest surprising, novel, and counterintuitive behaviors; e.g. emergence". Following Kay and Regier (2000), we can say that complex systems are characterised, as we shall develop later, by:

- non-linear behaviour (because of feedback);
- hierarchical structure (the system is nested within a system and is made up of systems);
- internal causality (self-organising causality characterised by goals, positive and negative feedback, autocatalysis, emergent properties, and surprise);
- the fact that there may not exist equilibrium points;
- multiple attactor points (steady states) are possible;

- they show catastrophic behaviour, with bifurcations and flips between attractors;
- and even chaotic behaviour, where our ability to forecast and predict is limited.

We now develop some of these characteristics in more detail.

3.4.2. Teleological entities: 'natural' tele

Dissipative structures behave as a whole (Clark et al., 1995). They have a goal, a telos (telos = goal, aim, end; tele is the plural), which is the self-maintenance and development of the system, as is shown below. This telos can be termed a 'natural' telos. Dissipative structures also have different tele for each hierarchical level of the system; that is, their respective role in the system.

Faber et al. (1996) related teleology[29] with the idea of causation towards a future state. For them there are two ways of understanding causation; one is mechanical, based in past and present events, while the other is teleological, trying to understand causation in terms of future events (or goals, ends; that is, tele). In this way, the evolution of complex systems could be explained as goal- or end-oriented; that is, the cause of their behaviour would be the achievement of the telos. The future will determine the course of historical events (Haken and Knyazeva, 2000).

This kind of behaviour would not be planned. Rather, the telos would be the intrinsic nature of the organism. It would direct the organism's development, which would be realised during its lifetime (Faber et al., 1996). This is why the causation is understood here in terms of the future realisation of the end.

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[29] Faber et al. (1996) made the distinction between three different tele: i) self-maintenance, development and self-realisation; ii) replication and renewal; and iii) service to other species, to the whole of nature. Here, however, the first one is stressed and this is the one considered different for non-human and human systems (the distinction between 'natural' and 'social' tele). The concept of telos is used to stress the fact that the goal is inherent to the organism, it is thus an *end*, something that is not planned beforehand (personal communication with John Proops, 30/01/2001).

Complex systems have the telos of self-maintenance and development. This telos can be considered as a definition of organisms, or life. Non-human systems would have, then, this 'natural' telos. We can approach this natural telos from science, to a certain extent. We can try to translate it by using the insights of different disciplines, for example of ecology, finding a way to translate their necessity of maintenance and development into some critical thresholds that define maximum use of resources or maximum absorption capacity for pollution[30] (i.e. stabilising natural cycles). However, as will be argued in the next chapter, the 'social' tele of human systems can be in conflict with these 'natural' tele. Therefore, for sustainability purposes, the coordination of 'natural' and 'social' tele is essential.

This teleological approach to complex systems undermines the use of mechanical-deterministic descriptions of such systems that are based in past causation, as is argued in Chapter 5, when analysing the role of empiricism for complex systems analysis.

3.4.3. Hierarchical structure

Typical open complex systems, such as human societies and ecosystems, are examples of hierarchical systems. "A system is hierarchical when it operates on multiple spatiotemporal scales" (Giampietro and Mayumi, 1997: 453). Such systems can be divided into several components, which are, at the same time, composed of smaller components, and so on.

Each component of a hierarchical system is called a 'holon' by Koestler (1969). A holon would have a double nature. On the one hand it is a component of a greater whole, while, on the other hand, it is a whole composed of many parts. It is because of this characteristic of belonging to the whole and being a whole in itself, that Koestler called

[30] Ciriacy-Wantrup's 'Safe Minimum Standards' (Hueting and Reijnders, 1998).

‘holarchy’ this kind of hierarchy. Complex systems are thus ‘nested holarchies’. In the case of ecosystems, this structure is exemplified by the existence of subsystems among larger systems (Odum, 1971). Thus, when analysing throughput in these hierarchical systems we have to look at two different kinds of processes:

(i) The circulation of energy and matter within the system (between the lower hierarchical levels)

(ii) The exchange of energy and matter of the whole system with the environment (focusing on the upper part of the holarchy).

That is, holons show a dual structure; they are structures in themselves at the lower levels, but they contribute to the overall structure as well, in what is an example of ‘emergent properties’ in structuring due to increased complexity.

This duality implies that, even though processes at one level can be seen as partially autonomous, they actually affect the rest of the structure, and its ‘unfolding’. This is one of the sources of the non-linear behaviour of complex systems. This is why it is not possible to intervene in one of the hierarchical levels without affecting, as a consequence, the rest of the levels, and the behaviour of the system as a whole. When one intervenes at one level, this will change the boundary conditions of other levels, leading to changes in those levels to adapt to the new conditions. The different hierarchical levels are, then, interdependent. They are linked by different feedback loops, in which the outcomes of processes at the lower levels are the inputs of higher levels, and higher levels impose the boundary conditions on the lower levels. This fact limits the use of extrapolations from lower levels to upper ones in the analysis of complex systems.

This hierarchy should not be understood as a ‘top-down’ one. On the contrary, the interconnectedness of the different levels guarantees that every level will change at one spatial and temporal rate, and will affect the rest of the levels. *“Therefore scaling up from* *small to large cannot be a process of simple linear addition; nonlinear processes organize the shift from one range of scales to another. Not only do the large and slow variables control small and fast ones, the latter occasionally 'revolt' to affect the former*" (Holling, 1996: 32, emphasis in the original).

The result, from an analytical point of view, is that we have to analyse complex hierarchical systems using *parallel non-equivalent descriptions*; that is, the incorporation of the insights of other disciplines and their different ways of explaining the same facts is needed. Moreover, an analysis for each hierarchical level is also needed, as well as congruence relations that link the different levels. This will sometimes bring some redundancies, but this is good since it enhances the robustness of the analysis.

However, due to the hierarchical structure, for us to understand the behaviour of complex systems, a higher level has to be defined as in quasi-stable conditions (considering the lower levels as quasi-fixed) in order to proceed with the analysis. This relativity (temporal and spatial, since we are assuming quasi-stability of the system when analysing it) is what makes complex systems analyses context dependent, only relevant for that temporal and spatial frame that we have chosen for the analysis.

3.4.4. Autopoiesis and autocatalytic loops

Autopoiesis (Varela et al., 1974; Maturana and Varela, 1980) refers to the characteristic, discussed above, that living systems have to renew themselves and maintain their structure; that is, their capacity for self-reproduction has to be understood bearing in mind that they are teleological entities, or end-oriented.

The process of autopoiesis, or self-production, to maintain and develop the structures of the system, can be understood as a process involving autocatalytic loops. An autocatalytic loop is a representation of an autocatalytic process. In that kind of process the outcome of the process, the product, is necessary to generate the product itself, entering the process again as a necessary input to unleash the process. In chemistry, autocatalysis means the chemical influence on a reaction of a substance that is not itself permanently changed (i.e. the catalyst), which is itself a product of that reaction. The product is necessary to drive the reaction that will generate the product itself. In biology we talk of the reaction of a cell or tissue due to the influence of one of its own products. In an ecosystem, one can see the autocatalytic loop as consisting of "the self-reproduction of a species in the presence of sufficient supply of food in the environment" (Jantsch, 1987: 56). In particular, we can interpret human reproduction as an autocatalytic process in which the presence of human beings is necessary to generate other human beings. The same happens with many other systems and processes. For example, the computer industry may be seen as an autocatalytic process, in which computers are needed to design, produce, assemble and deliver brand new computers. This kind of circular relationship leads to a growth in the system, as noted below, and to the potential for growing complexity reflected by new components and new relationships among them.

In the words of Ulanowicz (1996: 224), "autocatalytic configurations, almost by definition, are *growth enhancing*. An increment in the activity of any member engenders greater activities in all other elements. The feedback configuration results in an increase in the aggregate activity of all members engaged in autocatalysis greater than what it would be if the compartments were decoupled" (emphasis in the original). In this sense, an autocatalytic cycle cannot be understood only as reacting to its environment; it also influences the environment by means of, for example, its greater number of components.

There is no doubt that ecosystems and human systems (as open complex systems) are autopoietic systems, which hold the essential characteristics of openness to the entry of energy and matter; the presence of autocatalytic loops (closed to the system) which maintain the system; and differentiation, that allows the systems to adapt to the changing boundary conditions.

This view of representing self-production as an autocatalytic loop helps to explain the nature of hierarchical complex systems, especially when is complemented with the idea of the hypercycle (Ulanowicz, 1986). When describing ecosystems, Ulanowicz distinguishes between two main parts, the hypercycle, and a pure dissipative structure. The hypercycle is formed by those processes that are responsible for supplying the necessary net energy to the system. That is, they take primary energy from the environment and convert it into available energy (for example in the form of different energy carriers) for the system. We might think of photosynthesis in plants, or the mining and energy sectors in an economy. When doing this, the hypercycle is guaranteeing the functioning of the system by providing the necessary net energy. Net energy because we have to bear in mind that this process of making energy available for the system is energy intensive, thus consuming a certain amount of energy itself. Thus we can say that the hypercycle can be seen as an autocatalytic loop, as described above. The role of the hypercycle is, therefore, "to drive and keep the whole system away from thermodynamic equilibrium" (Giampietro and Mayumi, 1997: 459).

The dissipative part would stabilise the system by degrading the remaining net energy, controlling the process of energy degradation of the whole system[31], and eventually, would build and maintain structures at lower levels.

The same was said before (Proops, 1979; Weissmahr, 1991) using different words. Both authors distinguished between the dissipation that goes to the maintenance of the conditions for the functioning of the system, and the dissipation that goes to the

[31] For example through 'regulatory processes' (Nicolis and Prigogine, 1977), in which processes ensure the co-ordination of the activities of the different populations (sub-systems) in order to favour those activities that benefit the whole population (system).

maintenance and growth of the system itself. In this analysis, the development and growth of the system can be seen as a reinvestment of the energy surplus generated by the hypercycle. This positive feedback loop would lead, eventually, to an increased complexity of the system reflected in changes in the structure of the system, i.e. increased organisation in order to dissipate that surplus energy.

3.4.5. Attractor points

The hierarchical structure of complex dissipative systems, as well as the working of the feedback loops between the different hierarchical levels, induces non-linear[32] behaviour in the systems. This is so because positive feedback loops might generate self-reinforcing mechanisms. That is, it gives path-dependency, "the possibility that even minimum divergence, caused perhaps by a small random event, may evolve into an accumulated advantage and determine the future development of the system" (Dalmazzone, 1999: 45). This non-linear behaviour is not only induced by external shocks as normal economic theory implies, but also by internal causes within the system, and is reflected by the presence of attractor points. An attractor represents a region in which the behaviour exhibited by the system is coherent and organised (Kay et al., 1999). For an isolated system, thermodynamic equilibrium in which the entropy generation is zero might be seen as an attractor. By contrast, in far from equilibrium systems, thanks to Boltzmann's result, it can be said that the attractor point might be seen as the 'state of maximum probability' in that particular space and time. That is, one of the multiple stable states available for the system[33].

[32] Understood here as non-continuous; that is, there are changes that do not occur smoothly. The term non-linear is used since it is the one found in the literature, although non-continuous might be considered as more proper.
[33] Holling (1996: 32) said, "*ecosystems are moving targets, with multiple potential futures that are uncertain and unpredictable*" (emphasis in the original).

Both non-linear behaviour, and far from equilibrium situations lead to the existence of a multiplicity of stables states (Proops, 1985) or attractors. This situation leads to a series of 'bifurcation'[34] points (Prigogine, 1987), in which, for given boundary conditions there are many stable solutions. Following Faber and Proops (1998: 88, 89) a "bifurcation may occur when the stable equilibrium for a dynamic system is sensitive to changes in the parameters of the system". Thus, when the parameter goes beyond a critical threshold, the system becomes most sensitive and therefore unstable. In this case, tiny perturbations may trigger drastic changes (Dalmazzone, 1999), leading to a set of new different stable equilibria to which the system might eventually flip. These are the so-called 'thermodynamic branches'. This behaviour may continue as long as the parameter changes, leading to a cascade of bifurcation points. It is then that Prigogine's random fluctuations may induce the system to shift from one attractor to another, in a way that is not smooth and continuous, but step-wise (Kay et al., 1999).

Once the system reaches the attractor, it fluctuates around it and its parameters move only short distances, at least for a certain period of time. This is known as 'lock-in', and prevents the system from taking another trajectory for a period of time (Dyke, 1994; Kay et al., 1999). The fact that a particular system is stabilised around one attractor point constrains the future available trajectories and attractors by paving the path for future developments, in an example that history counts. As Haken and Knyazeva (2000: 63) said, "if a point of branching (bifurcation) is already passed, a certain 'choice' is already made, the other, alternative paths of evolution become to be closed; the process of evolution is irreversible".

The conclusion, thus, is "that a sufficiently complex system is generally in a

[34] May and Oster (1976) first introduced the concept of bifurcation when analysing the behaviour of chaotic systems.

metastable state", and that "the value of the threshold for metastability depends, in a complicated fashion, on the system's parameters and the external conditions" (Nicolis and Prigogine, 1977: 463). This metastability is achieved through the dynamic stability between the different hierarchical levels of the system, that always leave room for future development.

3.5. Self-organisation: the Second Arrow of Time

As shown above, open systems have the tendency towards more organisation and ordering of their structures. This is a continuous process, an evolutionary process. This is why interest should be shifted away from analysing the final structures or outcomes of processes to analysing the process of developing the structures, the process of 'becoming'. As Kay and Regier (2000) said, self-organisation is not something static that tries to maintain ecosystems in specific states, but rather tries to maintain the integrity of the process of self-organisation itself. Therefore, the way we understand systems changes; as Jantsch (1987: 6) said, "a system now appears as a set of coherent, evolving, interactive processes which temporarily manifest in globally stable structures that have nothing to do with the equilibrium and the solidity of technological structures". Then, following Prigogine, he announces the principle through which order is achieved, "the new ordering principle, called 'order through fluctuation', appears beyond the thermodynamic branch in open systems far from equilibrium and incorporating certain autocatalytic steps".

But how do open systems organise? First, they behave as a whole, as an entity (Prigogine and Stengers, 1984). We have already said that they have a natural goal (or telos), that of self-maintenance and development. Then it follows that the structures they achieve are not only due to external shocks, but also involve some internal causality. This is why a self-organising system can maintain itself at an attractor, despite the changes in its surrounding environment (Kay et al., 1999).

As stated, when developing the theory of dissipative structures, this 'order through fluctuation' can occur only in open systems which are far-from-equilibrium. An open system receiving exergy from its environment is moved away from equilibrium through the irreversible dissipation of that exergy. Once the distance from the equilibrium reaches a critical threshold, the 'old' structure becomes unstable, and it is through the dissipation of more exergy that the system responds with the spontaneous emergence of new organised behaviour that, using the inflow of exergy, organises and maintains the new structure achieved. The more exergy is pumped into the system, the more organisation will emerge in order to dissipate that exergy. We can see therefore the emergence of the self-organised structures as a response from the systems as they try to resist and dissipate exergy that is moving them away from equilibrium (Schneider and Kay, 1994).

In this scheme, applying the theory developed above, the tendency of the system to dissipate more exergy reflects the Second Law of thermodynamics' tendency towards disorder. For the system to maintain its organisation, it is necessary to dump the entropy generated into the environment (negative dS_e), making compatible, as we saw above, entropy generation and order.

Therefore, "the theory of non-equilibrium thermodynamics suggests that the self-organization process in ecosystems proceeds in a way that: a) captures more resources (exergy and material); b) makes more effective use of the resources; c) builds more structure; d) enhances survivability" (Kay and Regier, 2000).

Under this framework, the stability of the system would be constrained by the boundary conditions of the system and by the random fluctuations. As Prigogine and Stengers (1984: 188) said, "the more complex a system is, the more numerous are the types of fluctuations that threaten its stability". This means that in systems that show this behaviour, even small causes can have large effects, leading, then, to an increase in the difficulty of making predictions of the behaviour of these systems.

In fact, between bifurcations (the point at which the system flips from one attractor to other, as was noted above) the deterministic aspects are dominant, since the system has reached or is reaching a new structure (i.e. it is metastable). This fact allows for some kind of prediction or finding of regularities (i.e. historical tendencies in the variables analysed). On the other hand, near a bifurcation point, fluctuations or random elements will be dominant, leading to unpredictable outcomes (i.e. novelty).

Thus, in the process of the self-organisation of open systems, two contradictory effects exist. First, there is the inherent tendency towards increasing energy dissipation, whereas, on the other hand, these systems also show a tendency towards an increased efficiency in the rate at which energy is dissipated. This latter effect is more obvious near an attractor point, where the system is in a metastable situation, and most of the energy dissipation is due to the maintenance of the structure. However, when the system is shifting from one attractor to the next, the size of the energy degradation outweighs the efficiency gains, since more energy is used for the development of the system towards the new metastable state than the one saved by the efficiency gain.

One can establish a link between environmental problems as defined above and self-organisation. Indeed, environmental problems arise because the capacity for self-organisation may be partially, temporally or spatially, lost.

In sum, as was said earlier, self-organisation might be considered as an emergent property of complex systems through the dissipation of energy and matter.

3.6. Conclusion

This chapter began by presenting the thermodynamics of open systems or 'far-from-equilibrium' thermodynamics, by showing that the entropy within a system may eventually decrease, depending on how the system takes exergy from the environment and dumps entropy into it (i.e. depending on dS_e).

When dealing with equilibrium thermodynamics in Chapter 2, a 'contradiction' between life and the laws of physics was discussed. This chapter has presented the issue in broader terms, introducing the theory of far from equilibrium systems. With that theory, Section 3.3 has shown that the increasing organisation of systems through the dissipation of energy and therefore the generation of entropy is possible. The most important insight from the theory of dissipative structures is that open systems far-from-equilibrium maintain their order and structure, and even develop, thanks to irreversible processes that dissipate energy and matter from the environment, thus generating an increase in the entropy of the environment. This generation would be higher as the systems moves away from thermodynamic equilibrium. This theory thus solves the false contradiction mentioned above, and it means that the two Arrows of Time are two sides of the same coin; one applies to isolated systems, the other to open systems.

In Section 3.4 some characteristics of open complex systems were presented, focusing on the fact that they are teleological entities that structure themselves in a hierarchical way. They are also autopoietic; that is, self-reproductive, through autocatalysis, in which the outputs of some processes are inputs to themselves. It was also said that their evolution is step-wise, flipping from one attractor point to the next.

Finally, Section 3.5 presented open complex systems as dissipative structures that show a tendency towards increasing complexity, developing new structures that allow the processing of more energy and matter, in an increasingly efficient way. We can also say that they show this increased order or structuring because recognisable patterns are found in them. They evolve towards more order, by dissipating more energy. But this evolution is caused by their teleological behaviour; that is, they have the end or telos of self-maintenance and development.

4. HUMAN SYSTEMS AS COMPLEX, ADAPTIVE, DISSIPATIVE, SELF-ORGANISING SYSTEMS

4.1. Introduction

This chapter is about interpreting or understanding human systems, and economies in particular, using the insights developed in Chapters 2 and 3. This will allow comparisons between the developments of natural systems and economies, as will be done later in the thesis. But this will also make evident that the present way of analysing economies is no longer valid, which is why a new epistemology for complex systems is presented in Chapter 5.

The structure of the rest of the chapter is as follows: Section 4.2 characterises human systems as complex systems, by focusing on their teleological and hierarchical nature, on their metabolism to maintain and enhance organisation, and on the consequences of their metabolism upon the environment. Section 4.3 presents an explanation of how economic systems evolve, following a complex-systems perspective by focusing on the energy metabolism of such systems. Finally, a conclusion summarises the relevant points.

4.2. Characterisation of human systems

When approaching the economic system from a thermodynamic point of view, production can be seen as the process of upgrading matter into low entropy goods and services. This process implies a unidirectional flow of low entropy energy (exergy) that is ultimately degraded into high entropy energy (waste heat). The economic system can thus be seen as an open, unidirectional system, a sub-system embedded in the larger natural system Earth, which can be approximated as a thermodynamically closed system. Therefore, economic systems might be considered to be dissipative structures far from thermodynamic equilibrium, which, as argued above, are complex systems.

4.2.1. Analogy or isomorphism

Some authors, such as Stock and Campbell (1996), see the human system as a superorganism, in a clear *analogy* to other kind of organisms like cells, and try to apply theories from biology to explain them. However, most of the analysts of human systems, and economic systems in particular, do not go so far, and only interpret the economic systems as dissipative structures. Thus, economic systems are seen as maintaining and developing structures far from equilibrium through the dissipation of energy (Nicolis and Prigogine, 1977; Proops, 1983; Prigogine and Stengers, 1984; Adams, 1987; Binswanger, 1993; Witt, 1997; Giampietro, 1997; Giampietro and Mayumi, 1997; Faber and Proops, 1998).

For example, Proops (1983) said that an economy may be seen, from a physical perspective, as the 'same sort of thing' as an organism, a flame, or a convection cell, but he did not advocate a 'pure' analogy. It can be said thus that an *isomorphism* exist between economies and other kind of organisms. The view adopted here is the latter; that is, the view of economies as the 'same sort of thing' as organisms, since they share a common language and characteristics to describe them.

4.2.2. Teleological entities: 'social' tele

Although they share similar features, as argued by Witt (1997), the economy is not organised, controlled, and developing in the same way as natural systems. For natural, or better, non-human systems, the idea of a 'natural' telos was presented in Chapter 3. In the case of economic systems there are at least two important differences. One is that human intelligence influences the development of both the tele of the society and the regulatory processes. The other is that human systems are anticipatory systems. In this sense, we can interpret the economic process in a different way than 'natural' processes. As Georgecu-Roegen said (1971: 277), "the primary objective of economic activity is the self-preservation of the human species. Self-preservation in turn requires the satisfaction of some basic needs – which are nevertheless subject to evolution". Thus, the relevant factor here is the *human* intervention in deciding the basic needs; that is, the values held by the people involved.

Regarding the 'social' tele, economies are formed of individuals at a lower hierarchical level. Human beings share with non-human organisms the telos of self-maintenance and development. However, even though this social telos can be considered an end in itself (intrinsic to the organism), it is different from the 'natural' telos in, at least, two characteristics. First, human beings are *aware* of the existence of that telos, so they pursue it tenaciously. Second, different human beings show different ways of pursuing and fulfilling that end; that is, they incorporate their own created wants and wills. Thus, in contrast to the 'natural' tele, that we said could be approached by science, 'social' tele are more related to value judgements, to moral concerns, even to issues like spirituality. The consequence for the analysis of human systems is that they are much more complex than non-human ones, since different tele have to be considered, and their number seems to be increasing as some *values* are generalised to the entire population. In this sense we say, following Georgescu-Roegen (1971), that the outcome of the economic process is not only high entropy, as is true for 'natural' processes, but also the *enjoyment of life*. This can be considered a telos in itself, as Georgescu-Roegen acknowledged when talking of economic processes as *purposive activity* for the enjoyment of life. For him, the enjoyment of life is unmeasurable, but it depends in a positive form on consumption and leisure enjoyment, and in a negative way on work. This fact implies that the subjective has to be accounted for, and this is why here it is said that value (or moral) judgements more than science are to be used to understand the social tele.

The attainment of such tele or ends implies an increase in regulatory activities (i.e. energy used to run productive and reproductive activities). Adams (1987) said that there is a relationship between the further development of structures in societies (i.e. organisation) and the size of the regulatory system, defined by him as public administration, security, education, religion, law, science, and commerce and finance. This fact would imply that the more structuring we find, the more organisation is needed to *regulate* the dissipation of energy, a result that was advanced above, and that Georgescu-Roegen (1971) related to *exosomatic evolution.* That is, with the evolution of economic systems we are using more exosomatic devices, with the consequent appearance of new *elite* of ‘supervisors’ and ‘regulators’ and their activities. These regulatory activities might be considered as net dissipative systems, following Ulanowicz’s (1986) distinction.

In sum, economies can be seen as teleological systems, but in a different way than non-human systems. They incorporate new tele, and they are capable of incorporating the guessed consequences of their fulfilment into the present decisions and definitions of new tele; they are therefore anticipatory. They also learn from mistakes and from present developments, and they react, by changing both the actions undertaken and the tele defined; they are thus self-reflexive. They also have the ability to adapt to new changing boundary conditions (a property also shown by non-human systems), but they may *consciously* alter the boundary conditions. This is why the economy, as a human system, can be understood as a complex, adaptive, *self-reflexive*, and *self-aware* system.

4.2.3. Hierarchical structure and autocatalysis

When analysing their structure, economic systems can be considered to be nested hierarchical systems. In the case of economic systems, we can distinguish several subsystems within them, and every sector may be split into different industrial 'types' (sharing common features) and so on. The various levels of an economy exchange human activity and energy between themselves, reflecting the autocatalytic nature of those systems.

Ecological and human systems' dynamics are characterised by the presence of both positive and negative feedback loops, operating at different temporal and spatial scales, that stabilise the system around certain attractors, with an ordered configuration. Positive feedback loops play a special role in autocatalytic processes leading to systems' development. A "positive-feedback is a deviation amplifying process which promotes further growth and can lead to increased complexity and large scale changes in the system" (Weissmahr, 1991: 538). In the case of economic systems, reinvestment of economic surplus (added value) can be seen as a positive feedback for development (Odum, 1971). Money, in exchange for work done, generates positive feedback loops that reward all agents when it is exchanged. Another example of a positive feedback loop is the water cycle, by which forests recycle water and provide it to the rest of the elements of the ecosystem. Conversely, pollution levels above the assimilative capacity of the system is a clear example of a negative feedback loop, because it might imply even a regression in the development of the system.

The autocatalytic loops appear in economic systems in different ways, such population growth or "production of money by money" (Jantsch, 1987: 69, 70). Both population growth and economic production can be understood in autopoietic terms. They precede, and create, the conditions for subsequent reproduction (Zeleny, 1996). In fact, as a part of autopoiesis, individuals in a society adopt behaviours that are compatible with their existence within the whole, and also with the existence of the whole itself.

Using Ulanowicz's (1986) terminology as presented in Section 3.4.4., the autocatalytic loop that transforms energy and delivers it to the rest of the sectors, by reinvesting a large amount of energy and materials to make that net energy (or commercial energy) available, might be called the 'hypercycle' of the economy. This is what generates the continuous flow of low entropy energy towards the economic system. We have to bear in mind, however, that due to its autocatalytic nature it requires the outputs of other different sectors (i.e. physical capital, machinery, etc.) as inputs for its functioning. In an economy, the energy sector, plus the mining sector, might be considered as the hypercycle.

Also, the autocatalytic loop of human activity may be described by its duality. In one sense it represents human control over efficiency; that is, regulating the interaction between the focus level (the one under analysis) and the lower levels, and taking for granted, and fixed, the boundary conditions based on upper levels. On the other hand, human activity is also in control of adaptability, regulating the activity of the focus level with the higher level, and, in this case, accounting for the history of the system, for its evolution (Giampietro and Mayumi, 1997), as is further developed in Section 4.3.3.

4.2.4. Metabolism and self-organisation

If sustainability has to do with the compatibility between 'social' and 'natural' tele, then the metabolism of human systems has to be analysed, since it reflects the way human beings have to fulfil the defined tele, and their fulfilment might contradict natural tele. Thus, the flows of matter and energy into the society, through the society and out of the society, can be described by the metaphor of metabolism. In fact, as has been stated above, we owe this metaphor to Georgescu-Roegen (1971) who called it the 'metabolic flow'. Later, Daly (1991) introduced the concept of 'throughput', which is more usual nowadays.

In this sense, the 'exosomatic metabolism' of societies, or societal metabolism (Fischer-Kowalski, 1997) can be analysed, in which the consumption of exosomatic energy would be related to the internal organisation of that society. In fact, modern societies depend on a unidirectional flow of vast amounts of fossil fuels and materials, whereas natural systems instead depend on flows of 'solar' energy and material cycles (Weston and Ruth, 1997). As Georgescu-Roegen (1971: 281) said, "the conclusion is that, from a purely physical viewpoint, the economic process is entropic: it neither creates nor consumes matter or energy, but only transforms low into high entropy". Because of the relationship between the exosomatic consumption of energy and the internal organisation of systems, one might expect energy consumption to increase over time (due to the increased organisation), depending on the net effect of efficiency improvements.

Therefore, in biophysical terms, the process of self-organisation of human systems, as identified in Section 3.5, is seen as the stabilisation of matter and energy flows in time and space that represent what is produced and consumed in the economic process (Giampietro and Mayumi, 2000). This stabilisation, as pointed out by Proops (1983), will be coupled with a tendency to dissipate more energy, the Second Arrow of Time discussed above. Proops (1983) also showed that this fact has been confirmed by empirical evidence for a range of countries including both developed and developing countries.

4.2.5. The relationship with the environment

Unless efficiency improvements outweigh it, more organisation means more energy dissipation. If this happens, and the tendency of economies is towards more organisation, this tendency might have some impacts on the environment. In particular, human activity is not regulated by natural cycles providing a regular flow of low entropy energy (as it used to be in the past), but rather by an exploitation of the fossil reserves found in the earth's crust. This fact implies two things:

(i) That when we run out of fossil fuels and other minerals we might be in difficulty if an alternative fuel that is economical is not developed or found.

(ii) That when the assimilative thresholds for related emissions are surpassed, they might threaten the present meta-equilibrium in the environment.

Therefore, an analysis of the sustainability (in a broad sense) of the different paths of development of economic systems is needed. This assessment has to take into account the compatibility of the path with:

(i) The tele of the society.

(ii) The stability of natural ecosystems (what is called above the 'natural' telos of self-maintenance and development).

(iii) The stability of social and political institutions.

Moreover, it has to be technically feasible, and economically viable (Giampietro and Mayumi, 2000). Let us see, therefore, how we can approach the evolution of economic systems from a complex systems perspective, in order better to understand their energy metabolism and their compatibility with the surrounding environment.

4.3. Energy metabolism and the evolution of economies: Complex-systems perspective

Under this approach scientists, influenced by complex systems theory, as well as by chaos theory, fractal geometry, evolutionary and ecological economics, etc., have given alternative explanations of the evolution of the energy consumption of societies. This approach is thus more concerned with the evolution of economic systems, their process of structuring, i.e. their process of 'becoming'. It has been used mainly by human ecologists who, in recent years, and heavily influenced by H.T. Odum's work, have dealt with the energy and materials flow (the throughput) used up by human systems (Cleveland et al., 1984; Hall et al., 1986; Kay et al., 1999).

They focus the analysis on the hypothesis of a relationship between economic development, the structuring of economic systems, and energy dissipation, but taking other variables such as human time into account. They are, therefore, more biophysically oriented.

4.3.1. Scope of the analysis

The approach used throughout this dissertation accounts only for the exosomatic energy metabolism that can be approximated by commercial energy. There are, however, other studies that incorporate, to a certain extent, the non-technical energy, such as biomass used for human or animal nutrition. This is the case of Haberl (2000a; 2000b) and Krausmann and Haberl (2001), where the authors extend the concept of energy metabolism in order to consider also flows of nutritional energy for both livestock and humans. Therefore, they treat all biomass as energy input, instead of considering only the biomass used for technical energy generation, as do energy statistics. This accounting for biomass is especially relevant when analysing developing countries, where that kind of energy carrier represents a high percentage of the total energy consumption. We accept, therefore, that this approach might offer some explanations that are omitted when we analyse only commercial energy, especially for developing countries.

As Krausmann and Haberl (2001) show when analysing the case of Austria, even for developed countries absolute consumption of biomass is still important, although it has decreased in relative terms. This kind of analysis represents an improvement for the studies of energy metabolism that will surely be incorporated in future empirical analysis, despite the subjectivity implied (not all biomass is accounted for, only that used for human and animal nutrition, and sometimes some coefficients found for communities are extrapolated to find the national figures). However, in order to be more comprehensive, I also believe such studies should incorporate insights from complex-systems theory.

Thus, when analysing the economic process from an energetic point of view, we realise that, when transforming matter to convert it into a final good, we are consuming exergy; that is, we are degrading high quality energy into low quality energy, generating waste in the form of heat and making that energy no longer available as a resource. Moreover, as noted by Hall et al. (1986), energy has to be expended in order to maintain matter in its low entropy, organised state. That is, we have to expend exergy also to maintain the goods and keep them from degrading, from rusting or decaying. This would be the equivalent to amortisation for capital goods, and has the implication that not all available energy is to be used in expanding the system, but rather, some has to be expended in maintaining the system's ability to function. We can suppose that this fraction of exergy expended in maintenance will increase as the system does. Let us see now how economic systems use energy as they evolve.

4.3.2. On how economic systems evolve

Following Faber et al. (1996), evolution is defined here as the process of changing of something over time. Therefore, the evolution of economies means the changes that those systems are undertaking[35]. On evolution, Foster (1997: 444) says, "from a self-organizational perspective, economic evolution contains four fundamental characteristics. Firstly, self-organizational development is a process of cumulative, nonlinear *structural change*. Secondly, as such, it is a process which contains a degree of *irreversibility.* Thirdly, this implies that systems will experience discontinuous nonlinear structural change in its history; therefore, *fundamental uncertainty* is present. Fourthly, economic self-organization involves *acquired energy and acquired knowledge* which, in

[35] For Georgescu-Roegen (1971: 320) "evolutionary elements predominate in every concrete economic phenomenon of some significance – to a greater extent than even in biology". This is due to the importance of the Second Law of Thermodynamics for economic systems (because it determines the irreversibility of processes).

combination, yield *creativity* in economic evolution" (emphasis in the original), something that can be understood as an increase in the diversity of the system. All of these characteristics will be discussed in this section.

Over half a century ago, Schumpeter (1949) understood non-linear evolutionary development and discontinuity by means of his theory of creative destruction (Foster, 1997). For Schumpeter, growth was the result of innovation, which he defined in terms of novelty (new products, processes, markets, etc.). "He was describing a process through which the macro evolves out of the micro" (Clark et al., 1995: 51). Actually, Schumpeter saw development as "spontaneous and discontinuous changes in the channels of the flow, disturbance of equilibrium, which forever alters and displaces the equilibrium state previously existing" (Schumpeter, 1949: 64). This idea has been later named 'punctuated equilibrium' by some analysts, using the same term that is in use in palaeontology to describe this step-wise evolution. Thus, as we can see, the debate about the evolution of economic systems as non-linear behaviour has a long history in economic thought.

As noted above, energy dissipation can be seen as the driving force of evolution. For instance, Nicolis and Prigogine (1977) say that a necessary condition for the transition between states is the presence of 'evolutionary feedback', by which a system's self-organisation itself increases the distance from equilibrium (and therefore the potential for more self-organisation). Odum (1971) saw the same kind of behaviour in populations which react to cheap energy by increasing reproduction and survival, boosting the demand, in a feedback loop that will eventually increase energy dissipation. This can be understood as an implementation of his 'maximum power principle', which states that the criterion for natural selection is the maximisation of useful work obtained from energy conversion. "Where such a positive feedback mechanism exists, the boundary conditions of the self-organization process (here the energy flow from the environment) are no longer exogenously given, but are modified by the system's development itself" (Buenstorf, 2000: 127).

The further the system moves from equilibrium (due to the dissipation of available energy), the more numerous become the possible structures. When this development takes place, we can identify two different phases in the dissipation of energy in intensive terms. The first is a phase characterised by higher rate of energy dissipation. In the next, energy efficiency increases. Jantsch (1987) said in this respect that at first, the stabilisation criteria for the system is the maximum dissipation of energy and entropy generation, while once the basic structure is established, there is a shift toward a criterion of maximum efficiency, or minimum entropy generation per unit of mass.

Schneider and Kay (1994), as for many other ecologists, defend the hypothesis that growth, development and evolution can be seen as the response to the thermodynamic imperative of systems to dissipate gradients[36]. This is a view which is influenced by Lotka's words on evolution (1922) and Odum's (Odum and Pinkerton, 1955; Odum, 1971) maximum power principle. Thus, following this explanation, evolution of systems would imply (Schneider and Kay, 1994):

1. More energy capture
2. More energy flow activity within the system
3. More cycling of energy and material
4. Higher average trophic structure
5. Higher respiration and transpiration
6. Larger ecosystem biomass, and
7. More types of organisms, i.e. diversity

[36] This is another way of explaining that what moves systems is the fulfilment of a final end, a telos.

The equivalent can be said of human systems such as economies, which would evolve towards a greater organisation and structuring through the dissipation of greater amounts of energy. However, I agree with Buenstorf (2000) in considering Lotka's argument in a rather more subtle way than it is usually done. That is, we should interpret regularities in energy flows as outcomes of the self-organisation of dissipative structures. Lotka did not say that evolution implies maximising energy flows. He just said that "due to selection pressure on the species, at the system level both the energy efficiency processes and the total energy flow tend to increase" (Buenstorf, 2000: 121). This is a far less deterministic interpretation of Lotka's words than Odum's. I would say that this non-deterministic interpretation follows the phenomenological approach that was at the origin of Lotka's contribution. Under this interpretation, one can identify historical regularities and can use them for the analysis of the energy metabolism of societies, but one cannot extrapolate them (temporally or spatially).

As Proops (1979) noted, economies work because they use organised structures, Lotka's 'exosomatic instruments' (capital equipment for economists). These instruments have been produced by upgrading matter, also reducing the entropy involved. Therefore, the specific entropy of the economy will reduce as we change high entropy ores into low entropy machines. However, the functioning of these machines will increase the rate of energy dissipation of the economies.

As we see from the above, the debate about the energy de-linking of economic growth is old. As Hall et al. (1986) noted, there are some authors who support and some who reject what is now called the Environmental Kuznets Curve (EKC) hypothesis[37]. Among the latter (de Bruyn et al., 1998; Suri and Chapman, 1998; Unruh and Moomaw, 1998; Costanza, 1980 and Cleveland et al., 1984), the last two argue that there is a strong link between energy dissipation and economic growth. Therefore, a reduction in the energy throughput would probably imply a reduction in the goods and services produced by such an economy, something they do not see as something necessarily good or bad. That result, however, is in line with what Proops (1983) found when analysing the structuring of economies: they would show the tendency to dissipate more energy as they develop further structuring and organise themselves, i.e. the Second Arrow of Time discussed above. Do we have to take this result in a deterministic way as Odum does when proposing his maximum power principle? Or rather should we just consider the fact as an historical regularity shown by several economies? My opinion is that, for the moment, we should adopt the second approach; that is, to be careful about talking of possible 'laws'. In any case, to support their views, Hall et al. (1986) use a battery of empirical results for the USA and other countries in which they find that the correlation between GNP and fuel use is about 99%. However, the authors are aware of the possibility of being misunderstood and, therefore, they modify their conclusion by saying that the correlation found "might reflect *time trends* in fuel use and the GNP in a growing economy rather than a close relation between fuel use and the GNP produced in a given year or set of years" (Hall et

[37] This is the so-called inverted-U shaped curve, which states that income is the main factor that explains consumption of materials. That is, during the process of economic development countries would tend to increase consumption of energy and materials at the same rate than growth in income, until one defined level of income is reached. Beyond that level, however, we have to expect a de-linking between the economic growth and the consumption of materials. That is, further increases in the level of output will no longer be followed by increases (at the same rate) of energy and material consumption. The same has been hypothesised for the case of key pollutants.

al., 1986: 51, emphasis in the original). In any case, even accepting there is this relationship between GNP and energy consumption, this is not a linear relationship. As Giampietro and Pimentel (1991) noted, changes in the levels of energy dissipated by societies seem to imply jumps in the energy expenditure and the size of the system. "For example, there is a jump in the level of energy expenditure from 15,000 kcal/day per capita in a prosperous rural village to 70,000 kcal/day per capita for urban population. There appear to be no stable intermediate values" (Giampietro and Pimentel, 1991: 141). This argument is exactly the one defended by those who argue for the application of punctuated equilibrium to the development of the energy metabolism of societies.

The nature of complex adaptive systems, evolving over time, reacting to the changes in boundary conditions, as well as inducing some changes upon themselves, lead us to agree that the process of evolution is related to the dissipation of energy. In fact, economic evolution is linked to organisation. Organisation, by the way, can be seen as an emergent property of complexity. Therefore, systems build structures (develop and use new exosomatic tools) as a response to try to dissipate exergy (for instance from fossil fuels) that is moving them away from equilibrium. This is one reason to see development in a step-wise manner, since new energy developments deliver more exergy to the economic system and the system has to react by dissipating it building up new structures. Therefore, "because of its dissipative character, economic evolution will continue to make new claims on the energy and material resources of the natural environment" (Buenstorf, 2000: 130).

So far we have seen several explanations of the evolution of economies that tend to say that in the foreseeable future we can expect an increase in the material and energy throughput of societies as they develop. This fact brings the issue of scale into the discussion. Economies may combat the tendency towards increasing consumption by improving efficiency. This is also the basis of capitalism (reducing costs, improving competitiveness). However, there are two limitations to increasing efficiency. One is the thermodynamic one, and is reflected by the fact that we can increase efficiency up to a certain limit, beyond which, due to the Second Law of thermodynamics[38], we cannot go. It may be true, however, that we can solve our energy problems (basically sink problems) well before we reach that thermodynamic limit, but the opposite may also be possible. The second limit is related to the nature of human beings. Even assuming that we are not going to reach the thermodynamic limit before the human species disappears, we may face a limitation due to bounded knowledge and rationality, which means that we may not be able to develop the necessary technology to keep on improving efficiency. If that is the case, and for policy formulation regarding sustainability we should take such a precautionary approach, we may rely only on changing human behaviour to meet our targets of pollution and system size. This means that we should stress demand policies to slow, and even reduce, energy consumption, not only in per capita terms, but also in absolute terms. That is, Odum's *prosperous way down* (Odum, in press).

4.3.3. System energy efficiency vs. adaptability

When analysing the energy metabolism of complex adaptive self-organising systems, two competing effects can be identified. One is the hypothesised effect of dissipation increasing with organisation. The other is an 'efficiency' effect, by which dissipation would decrease with organisation (Proops 1979)[39]. Regarding this point, Proops (1983), when undertaking an empirical analysis of organisation and dissipation in

[38] No process is 100% efficient in the conversion of energy.

[39] Authors such as Buenstorf (2000) argue that the same occurs with technical processes, which tend to become increasingly energy efficient over time when performing constant operations.

economic systems, reached the conclusion that there was good evidence to support that energy dissipation increases with organisation, while the evidence for the 'efficiency' effect was much weaker. This double effect that we can see for self-organising systems can be understood as follows. Both characteristics have to do with two functions in the evolution of systems. Efficiency would be related to sustaining the short-term stability of processes by taking advantage of favourable gradients, that is, of present boundary conditions. Therefore, it would be related to lower level processes engaged in the holarchy that represents the system.

On the other hand, the tendency towards more energy dissipation that goes with greater organisation would be related to the adaptability of the system. That is, this increased dissipation of energy would be related to sustaining the long-term stability of the process, by maintaining the compatibility or integrity of the system in a context of changing boundary conditions (Giampietro and Mayumi 1997). This idea of adaptability, as well as flexibility of responses to changing environments, depends on the ability to preserve diversity in systems. There is, however, a competition between preserving diversity (enhancing adaptability) and improving efficiency. The latter requires an amplification of the most efficient processes, and therefore the elimination of those activities that are under-performing under certain criteria (Mayumi and Giampietro 2001). In the words of Odum (1971: 121), "with diversity the advantages of mass production are lost". The former, on the other hand, requires the dissipation of more energy precisely to maintain those under-performing activities (or processes, or species) in order to maintain a certain diversity that can allow us to face future changes in the boundary conditions (i.e. we may interpret in this way the return of 'old' technologies such as the 'fuel cell', which may be a solution to the scarcity of fossil fuels nowadays. This is achieved thanks to the energy dissipated over time in order to preserve it). Funtowicz and Ravetz (1997) link this apparent contradiction with the hierarchical structure of self-organising systems. For them, each holon must hold both properties of efficiency and adaptability, as they have to be seen as robust against the changes in the inputs from lower levels, but also flexible against the requirements of upper levels.

Efficiency cannot be seen as the only criterion for natural selection. As Clark et al. (1995 : 30) noted, "evolution was shown to select for populations with the ability to learn, rather than for populations with optimal behaviour". This is why redundancy and disorder (which Ulanowicz (1980) calls overhead), or diversity, "can contribute to system persistence. Overhead may act as a reservoir of potential adaptations available for the system to implement in response to novel perturbations" (Ulanowicz, 1996: 229). This is why maintaining diversity, by dissipating more energy, can be seen as a strategy for maintaining the sustainability of the system (i.e. we may think of wind energy, as well).

Holling (1996: 32) relates these dual characteristics of self-organising systems to the existence of multiple equilibria and the fact that they are far from equilibrium systems. For him, movement between states maintains structure and diversity. In his own words, "*on the one hand, destabilizing forces are important in maintaining diversity, resilience, and opportunity. On the other hand, stabilizing forces* [which improve efficiency] *are important in maintaining productivity and biogeochemical cycles, and even when these features are perturbed, they recover rather rapidly if the stability domain is not exceeded*" (emphasis in the original). Gowdy (1994: 118) puts it in different a way when he says that in the context of uncertainty, novelty and multiple equilibria, the flexibility to adapt to new situations and boundary conditions may be as important as efficiency in a particular environment. In particular, he argues that "a 'less efficient' agent might have a greater chance of surviving than a more efficient one if it could better adapt to uncertain change. An implication is that there might be an evolutionary advantage to having a variety of characteristics seemingly unrelated to the particular environment [that is, diversity] in which an agent finds itself". Therefore, from a sustainability point of view we have to admit the importance of both characteristics. Efficiency is needed to guarantee a higher return from the energy invested, and therefore provide more energy to be spent in maintaining diversity, in order to improve the systems' adaptability and flexibility to changing boundary conditions. From a policy perspective, this lead us to accept the existence of trade-offs between efficiency and adaptability which are at the core of the sustainability trade-offs. Moreover it has implications from a technological point of view, as shown below.

4.3.4. The relationship between energy and technological development

Faber and Proops (1998) identify *technology* as the set of techniques which are known, regardless of the fact that they are being used or not. They called *invention* the addition of a novel technique, which expands the technology. Finally, they called *innovation* the process of introducing a technique of the technology which was not used before. The authors also see resource limitation as a challenge for the appearance of new techniques to cope with it, in an unpredictable manner, which either use less of the diminishing return (resource-saving inventions) or which make use of alternative resources (resource-substituting inventions) (Faber and Proops, 1998). This is part of the process of genotypic change which drives the behaviour of economies as complex adaptive systems.

Giampietro and Pastore (1999: 291) note, "the term 'autocatalytic loop of exosomatic energy' indicates the possibility of using energy inputs converted outside the human body in a way that dramatically amplifies the amount of energy used by society. In fact, in modern societies, machine power and fossil energy are used to get more machine power and more fossil energy. This hypercycle generates a surplus that can be considered a 'disposable energy income' for society". Clark et al. (1995) talk about an increased 'roundaboutness' of economic production due to the growth of the capital goods sector of the economy.

Due in part to the hypercycle seen in economies, i.e. an autocatalytic loop, and to its characteristic as growth enhancing, "industrial economies have become locked into fossil fuel-based technological systems through a path-dependent process driven by technological and institutional increasing returns to scale" (Unruh, 2000: 817).

Some authors relate technological change and productivity improvements to an increase in the exosomatic energy consumption of societies. Therefore, as societies develop they would expend part of the net energy available thanks to the hypercycle in developing new techniques (i.e. enhance diversity, and therefore, adaptability). This result is not bad in itself. However, as pointed out by Georgescu-Roegen (1971: 304), "up to this day, the price of technological progress has meant a shift from the more abundant source of low entropy – the solar radiation – to the less abundant one – the earth's mineral resources", and therefore, "it is not the sun's finite stock of energy that sets a limit to how long the human species may survive. Instead, it is the meagre stock of the earth's resources that constitutes the crucial scarcity". For instance, when talking about the USA, Cleveland et al. (1984) said that over the last 70 years, a great part of the labour productivity increase was due to the increasing ability of human labour to do physical work thanks to their empowerment with fossil fuels, both directly and indirectly in the form of machinery and technologies. In fact, Hall et al. (1986: 43, 44) report that in the case of the USA, "the amount of fuel used per worker-hour accounts for 99% of the variation in manufacturing labor productivity between 1909 and 1980". The logical sequence is as follows; labour productivity improves because people uses technological advances that allow them to consume more energy, both directly (in the form of fuels) or indirectly (in the form of capital). However, in order to produce those advances, we have to consume more higher-quality fuels. Thus, one might think that future technologies and their productivities will depend on high-quality energy supplies[40]. Therefore, control over energy sources is of special relevance for economic growth. This is what drove Odum (1971) to combine Darwin's theory of natural selection and Lotkas's (1922) hypothesis of natural selection as an energy maximising process into a general law: the maximum power principle. For Odum, "societies with access to higher-quality fuels have an economic advantage over those with access to lower-quality fuels" (Cleveland, 1987: 58), because they could expend more energy in new techniques to incorporate to the technology. In any case, as Giampietro and Pimentel (1991) noted, either accepting Odum's maximum power principle or looking at historical trends, it seems that there exists a relationship between the increase in energy dissipation by human activity and technological development.

For Odum (1971: 185), "as fossil fuels are injected, the role of machines increases, outcompeting man in simple, mechanical work. The increased total work done increases the standard of living but only to those who can plug into the economy with a service that has an amplification [of economic] value greater than the machines". The logical consequence of using 'exosomatic organs' such as machinery is the rise of social conflict, since the use of exosomatic tools requires the emergence of supervisory classes, that is, managers and bureaucrats, as noted by Georgescu-Roegen (Beard and Lozada, 1999). If this is true, one way of analysing the further structuring of economic systems may be by analysing the size of this group of supervisors.

[40] Actually, as stated by Cleveland (1987) these ideas were put first forward by Cottrell (1955). Cottrell observed that, "in general, societies adopted a new energy technology only if it delivered a greater energy surplus, and hence a greater potential to produce goods and services" (Cleveland, 1987: 56).

Giampietro and Pastore (1999) see technological development as an acceleration of the energy throughput in the productive sectors of the economy (food security, energy and mining, manufacturing). This has been translated into a decrease in the human time spent in running such activities and a parallel increase in the dissipation of exosomatic energy by those sectors (machines fuelled by fossil energy). This increase in labour productivity has been realised thanks to the human ability to tap fossil fuels, which have been used to subsidise human work by empowering it. This would be an explanation of societal development which would follow Odum's maximum power principle, and which explains why most developed countries are also the biggest consumers of energy. It is not, however, a deterministic result which should be applied to other countries. Rather, it has to be seen as the description of an historical regularity.

4.3.5. Co-evolution, non-linearity and punctuated equilibrium

As Jantsch (1987) noted, organisms in ecosystems participate in more than one niche. They co-evolve by means of positive feedback loops that link them all. The consequence is the overall evolution of the larger system. The same applies for economies, where certain sectors or group of sectors co-evolve by interacting with each other and with the changing boundary conditions, leading to an evolution of the national economy (which itself is embedded in world's economic system). Co-evolution means that the units of evolution are no longer individual components, but rather networks capable of self-organising configurations (Zeleny, 1996).

Up till the present, the relationship between energy and development or structuring of economies has been analysed in a quite straightforward way, i.e. either under the EKC hypothesis, or under this approach that admits the presence of both tendencies, increasing energy efficiency and increasing dissipation of energy. However, due to the inherent characteristics of economic systems as complex adaptive systems, discussed above, it is difficult to describe the exosomatic energy metabolism of economies by adopting traditional approaches. Rather, it seems that non-linear dynamic techniques allow us to observe patterns of temporal behaviour and intermittent or step-wise changes in the set of considered variables when analysing the evolution of economic systems over time.

That is, economic systems might stay in a stable phase, in which the parameters of the dynamic equilibrium of their energy budget move around attractor points. These stable phases can be followed by radical changes in the technological paradigm and in the industrial structure (i.e. genotypic change). This can be seen as the movement to a different attractor point, which provides stability to the dynamic equilibrium, but in a different area of the viability domain. The evolution of societies, or development, could be described as going from one attractor point to another, or using Schumpeter's words (1949: 66), "carrying out new combinations", meaning structural and institutional changes.

As Haken and Knyazeva (2000) note, there is a definite set of evolutionary structures-attractors that are available and feasible for implementation by systems, but not every state is possible. For them (2000: 62), "the spectra of evolutionary structure-attractors are determined exclusively by the own properties of a corresponding complex system".

One way of analysing the existence of this discontinuity is by means of a phase diagram. This methodology has been used in the case of CO_2 emissions (Unruh and Moomaw, 1998), and in the case of energy intensity (De Bruyn, 1999). The phase diagrams are intended to show whether the development of certain variables over time are regular or irregular. They are also useful to find if there are or not attractor points. If so, we can check how persistent are those attractors as well as the magnitude of the fluctuations around them (Unruh and Moomaw, 1998). A useful approach, as the authors said, is a time-evolving space in which we compare the evolution of the variable (i.e. energy intensity) in the previous year (y-axis) with that of the current year (x-axis). This representation allows us to see whether we are facing a 'punctuated equilibrium' behaviour or not. If we are, then we will see how the variable concentrates around certain attractors. If not, the evolution of the variable will be different, showing a more or less straight line. As the results from de Bruyn (1999) indicate, several developed economies seem to show attractor points for energy intensity. This means that the process of development is step-wise, and therefore, we should focus future empirical research on identifying the attractor points and the causes of the flips between them.

Despite the power of punctuated equilibrium as an explanation of evolution, Gould and Eldredge (1993: 225) warn us that "punctuated equilibrium is a claim about relative frequency, not exclusivity". That is, it is not a deterministic hypothesis, rather it has more to do with historical regularities.

4.4. Conclusion

The use of intensive variables, such as energy intensity, is certainly useful, for example, to choose between processes. However, this analysis is not sufficient to show whether their evolution is continuous or not. Moreover, it is also not relevant from an environmental point of view, because if we are interested in the metabolism of the society, we have to look at the extensive variables that reflect behaviour of the total throughput. It is when looking at these kind of variables (mixing extensive and intensive) that we have an overview of the real throughput of the economy in relation to its possible environmental impact.

The existence of feedback between processes occurring at different hierarchical levels in complex adaptive systems implies that we cannot extrapolate results from one level to the other in a simple way. Therefore, we need different tools to represent the non-linear behaviour of the variables considered. Paraphrasing Sun (1999), we can say that the EKC is only a reflection of *our perception of* the past development of the energy intensity, and it is not a guide that tell us when a country is improving or not in environmental issues. Moreover, we can decrease energy intensity in whatever stage of development (we do not have to wait to reach some wealth level) if we are willing to change the parameters determining the stability of the dynamic energy budget.

This implies that we cannot just wait for economic development to solve, by default, all of our environmental problems. On the contrary, structural and institutional changes have to be sought in order to avoid both the re-materialisation phases and the repetition of the same mistakes (or trends) by developing countries (getting into attractor points characterised by larger energy consumption).

As we have seen, applying the insights of complex-systems theory, evolutionary economics and far from equilibrium thermodynamics proves to be more suitable for describing the exosomatic energy metabolism of societies. When doing so, two major tendencies have been identified. One is the increase in energy efficiency of processes. The other is an increase in the overall dissipation of energy as long as the system increases its organisation and structuring, which is as long as it develops. These two characteristics are also found in technological development, which is more efficient in single processes, but that induces a further dissipation of energy (new technologies encourage new activities, a fact that might outweigh the efficiency gains). This latter fact is called the Jevons' paradox[41].

The fact that economies show non-linear behaviour in key variables and step-wise development makes the use of the 'punctuated equilibrium' hypothesis useful, since it allows one to represent the multiple meta-stable attractors that are available for economic systems when admitting the openness of future. This latter fact asks for a new kind of empiricism and for a new epistemology of complex systems.

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[41] The Jevons paradox (Jevons, 1990, another scholar with the same surname as W.S. Jevons), which is also called 'rebound effect', or the 'Khazzoom-Brookes' postulate, states that an increase in efficiency in using a resource leads, in the long term, to an increased use of that resource rather than to a reduction. In the case of energy, it implies that a promotion of energy efficiency at the micro-level (individual economic agents) might increase energy consumption at the macro-level (whole society) (Herring, 1999). That is, increasing the efficiency of a process only implies improvements in intensive variables. This will lead to effective savings in resources, *only if* the system *does not adjust* to this imposed change, by evolving and adapting over time. Increases in efficiency can be used either to lower the stress on ecosystems (producing the same goods and services with fewer resources) or to produce more goods and services, maintaining or even increasing the same level of stress (Giampietro and Mayumi, 2000). The latter solution is typical of human systems. Therefore, we can expect that in response to increases in efficiency, humans will increase their level of activity or even introduce new activities that before could not be afforded. The conclusion is that we can be more energy efficient but still consume more energy!

5. EPISTEMOLOGY OF COMPLEX SYSTEMS, EMPIRICISM AND THE ROLE OF SCIENCE

5.1. Introduction

As we have seen from previous chapters, the analysis of complex systems is rather difficult and implies that we can no longer apply 'normal' procedures of analysis. This is why Section 5.2. presents an epistemology for complex systems. After arguing for its necessity, it presents post-normal science, which implies a new role for empiricism and for knowledge in policy recommendations. The necessity for methodological pluralism in opposition to reductionism is also stressed. Later, Section 5.3 deals with what the author thinks should be the way ahead for analysing complex systems; that is, a particular approach to empiricism which will emphasise a specific role for science, and which is better fitted to apply in practice the predicaments of post-normal science. Finally, a conclusion summarises the relevant points.

5.2. Epistemology of complex systems

After describing complex systems and presenting human systems as an example of these, this section presents a new epistemology necessary to deal with them, the so-called 'post-normal' science. Later, it finishes by advocating a need for methodological pluralism or, as Otto Neurath (1944) said some time ago, an orchestration of sciences.

5.2.1. The need for a new epistemology

The main characteristics of the new environmental problems are that they are global (depletion of the ozone layer, enhancement of the greenhouse effect, deforestation or loss of biodiversity) as well as that their time frame is the long term. Thus, in order to take decisions we have to assess the future; we have to state now how we want the future to be; we have to define what we understand by sustainability. Moreover, these problems are characterised by the point that facts are uncertain, there are values in dispute, the stakes are high and decisions needed are urgent (Funtowicz and Ravetz, 1991). They are, in sum, complex.

All of these characteristics of complex systems made Faber and Proops (1998) argue that the normal 'human condition' is that of pure ignorance, not even uncertainty. Dalmazzone (1999: 23) puts it a different way when she says that "inherent randomness in the variability of a natural resource, a population or an ecosystem, makes the resulting uncertainty irreducible *even in principle* (my emphasis)". Both uncertainty and ignorance are important for the generation of novelty, not only because of the unknown results, but also because of the stimulus they pose for human invention (Faber and Proops, 1998). Small influences cannot be neglected anymore, as chaos theory shows (Lorenz, 1963).

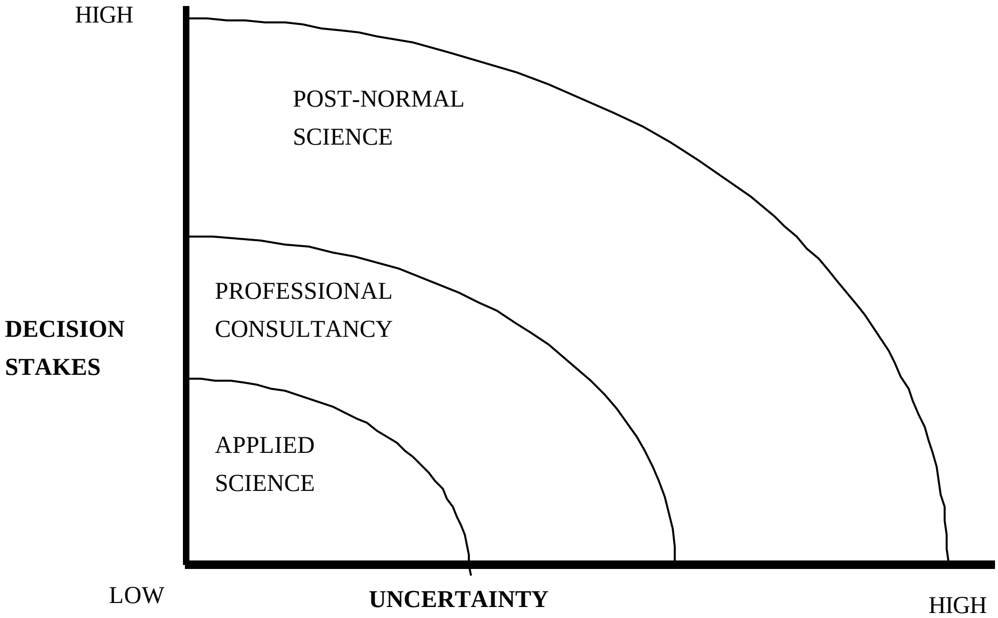
In this context, dominated by uncertainty and ignorance (we do not know what we do not know), a new approach to tackle these problems is needed. This approach has been called 'poststructural' or 'post-modern' (Denzin, 1994), 'civic science' (O'Riordan, 1996), or 'post-normal science' (Funtowicz and Ravetz, 1991).

5.2.2. Post-normal science

In this approach it is not said that present scientific knowledge is no longer valid or applicable, but rather, that there exist some emergent problems characterised by complexity and uncertainty in which 'normal' science cannot be used with the traditional methods[42].

[42] The sequence of 'problem $\rightarrow$ science $\rightarrow$ technique $\rightarrow$ solution' (Faber and Proops, 1998).

Figure 4: Post-normal Science



Source: Funtowicz and Ravetz 1991.

In Figure 4 we have the classical representation made by Funtowicz and Ravetz on the use of knowledge and science. As long as the uncertainty involved and the stakes are low, applied science of the 'normal' sort can be used. But when both characteristics are increased, we have to go to professional consultancy (i.e. experts). Finally, when even professional consultancy cannot deal with the high uncertainty, 'post-normal' science enters into the scene. This is our case here with the issue of complex economic systems.

In post-normal science it is admitted that objective reality can never be captured and that research is influenced by values of the researcher and, therefore, there is no value-free science (Denzin and Lincoln, 1994; Prigogine and Stengers, 1984). With this background, policy-making becomes a multidimensional and multifaceted process (Rist, 1994) in which research is only one source of knowledge among others (such as common sense, beliefs, etc.) that seek to influence the final result.

In post-normal science, research and knowledge do not have the intention of providing the policy-makers with a solution to the problem and therefore avoiding them taking the political decision, and legitimating all of their acts. Rather, the idea is to create a contextual understanding about the issue (Rist, 1994) in such a way that we keep informed all the actors involved in the process of decision-making, but let them reach a satisfactory compromise solution. This compromise solution will not have the aim of being a reflection of 'truth', but it will be a socially constructed view of reality (Clark et al., 1995), an agreed understanding of both the problem and the ways of tackling it.

As Kay et al. (1999: 737) said, "The program of post-normal science is to provide a basis for the understanding necessary to unravel complexity (emergence, irreducible uncertainty, internal causality), so that we may successfully anticipate, when possible, and adapt, when appropriate or necessary, to changes in the self-organizing systems of which we are an integrated and dependent part".

Post-normal science is thus about assuming that in both science and the process of decision-making there exist value judgements. It is proposed, therefore, that we have to guarantee the quality of the process of decision-making rather than the final result (because there is no objective truth to find) (Funtowicz and Ravetz, 1994). To do that, we should shift from a result-oriented or substantive rationality (e.g. the relevant issue for neo-classical economics), to a new procedural rationality (Simon, 1983), in which the process of knowledge generation is the relevant issue. The important thing is to guarantee the quality of the process of decision-making by including the relevant agents in the process, those taking decisions and those affected by them, that is, by improving transparency. Thus, procedural rationality would imply an extension of the peer review community to people from other disciplines and to people affected by the issue. The task would be to manage the uncertainty that characterises every field, to get the highest quality information we can achieve (Funtowicz and Ravetz, 1994).

The extension of the peer community is seen by Martinez-Alier et al. (1998) as crucial in order to maintain the quality of the process of problem resolution when dealing with reflexive complex systems. Here, quality implies values, but explicit values that become part of the dialogue. But it also means transparency in the whole process, including in the way we use the mathematical models in our analysis (Munda, 2000), stating beforehand all of the axioms and hypotheses we are using.

5.2.3 Methodological pluralism

When we are dealing with complex systems that operate in different parallel hierarchical levels, there is no single explanation. Rather, "the existence of contrasting 'correct' scientific assessments is unavoidable" (Munda, 2000: 5). That means that we need *parallel non-equivalent descriptions* of the same phenomenon to comprehend it sufficiently. Therefore, even ecological rationality alone (e.g. when using the concept of carrying capacity to human beings), is not the best way of dealing with complex environmental systems. Instead, the idea of an integrative holism[43] is more suitable to tackle the description and understanding of complex systems. Post-normal science, with its multiple understandings and interpretations of the same facts, also asks for methodological pluralism.

Moreover, as Prigogine and Stengers (1984) said, every description implies that we have to choose the measurement device (the boundaries of the system, the properties to be analysed, the single unit of analysis, and so on). This leads to the fact that we can represent a system in multiple irreducible ways, each of them related to the specific set of parameters

[43] Holism here is not understood as opposite to reductionism, but comprehending all kind of possible explanations in a constructive and co-operative (i.e. non-exclusive, or non-competitive) way; that is, in Norton's way (1991).

and operators we are using for the representation, depending also on who is analysing the systems. Thus we can no longer talk about 'objective' descriptions. Rather, they depend on the choices of the researchers.

Therefore, both the complexity of the system analysed, and the inherent subjectivism in its description and understanding, advocate for the above non-equivalent descriptions of the system in order to gain robustness. That can be done by using the insights of different disciplines, common sense and even fairy tales. This is what has been called methodological pluralism (Norgaard, 1989), or 'consilience' (Wilson, 1998); this is the application of Otto Neurath's (1944) idea of the dialectical unity or the orchestration of sciences (as cited in Martinez-Alier, 1987: 207), and it is at the base of the concept of post-normal science, which also includes lay knowledge, not accounted for by Neurath. This is why biophysical or ecological economics, as a post-normal science, advocates the use of the insights of different disciplines, as it is being done here.

5.3. Empiricism and complexity

Post-normal science, as described above, represents that we have to change the way we understand the analysis of complex systems. Due to their associated novelty, non-linear behaviour, and so on, it is rather difficult to make prospective analysis based on extrapolations. A phenomenological approach, as argued below, seems better suited to deal with those systems.

5.3.1. Ecological economics and empiricism

Ecological economics, unlike neo-classical environmental economics, focuses on the evolution of economies, on the process of *becoming* instead of that of being, on structural change, and the emergence of novelty (in the form of technological change, for example), all features shown by complex adaptive systems such as economic systems. The presence of novelty, the feedback mechanisms between the different levels of the hierarchy, and their anticipation, ensure that uncertainty is always present when dealing with these systems. Therefore, tackling complexity means a different role for empirical analysis and for science in general, something ecological economics has been doing since its origins.

5.3.2. Empirical analysis under complexity

As noted by Ramsay (1998), empiricism is based on the idea that knowledge of the world is generated by experience rather than by reason. However, in empirical analysis there are two main branches, the positivist approach, and the phenomenological (or interpretivist) approach.

The positivist approach tries to use the 'scientific method' by deducing theories as a result of formulating and testing hypotheses based on statistical data analysis. It formulates hypotheses on cause-effect relationships and tests them. If they pass the tests, this is the basis for a future generally applicable law generated by induction. This approach assumes that the subject of the study, i.e. the functional relations that define the relationships between the variables describing the system, are uniform and unchanging. Under these assumptions, the view on empiricism is partial, as shown by several authors. For example, Heckman (2001: 3), notes, "empirical research is intrinsically an inductive activity, building up generalizations from data, and using data to test competing models, to evaluate policies and to forecast the effects of new policies or modifications of existing policies".

The phenomenological approach, on the other hand, takes a different view of the subject under analysis. It acknowledges that when dealing with economic systems, these have the intrinsic characteristic of changing and evolving over time, of 'becoming', due to external factors (i.e. shocks) or to internal causes, such as changes in preferences, technologies, or institutions (i.e. genotypical evolution as explained in Section 2.2). This fact makes them impossible to be considered as uniform and unchanging, so, in order to explain them, we have first to understand them. An historical approach is therefore needed. This implies that instead of inducing theory from the data with the help of econometrics, under this alternative approach, theory is generated from the collected data (Ramsay, 1998) in a more qualitative way. That is, by finding the regularities which reflect the emergent properties of the systems, but without the aid of econometrics, and perhaps by using non-linear techniques, such as phase diagrams[44].

To my understanding, neo-classical environmental economics defends a position favourable to the use of econometrics and thus to the positivist approach. It defends the notion that ex-post analysis can give insights about the structures of the systems, and by extrapolating them into the future, can generate an ex-ante prediction of the development of variables, which can then be used for policy. In particular, it supports an ex-post analysis for ex-ante predictions because is implicitly based on classical mechanics, where this is possible. This is so because the basic characteristics of physical systems are described by universal laws; that is, they are not subject to structural or genotypical change (i.e. gravity is stable, and so on). But this is not the case with biological systems and, in particular, with human and economic systems, where the underlying characteristics of systems (and therefore the same occurs in the case of the parameters that describe those characteristics) are *constantly* evolving, making prediction much more problematic (Faber et al., 1996, Chapter 8). So, neo-classical environmental economics would be extrapolating

[44] Following Forrester (1987) it can be said that in non-linear systems results are less able to be generalised, and therefore we might substitute theories by 'rules of thumb'.

past results into the future by assuming two things; one, that the parameters defining the system do not change in time; and two, that the functional relationship between the variables also remains stable for the period of time being predicted. For modern economic systems, however, these assumptions do not necessarily apply, since the systems are constantly evolving and becoming (i.e. technological and structural change), and therefore, if we want our representation of them to be updated, both the parameters and the functional relationships between them should evolve as well. This is not usually the case for the models in neo-classical environmental economics.

Because of the fact that ecological economics is interested in the process of becoming, it can therefore be considered as representative of the phenomenological approach. Since it deals with complexity, and complexity is characterised by irreversibility and stochasticity (Prigogine, 1987), it concludes that linear deterministic models are ineffective.

5.3.3. Recent empirical work in Ecological Economics

Most of the empirical work published in the journal *Ecological Economics* in the last five years, namely from volume 16 (January 1996) to volume 35 (December 2000), deals with complex systems in a simple way, for example by assuming constancy of the structure of agents' preferences (neglecting irreversibility or the history of processes). Some assume linearity and constancy in both the parameters and the relationships between the variables defining the systems; that is, stability of the genotypes. With this analysis, they can recommend policies based on the results of their projections, that is, based on the extrapolation of past results. The problem, however, comes when we see 'science' as seeking to 'model' the genotype so it can predict the phenotype. But, scientific data is only on the phenotype. So, if the phenotype changes, observations on phenotypes are a poor basis for modelling and prediction. This is what I think is happening with an important portion of empirical work in ecological economics, that they are not matching the technique to the problem analysed. In other words, they are not keeping updated the set of parameters and functional relationships to the changes in the genotype or the basic characteristics of the systems. They are not considering the evolution of the systems, or their process of becoming.

There is, however, another way of understanding empirical analysis in ecological economics. Casler and Blair (1997) use input-output analysis to find the structure of pollution between sectors of the economy by finding the pollution intensities. This allows the analysis of the historical causes for variations in the economy's pollution structures and it might be used to generate some policies, after understanding the present situation of the economy. Another example is that of Perrings and Walker (1997), in which they use a model of resilience and empirical analysis to explain the importance of fire in the self-organisation of semi-arid rangelands, this being seen as a vehicle of a destructive creation phase. That is, they explain the role of fire as a trigger of the shifting of the system from one meta-equilibrium to another. Proops et al. (1999) use an input-output model to assess the importance of trade for a weak sustainability indicator in an open economy. They thus use the empirical analysis to decompose the effects of savings, depletion of resources, trade and demand on the evolution of the indicator, by showing the regional and structural components. Another example is that of Jackson and Marks (1999), where the authors analyse the past distribution of consumer expenditure in the UK for a period of time, identifying some patterns of behaviour with different consequences upon the environment that can be accounted for when deriving policy. However, one of the topics in which this kind of analysis has been more successful is that of the environmental Kuznets curve, because it relates the evolution of income (and therefore of the economy) with some physical variables such as energy consumption or use of materials. Most of the papers published in different journals on that topic use ex-post analysis to make ex-ante predictions about the future, recommending economic growth as a solution for environmental problem. But, on the other hand, there are some exceptions that follow the phenomenological approach defended here, like Rothman (1998), Suri and Chapman (1998), Unruh and Moomaw (1998) or De Bruyn and Opschoor (1997).

All of these latter papers deal with an ex-post understanding of how the systems work, by trying to find statistical regularities that reflect the underlying characteristics of the systems, but without any aim of predicting the future using past parameters. Here I stress again that, in any case, the representation of reality we get under this viewpoint and with these papers is necessarily context-dependent. That is, the ex-post understanding achieved is valid for one specific period of time and one spatial scale, and is influenced by some values that help to define the set of parameters to be used in describing the structure of the system. On the contrary, the aim of these papers is to explain how the system 'got there', what were the mechanisms underlying the behaviour of some key variables, such as energy consumption, what triggered the shift from one attractor to other? This is why I think they are an example of the kind of empiricism we understand should be applied when dealing with open complex economic systems.

5.3.4. The way ahead

The criticism presented here on the use of the positivist version of empirical analysis does not mean that we cannot conduct some forecasts about the future behaviour of the variables. We can do it, provided that we are analysing the variable or the system when they are near or at, one attractor point (i.e. they are meta-stable) or when they are following a well-established trend identified historically; that is, when we are using history and our experience to generate useful information. In these cases, when the level of uncertainty decreases, prediction is possible, under certain limitations (a sudden change is always possible). However, when the system is at a bifurcation point, prediction is not possible because we might have novelty expressed either by an external shock or by internal causality[45], which will drive the system towards one attractor or other.

If we cannot use empiricism for prediction, as econometrics does, what kind of empiricism can we use? First we have to bear in mind that since stochastic processes are dominant in nature, scientific theories should be more down-to-earth, based on direct observations. Then we should use empirical analysis not to validate theories or to give the exact forecast values of the parameters in the future, but to discriminate between those theories which are consistent with reality and those which are not. We should, therefore, describe and understand instead of seeking to explain and predict, because the nature of evolutionary complex adaptive systems makes them largely unpredictable. Using the words of Dalmazzone (1999: 26), "the existence of stochastic variation in natural systems is also a source of model uncertainty. Because many forces acting on ecosystems dynamics are more or less random, relevant parameters can fluctuate in a non-deterministic way over longer or shorter periods. If the scale of observation does not match the scale of natural change, even cyclical fluctuations can be perceived as background noise that makes determination of the state of a system problematic". This problem arises because with our model we have to use a finite set of categories to encode an infinite information space, that of the ecosystem. Giampietro and Mayumi (2001) put it in the following terms: "in fact, the formal system of inference used to simulate the causal entailment among system

[45] For example, through feedback loops between the different hierarchical levels of the system. We should bear in mind that when differences in scale are too large, it is almost impossible to relate the non-equivalent information obtained from the different levels, making prediction almost impossible. This is a reflection of the unavoidable indeterminacy of the representation of these systems across scales (Mandelbrot, 1967).

qualities is not evolving in time, whereas the modelled system is 'becoming' in time. That is, the validity of an analytical tool does expire and therefore it has always to be linked to a limited duration of the simulation (smaller than the rate at which the modelled system is evolving in time). The ceteris paribus assumption expires". This is the reason why, as pointed out by Boulding (1987), the failure in our predictions is not the responsibility of human knowledge itself. Rather, it reflects an inherent property of complex systems, that of unpredictability. That is, ex-ante modelling is often not possible. We have to admit that there are no deterministic explanations (universal and a-historical) for such systems. Rather we can describe and understand these systems by finding historical and spatial regularities, and by looking at the emergence of such systems' properties.

Science applied to the decision-making process under the post-normal science framework would then be limited to assessing the consequences of the different policies, and to providing a phenomenological narrative or interpretation of how the future might unfold (Kay et al., 1999; Kay and Regier, 2000). In fact, the main contribution of science in relation to sustainability is that it explores and represents sustainability trade-offs at different levels at which the process of decision making occurs (Giampietro and Mayumi, 2001). This is part of the means of guaranteeing transparency and fairness in the process of decision-making, by promoting a continuous dialogue with stakeholders and policy makers[46]. Thus, "these narratives focus on a qualitative/quantitative understanding which describes:

- The human context for the narrative;
- The hierarchical nature of the system;
- The attractors which may be accessible to the system;

[46] Since modelling sustainability means facing uncertainty and ignorance, transparency in the process of problem structuring is crucial to determine the quality of the output (Mayumi and Giampietro, 2001).

- How the system behaves in the neighbourhood of each attractor, potentially in terms of a quantitative simulation model;
- The positive and negative feedbacks and autocatalytic loops and associated gradients which organize the system about an attractor;
- What might enable and disable these loops and hence might promote or discourage the system from being in the neighbourhood of an attractor; and
- What might be likely to precipitate flips between attractors" (Kay et al., 1999: 728).

The implication of the argument presented above is that complex adaptive systems such as economies are not computable at all. This fact leads us, when dealing with sustainability, to the issue of incommensurability of values as a key characteristic that should distinguish ecological economics from environmental economics and from other reductionist approaches (Martinez-Alier et al., 1998). That is, in every analysis of sustainability *we know* we have to face multiple values and attributes which cannot be reduced to a single unit (i.e. money, energy, or whatever). Moreover, some of them are incommensurable. Therefore, the logical consequence is that in our analysis we have to use multiple readings of the same facts, parallel non-equivalent descriptions (Mayumi and Giampietro, 2001).

Kay and Regier (2000) propose a kind of blueprint for analysing the behaviour of complex adaptive systems. For them, the first step is to identify the holons that form the system, that is, the self-organising entities of interest (in economic systems we may think of 'agents'). They acknowledge that this is a subjective process which depends on the question asked and which can only occur in the context of human values. The identification of the holons allows us to define the system under analysis (that to which the holons belong). Once that is done, the next step is to explore its self-organising behaviour;

that is, we have to analyse the multiple possible attractors (i.e. the different economic development paths), and the causes that drive the shifts between them, leading to a step-wise re-organisation (i.e. technological and structural change). “It is precisely these issues (that is describing the “flip” from one attractor to another through accounting for how environmental influences (context), acting at different spatial and temporal scales, disable one feedback system while enabling another) that we must understand, if we are to comprehend the relationships between human activities and changes in the integrity of ecological systems” (Kay and Regier, 2000)[47]. This analysis of the different attractors available to the system allows us to account for the trade-offs involved between the different attractors, and to incorporate this information in the process of decision making. For instance, in economic terms, we can assess the trade-offs associated with two different development strategies (i.e. the attractors) such as ‘imports substitution industrialisation’ and ‘export oriented industrialisation’ as used by several developing countries. We might also think about economic growth based on exporting raw materials and resources versus growth based on industrial products or services (Ecuador vs. Spain).

Faber and Proops (1998) note that flexibility is the appropriate response if we know the system is going to face some changes in its nature, which we cannot fully anticipate. This flexibility can be achieved by enhancing the diversity in the system. The more diversity, the more responses we will have to changing conditions, with more chances that one, or some of these responses, will be successful and will bring the system ahead in its development. That is, diversity increases the adaptive capacity of systems. In economic terms, a diversified economy developing slowly may be seen as better adapted than an economy largely based on one activity but which develops faster, since the latter will also

[47] For the authors, “ecological integrity is about three facets of the self-organization of ecological systems: a) current well being, b) resiliency, c) capacity to develop, regenerate and evolve” (Kay and Regier, 2000).

be more fragile to sudden changes in the boundary conditions. Therefore, sustainability would mean maintaining the integrity, as defined above, of the societal-ecological system (Kay and Regier, 2000); that is, maintaining the self-organising processes and structures. This implies that we have to make decisions about which attractors should be encouraged. Therefore, due to the impossibility of generating reliable forecasts about how the complex system will unfold in the future, soft management is necessary. This kind of approach is also called 'adaptive management'[48] in opposition to 'anticipatory management', in which prediction of the possible outcomes is the base. As Kay and Regier (2000) said, these approaches are not substitutes, but rather complementary. This fact means that we have to improve our understanding of complex systems in order to help unravel complexity, by anticipating, when possible, or adapting, when necessary, to the changes of the system or the boundary conditions.

When dealing with these issues related to management and sustainability, Holling (1996) distinguishes between 'engineering resilience' and 'ecological resilience'. The first focuses on stability near an equilibrium steady state, where the speed of returning to the equilibrium is used to measure that property. This concept therefore leads to a focus on maintaining the efficiency of processes, and is a basis of neo-classical economic theory. The latter, however, focuses on the "disturbance that can be absorbed before the system changes its structure by changing the variables and processes that control behavior" (Holling, 1996: 33). Holling, following Walker et al. (1969), called this 'ecological resilience'. This concept is related to the soft management mentioned above, because it takes into account that complex systems (i.e. ecosystems) are always involved in a process of continuous becoming, which is why ecological resilience focuses on maintaining the

[48] For Holling (1996: 41), key features of adaptive management are: "flexible, diverse, and redundant regulation, early signals of error built into incentives for corrective action, and continuous experimental probing of the changes in the external world".

existence of the functions. The distinction made here by Holling stresses again the inherent trade-off between efficiency and adaptability when dealing with sustainability.

In conclusion, in complex systems prediction is not possible not only because the parameters defining the relationships between variables change (phenotypic evolution), but also because the functional relation itself may also change (genotypic evolution), since they are involved in the process of becoming of the system, generating therefore more novelty. In different words, "economic systems must be understood as evolving processes. It is important to consider *not only* the system's dynamics, *but also* how the dynamics themselves change over time" (Dalmazzone, 1999: 49, my emphasis). Consequently, a predictive use of an ecological econometrics is not possible. Rather, the phenomenological approach presented here seems to us more suitable in the framework of ecological economics, to deal with the evolution of complex systems such as economies, involving novelty in the form of structural change. In the end, history *does count*.

5.4. Conclusion

Section 5.2 dealt with the epistemology of complex systems. It was argued that the characteristics of complex problems and systems demand a new paradigm that accounts for the increased recognition of uncertainty and ignorance. Post-normal science was said to be that paradigm, since it incorporates value judgements and its goal is no longer finding the truth, but providing the stakeholders with an understanding and narrative of complex systems of a high quality, to allow them to reach a 'compromise satisfactory' solution. It was also argued that in this context, the role of empirical analysis changes. Moreover, the existence of multiple readings of the same phenomena (due to both the subjectivism inherent in any form of research, and because of the different values involved), implies that complex systems can only be dealt with by using the insights of a range of different disciplines. This idea implies an orchestration, or unity, of sciences, a methodological pluralism.

Finally, Section 5.3 dealt with an argument in favour of a phenomenological approach to empiricism. This approach allows us better to understand the development of complex systems such as economies, by focusing on past trends and by finding historical regularities that may help us to guess how economic systems will unfold in future. This approach is not deterministic, and since it gives many interpretations of past facts, it can be used to implement post-normal science, public participation and dialogue between stakeholders, in order to agree a common description of facts and to design proper policies to deal with complexity. Policies must be addressed to enhance the diversity, and therefore adaptability, of economic systems.

6. CONCLUSION AND FUTURE RESEARCH

6.1. Conclusion

It has been pointed out throughout this dissertation that economies are complex adaptive systems; that is, they are composed of a large and increasing number of components and of relationships between them. Economies are also teleological systems, but in a different way to non-human systems, which have only the telos of self-maintenance and development of the systems. Economies incorporate new tele, those of the human beings belonging to the system, and they are capable of incorporating the guessed consequences of their fulfilment into the present decisions and definitions of new tele; they are thus anticipatory. They also learn from mistakes and from present developments, and they react, by changing both the actions undertaken and the tele defined; they are thus self-reflexive. They also have the ability to adapt to new changing boundary conditions (a property also shown by non-human systems), but they may *consciously* alter the boundary conditions. This is why the economy, as a human system, can be understood as a complex, adaptive, *self-reflexive*, and *self-aware* system.

The increased complexity of economies, their nested hierarchical nature, and the fact that they show adaptive and evolutionary behaviour, gives rise to two parallel outcomes. One is the non-linear, even chaotic, behaviour that these systems show. This is a short-run process that involves a given structure and the difficulty in comprehending it by using the traditional methods of analysis. The other is the emergence of novelty, which is long-run, and involves changes in the structure. An alternative way of presenting this is by using the concepts of phenotypic evolution (different realisations of potentialities, which are susceptible of prediction) and genotypic evolution (emergence of new institutions or techniques, which by definition are unpredictable; that is, new potentialities). This includes changes in the parameters defining the structure of the system. Therefore, when choosing the parameters to be used in our model of the system, we should bear in mind that the degree of relevance of the set of parameters considered as useful for the model can change over time, since they are also context-dependent. This fact brings uncertainty on to the scene, in the form of the selection of the set of parameters mentioned above. That is, who decides the set of parameters that are going to describe the structure of the system?

However, this chaotic behaviour gives rise to new ordered structures within systems that can be approached from complex systems theory. But as was pointed out above, even though the future is open, not every arbitrary evolutionary path is feasible in a system. This is because history counts and once a path is taken, some others are closed forever; this is called ‘path dependency’ and is a key characteristic of complex systems. This reduces the number of possible attractors, and it induces, again, non-linear behaviour in the development of the system. It also reflects irreversibility.

As we have seen, all of these facts make normal science less capable of describing the behaviour of these systems. This is why post-normal science and phenomenological empiricism have been defended here as better suited for analysing complex systems such as economies. The focus should change, therefore, from analysing final states to analysing processes; that is, to analyse what triggers changes in economic systems attractors, what induces technological or structural change, and what are the consequences of the development paths adopted upon the environment. This can be done by analysing the exosomatic energy metabolism of economies.

6.2. Future research

So far, the intention here has been to offer a theoretical background of this problem from the complex-systems perspective, and focusing on thermodynamics terms and concepts. There is, however, a lot to do from an empirical point of view. The research I am planning to do next is an application of the concepts, explanations, and blueprint for research presented here, on two different cases. One will be an analysis of certain key economies (from both the developed and developing world) from a historical point of view, so that certain attractors and tendencies can be identified in the process of development. The other will be a cross country comparison in a certain year, in order to identify in which stage of development those countries are (using the different trends identified in the previous step). Moreover, I shall try to include in the analysis biomass, as discussed by Haberl (2000a, 2000b).

Therefore, from a practical point of view, when looking at some key economies, I will try to identify the different attractors over time. Once that is done, the next step would be to identify what induced the flip between them; that is, to analyse the very process of self-organisation of the economies. It is believed that some patterns could be found between different economies, which would be very useful when making the cross-country comparison, in order to generate some useful information about how the future may unfold for different countries. This approach, however, is not deterministic, as was Odum's (the maximum empower principle). Rather, it will be based on some spatial and temporal regularities that might appear in the exosomatic energy metabolism of economies.

I am aware, however, that this research programme could be expanded to include structural decomposition analysis, more analysis on the relationship with the environment, in relation also to the behaviour of human beings (which affects energy consumption), and with the process of policy formulation, involving the participation of several actors in the context of post-normal science. However, all of these approaches to the exosomatic energy metabolism of societies are left for future research and/or for other people to deal with.

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