COMPLEX SYSTEMS AND EXOSOMATIC ENERGY METABOLISM OF HUMAN SOCIETIES

Jesus Ramos Martin

November 2005
Doctoral dissertation for the Programme in Environmental Sciences
(Ecological Economics and Environmental Management)
Universitat Autònoma de Barcelona

Director: Dr. Mario Giampietro
Head of the Technological Assessment Unit at the Istituto Nazionale di Ricerca per gli Alimenti e la Nutrizione – INRAN, Roma, Italy;
Visiting professor at Universitat Autònoma de Barcelona,1998-2000

Director: Dr. Joan Martinez Alier
Departament d'Economia i d'Història Econòmica
Universitat Autònoma de Barcelona,
Bellaterra (Barcelona – Spain)

Universitat Autònoma de Barcelona

COMPLEX SYSTEMS AND EXOSOMATIC ENERGY METABOLISM OF HUMAN SOCIETIES

Jesus Ramos Martin

November 2005

Doctoral dissertation for the Programme in
Environmental Sciences
(Ecological Economics and
Environmental Management)
Universitat Autònoma de Barcelona

Director: Dr. Mario Giampietro
Head of the Technological Assessment Unit
Istituto Nazionale di Ricerca per gli Alimenti e la Nutrizione
– INRAN, Roma, Italy; Visiting Professor at
Universitat Autònoma de Barcelona, 1998-2000

Director: Dr. Joan Martínez Alier
Departament d'Economia i d'Història Econòmica
Universitat Autònoma de Barcelona

Bellaterra (Barcelona – Spain)

Quotation

"*I shall argue that the postulates of the [neo]classical theory are applicable to a special case only and not to the general case, the situation which it assumes being a limiting point of the possible positions of equilibrium. Moreover, the characteristics of the special case assumed by the [neo]classical theory happen not to be those of the economic society in which we actually live, with the result that its teaching is misleading and disastrous if we attempt to apply it to the facts of experience*". Keynes, J.M. (1936), The General Theory of Employment, Interest, and Money London: Macmillan for the Royal Economic Society – opening paragraph

"*Analytical work begins with material provided by our vision of things, and this vision is ideological almost by definition*" Schumpeter, J.A. (1954) History of Economic Analysis, George Allen & Unwin, London - p. 42

DEDICATION

Dedicado a mis padres, Amalia y Antonio,

Con todo mi profundo amor y respeto.

Dignidad y amor.

(Andalusia, with fields full of grain,

I have to see you again and again,

Spanish Caravan, The Doors)

PREFACE

This Preface is to briefly explain why I am presenting this Thesis.

Being the 5th son (out of 6) of an ex-peasant steel industry worker, and the best economist I have ever seen, my mother, a traditional housewife who was amazingly able to make ends meet with only just one salary, living in a flat of 42 m^2 in the outskirts of Barcelona in a impoverished period, one can understand why when I was in the 6th grade in primary school and my teacher asked me what I wanted to be when I grew up I responded “an economist”.

The set-up was further constructed with stimulating debates about economic development that my elder brother, who at one point began studying economics, brought to our working class home. With this background, he became Marxist, and I soon decided to follow his path and study, as a consequence, economics, to fight against the many injustices, that was the ideal.

At the same time, my high school philosophy teacher, Pere de la Fuente, introduced me to epistemology, which conduced my interest even more and gave birth a passion that has been with me since.

Another impact was when I was at the University. Lluís Barbé, a lecturer of Economic Thought, said, “we will throw you in a pool and you are the ones who have to learn how to swim”, in other words it was *sink or swim*. Therefore, I decided to embark on a self-teaching road. In hindsight, I realise that the message was about how learning needs to be active and through discovery because only then does it become meaningful. Yet, at that moment, this statement was untimely. Up until that point the courses that I had taken, made me feel as if I had been deluded. I could not believe how far what we were learning was from reality. However, I was also lucky enough to have had lecturers such as Miren Etxezarreta (who introduced me to Development economics) and Giuseppe Munda (to Ecological economics and multi-criteria analysis). These courses gave me the opportunity to read Joan Martinez Alier’s book Ecological Economics, which had a pivotal effect in my life, in all senses and not only from an academic point of view. After finishing my degree and while still at the military service, I enrolled in the brand new PhD Programme in Environmental Sciences at UAB. This Thesis is the result of that. But “that” here does not mean the enrolment in the programme, but my whole personal history that I have just outlined. At times I wonder if just one of the elements that I mentioned here had not happened, who knows which bifurcation I would have taken in my life.

ACKNOWLEDGEMENTS

First I would like to thank all my family, Papá, Mamá, Paco, Toni, Mari, Puri, Susana, David, Oscar, Eva, Víctor and the rest, for helping me all the time and giving me all their love. I love you too.

This piece of work is not only the result of my research at one single place, Universitat Autònoma de Barcelona, Keele University, or Istituto Nazionale di Ricerca per gli Alimenti e la Nutrizione, but also of my acquired knowledge since I started studying ecological economics and environmental issues in general. I am indebted to Joan Martínez-Alier and Giuseppe Munda for introducing me to this world, for taking care of me, and for being my friends. I am grateful also to all the different lecturers during my graduate studies in Barcelona, like Joseph Vogel, Martin O'Connor, Mathias Ruth, José Manuel Naredo, Mario Giampietro, and many others. I owe Mario Giampietro and Kozo Mayumi (whose company I particularly enjoyed in Barcelona, Rome, and Penn State) for cultivating my distinct interest in the evolution of economies, the use of thermodynamic analysis and complex systems analysis to study them. From my years in Barcelona I want to thank my classmates as well. Particularly, I would like to thank Fran, Patrícia, Fander (for opening the door to Ecuador), Roldán, Sergio, David (for the mutual understanding), Tiziano, Marcelo, Ignasi (for the hidden sense of humour) and some colleagues like Paula (for the ability to be surprised), Daniela (for coping with sharing the office with me), Eduardo (for being there always), Begüm (for the trust) and Citlalic.

I acknowledge the opportunity to meet the 'gurus' of energy analysis (H.T. Odum, Robert Ulanowicz, Tim Allen, Charles Hall, Vaclav Smil, and others) that Sergio Ulgiati gave me and some friends in an international conference in Porto Venere, Italy on *Advances in Energy Studies* in 2000. That conference changed the orientation of my research to what has been the present thesis.

During my period at Keele University I have to thank many people. First I would like to thank John Proops, who was an excellent supervisor with his comments to drafts of part of this thesis and who always gave me his support. He also introduced me to some concepts relevant for ecological economics, like those of teleology, autopoiesis or self-organisation, which have changed forever my vision on

economic systems and on epistemology, knowledge, and science. I have greatly enjoyed the seminars organised by Proops with Steve, Eduardo, and Luis, with who we had very interesting, although sometimes tricky, conversations on ecological economics that now form the background of my viewpoint on this topic.

On the personal side, in my days in Keele I have been blessed in meeting really interesting and influential people. To mention only some of them, my flatmates Yoshi (with whom the 'late at night' conversations on international politics and economics around a cup of tea and a copy of *The Economist* have been enjoyable and useful), Mustafa, Leone, Antonios, and the rest of my friends, Swee Gim, Junko, Kazu, Dianne, Hernán, José Luis, Jon, and Annamaria.

During my stay in Rome, working with Mario Giampietro, I actually learned too many things. This overload almost brought me to having permanent brain damage through his continuous epistemological breakdowns. Nonetheless, the stay was very fruitful from a learning point of view. Moreover, working with Mario was continuous fun, so thanks Mario for making me smile and laugh so often. A word also for Sandra, and particularly Olga, and Sofía, what a great family! I also have to thank Stefania from INRAN, and some friends such as Pedro, Magdalena, Dina and Chiara. All made my stay more enjoyable.

From Santa Coloma I thank Imarchi, Arthur, Marcos, Abel, Ana and the rest of CD Puig Castellar for always being there to take care of me.

Apologies for those I forgot to mention. As Placebo said, "without you I am nothing".

John Coltrane, Bill Evans, Miles Davis, Chet Baker, Jimmy Smith, Pearl Jam, The Smiths, Lauryn Hill, Enrique Morente, Manolo García, Manu Chao, Led Zeppelin, Triana, Björk, Metallica, Control Machete, La Mala, Beastie Boys and others made everything a lot easier creating in my mind the necessary environment for research.

Finally, thanks to Ingrid for sharing her life with me.

Tolerance and universalism for an united world.

ABSTRACT

The present dissertation deals with the issue of the importance of energy flows in driving the evolution of economies on time, from less to more organised structures. From less to more complex systems.

Economic development is a process, not a final goal 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 Thesis comprises both a theoretical and an empirical part.

The first one consists of Chapters 1 to 5, which are mainly of theoretical content. This is the part dealing with the relationship between economic theory, complex systems theory and thermodynamics.

Chapter 1 briefly presents the relationships between complexity, energy, and economics that are developed with more detail throughout the Thesis.

Chapter 2 presents energy analysis under the framework of the different schools of economic thought. Stress is given to the revival of the classical interest in production, as we can find among those who call themselves "ecological economists". In fact, one of their major advances of this school has been the incorporation of the insights of thermodynamics to economic analysis. They have mainly used the Second Law of thermodynamics and its major result, the irreversibility of processes, and therefore the importance of History.

Chapter 3 deals with the issue of complexity and self-organisation.

Chapter 4 uses the concepts developed in previous chapters to characterise human systems (i.e. economies) as open complex systems far from (thermodynamic) equilibrium. Their major characteristics are presented, focusing on their hierarchical structure and their functioning via autocatalytic loops that link each level of the system.

The evolution of economic systems is analysed in Chapter 5, both from a traditional economic perspective and from an evolutionary one, in which 'history counts'. The explanation is based on thermodynamic analysis, in the sense than the relation between energy dissipation and development is the focus.

The second part consists of 4 published papers in international refereed journals (Chapters 6 to 9) and one paper to be submitted soon after it is presented at an international conference in July 2005 (Chapter 10).

The first of the papers (Chapter 6) is still theoretical, dealing with the issue of empiricism in the field of ecological economics to analyse the evolution of societies.

The second one (Chapter 7) presents the first application I made back in 2001 of the MSIASM methodology, to analyse the evolution of the Spanish economy over time, and helps the reader to be familiar with the methodology.

The third paper (Chapter 8) represents a step forward in the theoretical development of the approach used, and helps in fully understanding the potentialities of such methodology, by introducing key concepts such as 'mosaic effect' or 'impredicative loop analysis', that help developing better narratives for using when analysing sustainability.

The fourth paper (Chapter 9) presents another application of MSIASM, this time for understanding its possibilities to help explain past trajectories of development and to help elaborate scenarios of future development.

The fifth paper (Chapter 10) is the last application of the methodology. The paper represents an analysis of the economic development of a major actor nowadays, China, by applying MSIASM to try to get different answers to the usual questions regarding the relationship between economic development and energy dissipation.

RESUMEN

La presente Tesis se centra en la importancia que tienen los flujos de energía para explicar la evolución de las economías en el tiempo, de menor a mayor organización, de menor a mayor complejidad.

El desarrollo económico es un proceso, no un objetivo final para ninguna sociedad. Está relacionado con la evolución de los sistemas humanos así como con su interacción con el entorno. Por lo tanto, se necesita un enfoque biofísico para poder entender mejor el proceso de desarrollo. Por ello esta tesis incluye una primera parte teórica y una parte empírica.

La primera parte consiste en 5 capítulos, principalmente de contenido teórico. Esta parte trata la relación entre la teoría económica, la teoría de los sistemas complejos y la termodinámica.

El Capítulo 1 presenta de forma breve la relación entre complejidad, energía y economía, que son tratadas con más detalle en el resto de la tesis.

El Capítulo 2 presenta el análisis energético bajo el enfoque de las diferentes escuelas de pensamiento económico. Se da particular énfasis al retorno al interés clásico en la producción, tal y como recientemente surge entre aquellos que se llaman “economistas ecológicos”. De hecho, uno de los mayores avances de éstos ha sido la incorporación de aspectos de la termodinámica al análisis económico. En particular, se habla de la importancia de la Segunda Ley de la Termodinámica y de su resultado más importante, la irreversibilidad de los procesos, que pone de manifiesto la importancia de la Historia.

El Capítulo 3 trata de forma breve los temas de complejidad y auto-organización.

El Capítulo 4 usa los conceptos desarrollados en capítulos anteriores para caracterizar a los sitemas humanos (p.e. economías) como sistemas abiertos lejos del equilibrio (termodinámico). Se presentan, a su vez, sus principales características, entre las que destacan su carácter jerárquico y su funcionamiento a través de ciclos auto-catalíticos que unen los diferentes niveles del sistema.

La evolución de los sistemas económicos es el tema del Capítulo 5, tanto desde una perspectiva económica tradicional como desde una evolutiva, en la que ‘la

historia cuenta'. La explicación se basa en el análisis termodinámico, en donde el énfasis está en la relación entre la disipación de energía y el desarrollo.

La segunda parte de la tesis consiste en 4 artículos publicados en revistas internacionales (capítulos 6 a 9), y un artículo que será enviado próximamente a una revista y que será presentado en una conferencia internacional en el verano de 2005.

El primero de los artículos (Capítulo 6) es todavía de tipo teórico, tratando el tema del empirismo en economía ecológica para analizar la evolución de las sociedades.

El Segundo (Capítulo 7) presenta la primera aplicación que hice en 2001 de la metodología MSIASM, para analizar la evolución de la economía española en el tiempo, y ayuda al lector a familiarizarse con la metodología.

El tercer artículo (Capítulo 8) vuelve a ser de carácter teórico, pero representa un avance y desarrollo teórico, y ayuda a entender las potencialidades que presenta la metodología utilizada, por medio de la inclusión de conceptos como el 'efecto mosaico' o el 'análisis de ciclos impredicativos', que ayudan a desarrollar mejor la narrativas a usar cuando analizamos temas de sustentabilidad.

El cuarto artículo (Capítulo 9) presenta otra aplicación de MSIASM. En este caso se trata de entender las posibilidades que ofrece la metodología para ayudar a explicar trayectorias pasadas de desarrollo, así como para elaborar escenarios futuros de desarrollo.

El quinto artículo (Capítulo 10) es la última aplicación, hasta el momento, de la misma metodología. El artículo representa un análisis del desarrollo económico de un actor principal en la economía mundial en la actualidad, China, para ofrecer respuestas diferentes a las típicas preguntas sobre la relación entre desarrollo y disipación de energía.

Table of Contents

List of Tables

List of figures

INTRODUCTION

I decided to study economics because of my interest in economic development, and therefore in developing countries. At the same time, I have always been fascinated by the role of energy in our society, fundamental to run all processes. Reading Georgescu-Roegen I embraced his idea of a future solar society, and reading Phillip K. Dick's famous novel *Do Androids Dream with Electric Sheep?*, later brought to the screen as *Blade Runner*, I was hit with the idea of entropy and dissipation of energy, not only as a cause of disorder, but particularly as a means for order. Later on, Mario Giampietro, also based in that reference, introduced me to the critical concept of *Replicant Knowledge*, that allowed me to better understand the 'success' of economies such as the USA, Canada, or Australia. Since reading those two masterpieces in their respective ambits, all my personal learning process has been directed to understanding the role of energy for economic development, for the development of human societies, and its relationship with the environment.

The present Thesis has the main goal of showing the interrelations between economic theory, thermodynamics, and complex systems theory, in order to help better understand the way human systems unfold. This is done not only with a presentation of theoretical aspects, but also with the application of the so-called methodology of Multi-Scale Integrated Analysis of Societal Metabolism for the analysis of some relevant economies. The application of such procedure allows seeing internal biophysical constraints working at different hierarchical levels of economic systems, and its relations with the surrounding environment.

The work presented here is the result of my research since I began my PhD courses in 1997. Why such a long period of time? Because in the meantime I had the opportunity to spend 2 years in the UK with John Proops, and 2 years in Rome with Mario Giampietro, who changed several times my vision on what I was doing. Also because while I was in Barcelona I was engaged in too many academic and non-academic activities that distracted my attention from my research, but which definitely helped me later on to clarify my own points of view on the topic.

Note on the structure of the Thesis

This Thesis has two main parts. The first one consists of Chapters 1 to 5, which are mainly of theoretical content. Part of the content has been published in two papers, one in Spanish (Ramos-Martin, J. 2004a. "La perspectiva biofísica del proceso económico: Economía Ecológica". In F. Falconi, M. Hercowitz, R. Muradian (Eds.): *Globalización y Desarrollo en América Latina.* FLACSO, Quito, Ecuador.), the other in Catalan (Ramos-Martin, J. (2004b): "La perspectiva biofísica de la relació home-natura: Economia Ecològica", in J. Valdivielso (comp.), *Les dimensions socials de la crisis ecològica*, Ed. UIB, Palma de Mallorca). This is the part dealing with the relationship between economic theory, complex systems theory and thermodynamics. This part was mainly developed during my stay at Keele University, even though it has been subject to major changes.

Chapter 1 briefly presents the relationships between complexity, energy, and economics that will be developed with more detail in the rest of this Thesis.

Chapter 2 presents energy analysis under the framework of the different schools of economic thought, stressing the fact that it has not been until recently that economists have 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 multi-discipline trying to explain the 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, and therefore the importance of History.

Chapter 3 deals with the issue of complexity and self-organisation. After presenting the theory of 'far-from-equilibrium' thermodynamics, dealing with how open systems evolve in time and develop themselves, 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 it will be shown, non-linear behaviour that is difficult to forecast. This is why a new epistemology to deal with complex systems will also be presented in Chapter 6, 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, and in which an interdisciplinary approach is better fitted to cope with those characteristics of complex systems.

The evolution of economic systems will be analysed in Chapter 5, both from a traditional economic perspective and from an evolutionary one, in which 'history counts'. The explanation will be based on thermodynamic analysis; specifically the relation between energy dissipation and development will be the focus. The issue of dematerialisation of the economy (the use of less energy and materials to provide one unit of output) will be discussed using both frameworks of analysis, in order to show the limits of using only one framework of analysis and the need of opening the debate about development to other disciplines that can provide useful, but different, explanations of the same observations. The second approach, the evolutionary one, will focus on 'history', especially 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 this kind of systems which is the fact that they show two apparently contradicting features in their evolution. One is the increasing 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.

The second part consists of 4 published papers in international refereed journals (Chapters 6 to 9) and one paper to be submitted soon after it is presented at an international conference in July 2005 (Chapter 10). Even though these five chapters represent different pieces of work, they are closely linked to each other. Therefore, I have made the effort to reduce redundancies among them. However, sometimes this proved to be a difficult task, not only for the editing of the text, but mainly for the full understanding of what was said. This is why one can still find a certain degree of redundancy between them and with some passages of the first part. This is so because I consider when introducing new concepts, or old concepts but in a new manner, redundancy is always welcomed to help clarifying them and to keep a certain degree of coherence in the discourse. This is achieved by presenting the papers not in chronological order, but in a way that allows seeing the progress in the research. I have combined the different lists of references in just one bibliography that can be found at the end of the main text.

The first of the papers (Chapter 6) is still theoretical, dealing with the issue of empiricism in the field of ecological economics to analyse the evolution of societies. The original paper is: Ramos-Martin, J. (2003a): “Empiricism in Ecological Economics: A Perspective from Complex Systems Theory", Ecological Economics Vol. 46/3 pp 387-398. There is a Spanish version of it, Ramos-Martin, J. (2003c): “Empirismo en economía ecológica: una visión desde la teoría de sistemas complejos”, *Revista de Economía Crítica.* Vol. 1: 75-93.

The second one (Chapter 7) presents the first application I made back in 2001 of the MSIASM methodology, to analyse the evolution of the Spanish economy over time, and helps the reader to be familiar with the methodology. The original paper was published in a special issue of the Journal *Population and Environment* dedicated to that methodology, and is Ramos-Martin, J. (2001): "Historical analysis of energy intensity of Spain: from a "conventional view" to an "integrated assessment", *Population and Environment*, 22: 281-313. this paper has also a Spanish version with up-to-date data, Ramos-Martin, J. (2003b): “Intensidad energética de la economía española: una perspectiva integrada”, in *Revista de Economía Industrial,* Number 351(III): 59-72. In any case, this thesis now builds on and complements my earlier work on energy intensity in Spain, published in Spanish, Ramos-Martin, J. (1999): “Breve comentario sobre la desmaterialización en el estado español”, *Ecología Política*, 18: 61-64.

The third paper (Chapter 8) was developed jointly with the one that is the basis of Chapter 9, both of them with Mario Giampietro. This paper, Giampietro, M., and Ramos-Martin, J. (2005): "Multi-scale integrated analysis of sustainability: a methodological tool to improve the quality of narratives", *International Journal of Global Environmental Issues* (in press), represents a step forward in the theoretical development of the approach used, and in fully understanding the potentialities of such methodology, by introducing key concepts such as 'mosaic effect' or 'impredicative loop analysis', that help developing better narratives for using when analysing sustainability.

The fourth paper (Chapter 9) presents another application of MSIASM, this time for understanding its possibilities to help explain past trajectories of development and to elaborate scenarios of future development. This paper was a collaboration with Mario Giampietro on the theory behind, and the applications of MSIASM, Ramos-Martin, J., and Giampietro, M. (2005): "Multi-Scale Integrated Analysis of Societal Metabolism: Learning from trajectories of development and building robust scenarios", *International Journal of Global Environmental Issues* (in press).

The fifth paper (Chapter 10) is the last recent application of MSIASM. In an attempt to provide different explanations for the high oil price, and other raw materials, in recent times, Mario Giampietro, Kozo Mayumi, and myself engaged in the analysis of the economic development of a major actor nowadays, China, by applying MSIASM to try to get different plausible answers to the usual questions. The result is the paper Ramos-Martin, J., Giampietro, M., and Mayumi, K. (2005): "Multi-scale integrated analysis of societal metabolism applied to the study of the evolution of economies: the case of China", which is still unpublished, but will be presented at the 6th International Conference of the European Society for Ecological Economics, to be held in Lisbon in June 14 – 17 2005, and which will be sent for publication to the *Journal of Industrial Ecology*.

Finally, the conclusion is dedicated to four tasks. Summarising the theoretical aspects most relevant for the analysis presented in combining economics with complex systems, and thermodynamics. Developing on the usefulness of using MSIASM for analysing sustainability, with special regard to the issue of multiple scales. Driving some conclusions for the case studies analysed in the text, particularly Spain, Viet Nam and China. And finally, grasping which may be the future direction of my research in the coming years.

As required by UAB, at the end of the dissertation there is my updated curriculum vitae.

CHAPTER 1: COMPLEXITY, ENERGY AND ECONOMICS

Economic development is a process, not a final goal 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. Throughout this piece of work sustainable development paths are understood as those which are ecologically compatible, economically viable, technically feasible, and socially acceptable. The introduction of so many variables to be accounted for makes economic systems a kind of system called *complex*. In this sense, Ulanowicz (1996) warned us that, when dealing with the evolution of systems, our focus should be upon networks of processes rather than upon the final outcome of those processes. Therefore this analysis requires an understanding of the function of human as well as natural systems and their interacting behaviours. Among human systems, our focus will be upon the evolution of economic systems, their organisation and their relationship with energy consumption over time.

Traditionally, biologists and ecologists have been dealing with natural systems, and economists analysed economic systems. This approach has some advantages (i.e. it is simpler), but also has some disadvantages. For example, as systems develop, they become more and more complex. Due to this increased complexity, the tools developed by traditional economics are not best fitted to explain the behaviour of the systems. The insights of different disciplines have to be incorporated to deal with modern complex economic systems.

One feature of modern economic systems is that their *complexity* can be related to their degree of *organisation*. That is, the more complex the system is, the more organised it is. This characteristic can be found when analysing the organisation of the system related to the throughput of energy and materials through the system. The system increases its consumption (transformation or dissipation) of energy and materials as it develops, leading to a greater organisation necessary not only to keep the system working (metabolism), but also to allow it to grow further. An advantage of using the concept of throughput in our analysis is that it can be used as a proxy for environmental degradation. Thus, the higher the throughput, the higher our impact upon the environment. Metabolism can be considered as the totality of the biochemical reactions in a living thing. It comprises the conversion of raw materials and the build up of structures in order to maintain and develop the living organism. Humans have solved this problem of provisioning collectively, leading thus to the concept of 'societal metabolism' that can be understood as the flow of energy and materials from the environment, through the society, and back to the environment in the form of waste, something that will be called later the throughput or the metabolic flow, as it will be shown. For further information about the concept of metabolism and its application in social sciences, see Fischer-Kowalski (1997) and Martinez-Alier (1987). This concept has a long history in biophysical analysis of the interaction of socio-economic system with their environment, and can be consistently found in those authors that see the socio-economic process as a process of self-organisation. Pioneering work in this direction was done, among others, by Podolinsky (1883), Jevons (1865), Ostwald (1907), Lotka (1922; 1956), White (1943, 1959), Cottrell (1955). Cottrell worked out the idea that the very definition of an energy carrier (what should be considered an energy input) depends on the definition of the energy converter (what is using the input to generate useful energy). The idea that metabolism implies an expected relation between typologies of matter and energy flows has been explored by H.T. Odum, 1971; 1983 (for studying the interaction between ecosystems and human societies); Rappaport, 1971 (for anthropological studies); Georgescu-Roegen, 1971 (for the sustainability of the economic process).

It is in this framework of analysis that the present work has to be understood. The main goals of the thesis are as follows:

i) Explain the relationship between energy and the environment for the different schools of economic thought that deal with it.
ii) Present human systems as complex open systems.
iii) Defend the necessity of a new epistemology to deal with such complex systems.
iv) Present and defend a new approach to empiricism for dealing with complex systems' evolution, regarding sustainability, under the framework of ecological economics.

v) Present the methodology called Multi-Scale Integrated Analysis of Societal Metabolism (MSIASM), both in theoretical terms and with some relevant applications.

vi) Discuss the evolution of certain economies such as Spain, Ecuador, Viet Nam, China, and other groups of countries from a biophysical point of view by applying MSIASM and focusing in the energy throughput over time.

vii) Drawing some conclusions both in theoretical terms regarding the analysis of the evolution of economies in regard to their energy consumption behaviour, and in practical terms regarding the countries analysed.

This will require the presentation of some theoretical approaches that will help us to understand the dynamics 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 central concepts and approaches to be introduced are, entropy and thermodynamic theory in general, as well as complex-systems theory, so they have specific chapters. While a full empirical analysis is not presented here, insights about what should be analysed, and how, will be given. In other words, a kind of blueprint for empirical research on economic systems' evolution will be offered. This will include new 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, trying to explain the path of past developments (by finding some regularities that can be compared among countries, i.e. typologies) and trying to offer some keys for future developments. It will be argued that this can be done by finding some internal constraints on the dynamics of the system, which conventional analyses do not account for. For example, the appropriateness of measures encouraging energy efficiency, and their effectiveness will be analysed, once we account for the internal constraints of the system (i.e. fixed cycles of energy dissipation for the metabolism of the system, or fixed or quasi-fixed coefficients in dissipative processes).

CHAPTER 2: ECONOMICS, ENERGY, AND THE ENVIRONMENT

2.1 Introduction

The relationship between energy, economy and the environment has a long history in economic thought. It has been analysed in one way or another by all 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. Thus, Section 2.2 will deal with an overview of the relationship between the environment and the economy for the different schools. Section 2.3 will introduce thermodynamic theory. 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 for more details[4]). 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

---

[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*. I owe this first insight to attending the lectures on World Economic History by Joan Martinez-Alier in 1992.

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

[4] Mirowski (1989: 155) asserts that the *Tableau* can be seen as the “purest instance of the classical theory of value”.

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 the laws of conservation of matter (Lavoisier, 1789), and the laws of thermodynamics developed in the 1840s and 1850s. More accurately, they did use the law of conservation of matter and energy to explain manufacturing but not production from land, which, for some of them had a *quasi-sacred* character[5]. However, the introduction of the concept of the *steady state* by John Stuart Mill (1866) was an acknowledgement of the limits imposed by nature to economic development, something that would be explored later by ecological economics[6]. On the other hand, Malthus (1798) was the first to point out the apparent contradiction between a growing population and the scarce resources available, 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 integrate the work of Podolinsky, a Ukrainian socialist physician, in his analysis, in what can be seen as a myopic error of the philosopher[7]. 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[8]. In fact, Podolinsky's

---

[5] In fact, as stated by Mirowski (1989), Say's law – supply creates its own demand – can be seen as an application of the conservation principle.

[6] 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.

[7] 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).

[8] For instance, had he used Podolinsky's work, his conception of the crisis of capitalism due to the deterioration of the 'relations of production' would have changed towards the constraints to the further

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. He stated that the energy return to human energy input should be larger than the 'economic coefficient', by which he meant that man has the capacity to transform one-fifth of the energy gained from food into muscular work. This result could be seen as a biophysical foundation of the theory of value. As Martínez-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, 1999) 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). It is a shame that Marx, the last classical economist with interests in the production process through the transformation of the different inputs, did not use the insights from thermodynamic analysis to complete his analysis of the economic process.

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). As stated by Christensen (1989), by using the maximisation model, adapted from analytical mechanics, neo-classical economics shifted the focus from production dynamics to an analysis of exchange value[9]. 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 Jevons (1865) addressed, in *The Coal Question,* the issue of limited resources as a constraint for 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)[10]. 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

---

development of the 'productive forces' imposed by physical and ecological laws.

[9] For a deeper analysis on the influence of geometry and physics in neo-classical economics, see Mirowski (1989: chapters 5 and 6).

[10] Something called later Jevons' paradox by a different scholar with the same name (Jevons, 1990)

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[11] way, whereas production has a clear historical path, from resource exploration through to the manufacturing of the good.

In fact, neo-classical economics focuses, as stated before, on the exchange of goods and services among the economic agents, such as consumers and producers, emphasising the role of consumer preferences and resources endowments, to guarantee the economy's equilibrium. More specifically, for those 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 then history of processes), linearity[12], 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, guarantees *always* 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, 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*. However, one epistemological problem that arises with this conception of economic science is that we have to believe in some axioms that are actually deduced

---

[11] Or independent from history.

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

from the theories developed following those axioms, in what is a clear tautology. This is what led Norgaard (1989) to say that in fact, we cannot derive from the neo-classical approach universal policy recommendations which can be used in the real world. However, economists have been making prescriptive statements from the theory, in what can be seen as a misuse of the theory[13] as Keynes (1936, opening paragraph) already stated: "I shall argue that the postulates of the [neo]classical theory are applicable to a special case only and not to the general case, the situation which it assumes being a limiting point of the possible positions of equilibrium. Moreover, the characteristics of the special case assumed by the [neo]classical theory happen not to be those of the economic society in which we actually live, with the result that its teaching is *misleading and disastrous* if we attempt to apply it to the facts of experience" (emphasis added). In sum, the theory would be better used "to facilitate the argument, clarify the results, and so guard against possible faults of reasoning – that is all" (Knut Wicksell, quoted in Georgescu-Roegen, 1971: 341). But what we see in everyday life is that economists tend to *ask reality to adapt to the predictions of their models*, instead of using the theory to achieve better understandings of that reality. "So, it is for its dogmatism, nor for its use of abstraction, that standard economics is open to valid criticism" (Georgescu-Roegen, 1971: 319).

In particular, neo-classical economists see the economic system as an *isolated system*[14] 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[15]. 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

---

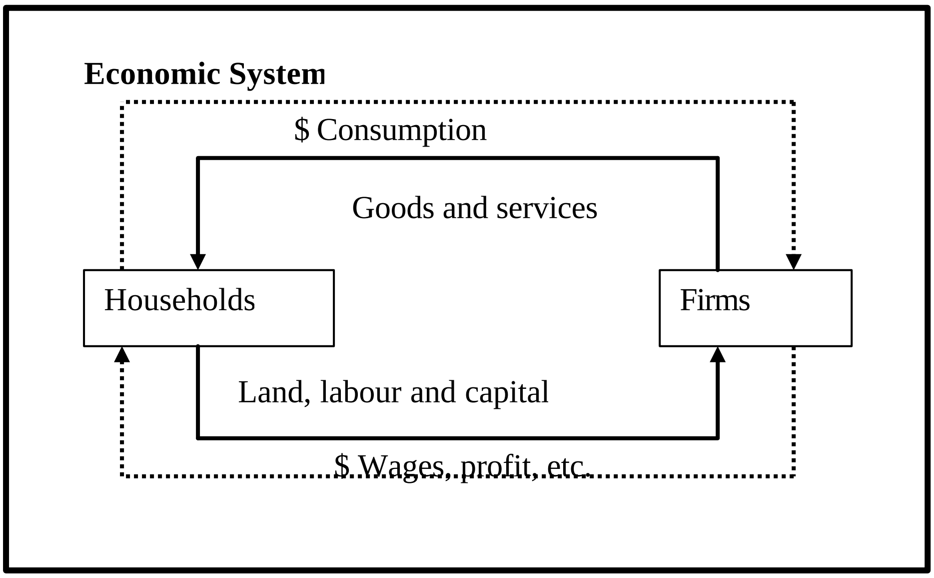
[13] One has to think, for example, of the macroeconomic advice that both the IMF or the World Bank give to their debtors (the so-called conditionality, basically deregulation, wages control, and privatisation), regardless of their particular historical and institutional characteristics. These kinds of prescriptive statements may lead to a lower inflation rate, but may also lead to an economic crisis (from the demand side) instead of boosting growth.

[14] An isolated system is one that exchanges neither matter nor energy with its environment. A fuller description of systems in thermodynamic theory will be given in Section 1.2.3.

[15] Economics, therefore, analyses prices. It is, then, a *chrematistics*, and has a metaphysical conception of the economic system as working like a *perpetuum mobile,* lubricated by money.

value (though different use value)". This cycle can be easily understood when looking at **Figure 1**.

Figure 1: The circular flow of exchange



Source: Hall et al. (1986: 39)

When representing the economic process in this way, we are just considering natural resources, technologies, preferences, etc, as 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 developed, natural resources (both inputs and sinks) were not scarce. This *historical reality* might explain why they 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 classical economists, 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)[16]. Later, Sraffa (1960) tried to find the 'single numéraire' using input-output analysis and a mix of produced goods. 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[17].

With its emphasis on allocation in markets, neo-classical theory cannot deal with the issue of the scale of the economy with respect to the environment (Daly, 1992). Rather, its analysis is supposed to be valid for any scale; that is, it is the same regardless of space and time. This is a key difference from ecological economics, as we shall see later, since it is precisely the issue of defining the boundaries of the system that is relevant for this trans-discipline. As Hall et al. (1986) said we can no longer afford to ignore or downplay the role of natural resources.

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 methodologies. The methods developed were:

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

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

This is why supporters of this approach are usually optimistic when dealing

---

[16] 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 relevance to that difference. I am in debt for this point to professor Lluís 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). An application of this distinction to environmental issues will be subject of my future research.

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

with environmental problems. For example, in the case of exhaustible resources they propose substitution between production factors[18], neglecting two basic things. On the one hand, there are services provided by nature that are not substitutable at all (like the water or the 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).

The same problem that is found with scale is present when dealing with time. 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 chapter, 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[19].

All of these characteristics of neo-classical economics led to it being viewed as not suitable for dealing with new and complex problems[20], such as environmental problems, as recent empirical research has substantiated (Cleveland, 1987). It also led to the proposing of new approaches, such as those developed by ecological economics. A very good summary of the weaknesses of neo-classical economics when dealing with environmental issues is found in Clark et al. (1995)[21] where they point out, among other things, that the mechanical character of economic models

---

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

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

[20] Complexity will be dealt with in more detail in Chapter 3.

[21] See also Daly (1985).

does not allow them to treat evolution or structural changes in the system. They also criticise the deterministic character of the explanations. That is, if one follows the axioms and applies the models to the variables, one finds a unique solution, leaving no room for spontaneous behaviour of variables or unknown feedback effects. In the words of Georgescu-Roegen (1971: 335), “an economist who sticks only to mathematical models is burdened with an even greater vice, that of ignoring altogether the qualitative factors that make for endogenous variability”.

Despite these limitations which, as it will be argued later, apply to all mechanical deterministic models dealing with complex problems, those models can be applied for 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 the neo-classical analysis is not being denigrated here, but rather the necessity of complementing it with new tools developed by other disciplines that might be better for analysing complex systems is being pointed out. Thus, the case for methodological pluralism (Norgaard, 1989) asks us to include also those methodologies as part of our tool kit of analysis and understanding of the relationship between the economy and the environment.

2.2.3. From resource limits to sink constraints

Following the tradition of Gray (1913, 1914) and Hotelling (1931) when analysing the optimal rate of extraction of an exhaustible resource, the economists of the 1960s started again to analyse the relationship between the economic process and the environment. The work of Barnett and Morse (1963) is usually set as a reference for this revival. Indeed, these new analyses updated the old insights of Malthus and Jevons in resource scarcity, by using the tools developed by neo-classical economics. These analyses led to the debate between technological optimists (those who think that either technology or substitution can solve our problems of environmental scarcity), and technological pessimists (those who have a different opinion). The debate was fuelled by the publication of the report to the *Club of Rome*, *The Limits to*

Growth by Meadows at al. (1972) and by the Arab oil embargo in 1973 (Costanza, 1989).

However, despite the fact that this debate is still alive[22], I am persuaded by authors such as Christensen (1989) to think that, in the near future, the constraints of nature upon the economic process may not be due to scarcity of resources, but due to the impossibility for natural systems to absorb the increasing amount of wastes generated by the economic system. Faber et al. (1996: 44) link this fact with ignorance and the emergence of novelty in the following terms: “Thus resource use can be said to generate scarcity, which is reflected in a market price, which in turn is likely to generate beneficial novelty. On the other hand, new pollutants are themselves a source of deleterious novelty, and generate only slowly, and often not at all, a search for a system of market pricing to encourage the reduction of their emission”. This fact may lead, then, to an overuse of the environmental service ‘sink’ beyond certain sustainable thresholds, leading to a shrinking of the service, constraining future economic development[23], constraining the ‘further development of productive forces’, in Marxist terms.

These ideas have been corroborated by recent research on biodiversity loss[24], ozone layer depletion and climate change[25], with the latter focusing on the incapability of nature to absorb the excessive pollutants generated by the human system through fossil fuel combustion. However, to see here a pure dichotomy is artificial, since both resource use and pollution are related, ‘the resource is the mother of the waste’, and thus environmental policies have to be designed bearing this fact in mind, “from an integrated and holistic conceptualisation of the production and consumption processes” (Baumgärtner et al., 2001: 370). This does not contradict the fact that, presently, pollution problems are more relevant when analysing the relationship of the economy and the environment.

---

[22] As we shall see in Chapter 5, the optimistic idea of dematerialisation of the economy (or the Environmental Kuznets Curve) is supported by scholars from the perspective of Industrial Ecology (e.g. Von Weizsäker et al., 1997) or Industrial Metabolism (e.g. Ayres, 1998) following results by Malenbaum (1978). But is questioned by some pessimistic (or maybe realistic) authors, such as De Bruyn and Opschoor (1997), De Bruyn (1999), Herring (1999), Jevons (1990).

[23] O’Connor (1988) has called the scarcity aspect mentioned by Faber et al. (1996) “the second contradiction of capitalism”.

[24] See Wilson (1993) for more details on biodiversity loss.

[25] For a comprehensive history of the science of climate change, see Paterson (1996, mainly chapter 2); Cline (1992); Houghton et al. (1990, 1992, and 1996). See also Paterson (1996) for an exhaustive explanation of the political process before the launching of the UNFCCC in 1992.

2.3 Setting the boundaries: thermodynamics

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[26]. This is why this section will stress some of the concepts developed by thermodynamic theory that will be useful later in the analysis.

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' theory 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.

2.3.1. The Law of Conservation of Matter and 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 principles of the conservation of matter and energy. We need here a classification of systems as defined in physics:

- *An isolated system* exchanges neither matter nor energy with its surroundings.

---

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

- *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). However, when trying to apply concepts from thermodynamics, we have to bear in mind what kind of system we are analysing, in order not to make mistakes that are very common among economists who deal with energy issues. This is why the definitions presented above are relevant for the analysis of the economic process.

The *First Law of Thermodynamics*, or the law of conservation of energy was developed in the 1840s, and states that energy 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. There is also a Law of Conservation of Matter (that goes back to Lavoisier, in 1789). In the case of open systems (relevant when analysing economic systems, as we shall see in the next chapter), "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 of conservation of matter, 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, all inputs used in every process will eventually be transformed into the same mass as of the mix of products plus wastes (Buenstorf, 2000). This fact led Ayres and Kneese (1969) 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 principle of conservation of matter 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[27].

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 the 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*. Indeed, all work can be converted into heat, but 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[28] is transformed into work and heat. "That heat, however, cannot be completely converted back into mechanical energy 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, e.g. temperature, 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 related to every transformation of heat energy into work is less than 100%. An alternative definition, in the same

---

[27] 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.

[28] 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).

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 Carnot's analysis of energy efficiency, basically in his analysis of how much useful work could be obtained from an energy transformation. Indeed, Sadi Carnot (1824) analysed the efficiency of a heat engine. This depends on the gradient of (absolute) temperature between the heat source (T_1) and the sink (T_2). Thus, the maximum efficiency is given by $E_{max} = (T_1 - T_2) / T_1$. That is, for any finite and positive heat sink temperature, E_{max} is always be less than 100%. This result can be considered as a 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 is why 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. 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 subject of 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 Boltzmann[29] 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 order 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 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". 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). 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.

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

---

[29] 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.

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. This result led Eddington (1928) to talk about the 'Arrow of Time' (which will be developed later), in which the increase in entropy determines the direction of Time in the sense of Georgescu-Roegen. The environmental implication, thus, for the economic system is that any use of resources that implies going beyond the 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). 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: "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); that is, provided that 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. Based on these grounds, however, Ayres (1999) proposed, in a way I disagree with, that 'imperfect recycling' in 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. Despite the assertion of Ayres himself this result is not in contradiction to Georgescu-Roegen's thought, as we will discuss in Section 2.4.

A final aspect, which will be analysed in more detail in Chapter 5 when dealing with the environmental Kuznets curve, is that, as derived from thermodynamic approaches, resource productivity, which relates to ecological efficiency, is not enough to guarantee the system's integrity (Binswanger, 1993). That is, relative improvements can be related to absolute increases in the use of resources and, from an environmental point of view, the latter is the relevant factor.

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, if the economy were an isolated system, then entropy would irremediately increase. Now, however, we see that the economy grows and becomes more complex, and the reason for this is that, from a thermodynamic point of view, the economy is a system open to the entry of energy and materials and to the exit of waste. Therefore, if we look at the economy from the vantage point of the Entropy Law, immediately we must give up the view of the economy shown in Figure 1, and choose instead the representation given in Figure 2 below.

2.3.3. 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).

As noted above, the Second Law of thermodynamics, the tendency of an isolated system towards maximum entropy, led Eddington (1928) to consider entropy as the 'Arrow of Time'. 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[30] (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, it is also useful for better understanding the economic process. However, regarding the economic process, as Faber et al. (1996) argued, production takes time, involving a description of time as duration ('time' for Georgescu-Roegen). But we can also see production processes 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.

2.3.4. Compatibility between ecological and human time scales: Georgescu-Roegen's Fourth Law of thermodynamics[31]

---

[30] 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.

[31] The ideas developed in this section help to clarify the concept of time as used in this dissertation,

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 "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 Costanza (1980), in which those authors argued that 'available energy' would be the ultimate limiting factor[32]. For him, entropy was a necessary but not sufficient condition for economic value (1971); there must also be the concept of purposive human action – the enjoyment of life – to give a good value, as we shall see later. But 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 Ayres (1998, 1999) as we have seen in Section 2.3.2. he argues, I think quite correctly, that Georgescu-Roegen's 'Fourth Law' is theoretically inconsistent with physics.

The arguments of O'Connor (1994), Cleveland and Ruth (1997), Mayumi (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 that proposed by Georgescu-Roegen[33], this might not be the case from a *practical* point of view, with reference to the 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 flows 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-

---

and help to clarify the constraints of thermodynamics on the economic process. For a deeper analysis of this point, see Mayumi (1993).

[32] 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).

[33] Kåberger and Månsson (2001: 167) noted that the division between energy and material entropy is fallacious because "there is only one kind of entropy, irrespective of whether the physical system is material or immaterial".

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[34]: Economic system as a

---

[34] 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*, and for other information, visit the web page of the International Society for Ecological Economics (http://www.ecoeco.org)

subsystem of the natural system

Ecological economics[35] 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 considering them within limits. This section offers a brief analysis of the origins of ecological economics, its understanding of the economic process and, finally, a description of the main areas of interest, relevant for the analysis developed later in this dissertation.

2.4.1. Introduction: 'Oikonomia'

Aristotle distinguished between 'chrematistics' and 'oikonomia'. To him, the former was the analysis of price generation and exchange, something that we, today, relate to what is called 'economics' in its traditional definition supplied by Robbins, as presented above. In contrast, 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 the discipline was still called 'political economy'. It is precisely that interest in the biophysical foundation of economic process, turning back to Aristotle and the classical economists, what distinguishes ecological economics from neo-classical economics.

2.4.2. Energy analysis

---

[35] Sometimes called biophysical economics, and later 'bioeconomics' by Georgescu-Roegen.

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 contribution to the debate was basically his statement that natural selection tends to:

(i) Increase energy flow through biological systems, and
(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 noted above, led some energy analysts to hypothesise that economic systems try to maximise power.

This kind of arguments, as stated by Martínez-Alier (1987), may lead to a social Darwinism[36], by which the explanation of the success of human species as analysed in terms of its learning to use energy sources, could be extrapolated intraspecifically to explain differences within human society. Using the natural selection theory intraspecifically should be mainly done in a metaphorical way. That is, taking into account that "the human allocation of energy and material resources to different uses cannot only be explained by natural sciences. Economics should *not*

---

[36] Actually, Lotka himself (1956: 304) made the point that some authors tried to build a system of "biodynamics (social dynamics)" based "on the mistaken identification of prices and related economic quantities with the intensity factor of an energy".

become merely human ecology" (Martínez-Alier, 1987: 15-16, emphasis in the original).

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 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[37] and endosomatic[38] energy flows is helpful in the analysis, as it 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). "The ratio between exosomatic and endosomatic energy indicates to what extent 'human technology' is boosting the ability of humans to control the production and consumption of goods and services. The ratio is about 5/1 in most subsistence societies (related basically to the use of biomass for fire and animal power as exosomatic conversions), while it reaches values as high as 90/1 in developed countries" (Giampietro et al., 2001; see also Giampietro, 1997).

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" as Costanza (1991) says, but rather of (un)sustainability, since ecological economics focuses on what is not sustainable. Also, following Redclift (1986), I believe that the concept of

---

[37] Use of energy sources for energy conversions outside the human body, for societal metabolism, but which are still operated under human control.

[38] 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).

sustainability is a social construction, which evolves with society[39]. In any case, ecological 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), as it will be seen in Chapter 4. In fact, economic systems use matter and energy to be sustained and to grow, and it is that production and consumption which transforms matter and energy and that changes the environment.

Armed with tools from ecology and economics, and with a wider scope of analysis, E.P. Odum (1989) distinguishes between three kinds of ecosystems:

(i) *Natural environments* or natural solar-powered ecosystems. These are the basic life-support systems, and they are self-supporting and self-maintaining.

(ii) *Domesticated environments* or human-subsidised, solar-powered ecosystems. Food and fibre producing systems, supported by industrial energy.

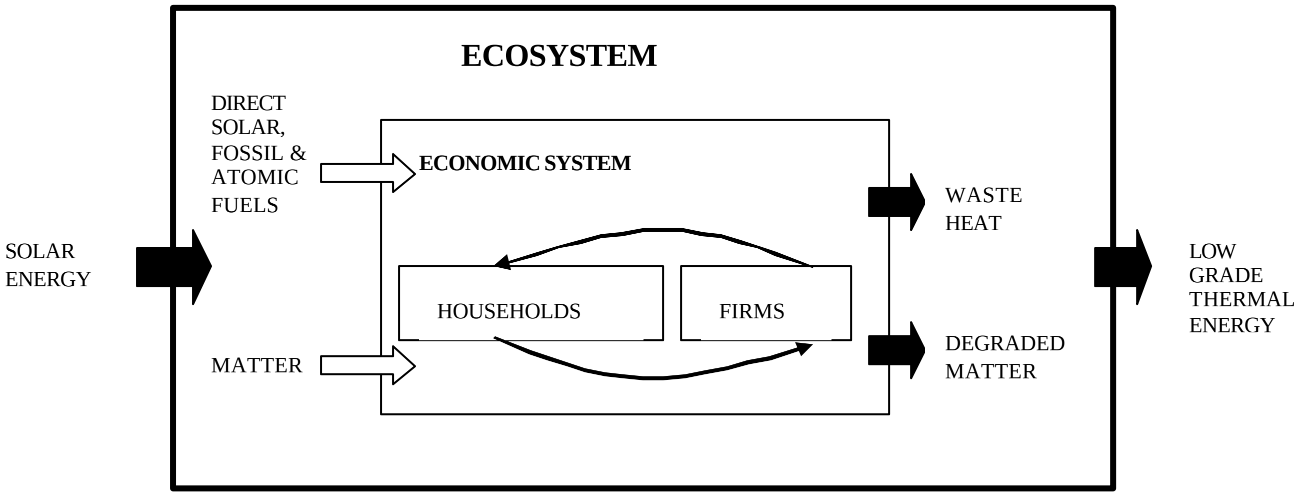
(iii) *Fabricated environments* or fuel-powered, urban-industrial systems, in which the main energy source are fossil fuels.

Using this distinction, it can be noticed that the fabricated environments (in which economic systems can be considered) are not self-maintained and therefore depend on the output of the other two kinds of systems.

---

[39] 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”.

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



Source: Hall et al. 1986

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 (see **Figure 2**).

Daly[40] (1991: 36) 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,

---

[40] Following Boulding, as he says.

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.

It is true, however, that **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 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.

Put in other way, we are just referring again to Georgescu-Roegen’s preoccupation about time (as seen in Section 2.3.2.), this time reflected in his fund-flow model

(Georgescu-Roegen, 1970). In that paper, he objected that the time factor is often ignored, that stocks and flows tend to get confounded. For him funds are characterised by "economic invariableness", because they are maintained during the economic process. Examples of funds are land in Ricardian terms, instruments and tools of production, or capital equipment. Flows, on the other hand, are only inputs or outputs to the economic process. Examples are raw materials, circulating capital, inflows for maintenance, and outputs either products or waste. As Kurz and Salvadori (2003) say, by accounting the system this way, Georgescu-Roegen was specifying the time element in the production process: the process has a beginning and an end, and its duration is finite.

2.4.4. The issue of scale

To say that the entropy law does not apply to closed systems like the earth, or open systems like the economic system, is not the same as arguing that there are no limits to human activity. It is true that in both open and closed systems, entropy can increase or decrease (in this case at the expense of an increase in the entropy of the larger isolated system in which it is embedded), but there are physical constraints. In fact, if there were unlimited energy sources and sinks, or our economy was based only on solar energy, we would have no problem at all, and we would not care whether the flow between them is unidirectional or circular and self-renewing. This is what happened historically when the scale of the economic system was small compared to the ecosystem, but now things are different.

Presently we depend largely on fossil fuels, a limited resource. That is, both sources and sinks are finite and this means "that the entropic nature of the throughput greatly increases the force of scarcity because finite sources run down and finite sinks fill up, and the latter cannot replenish the former. In the process, other species get evicted from their niche as more and more of the finite environment is converted into a source or a sink for the economic system. As other species are displaced and eventually become extinct, human beings lose the life-support services formerly provided by those species" (Daly, 1992: 200). In other words, because of the character of joint production that is involved in the economic process (generating the unwanted bads mentioned above), and because the assimilative capacity of the natural environment for pollutants is limited, there are limits to growth (Baumgärtner et al., 2001). Ultimately, these restrictions will pose limits to both the maintenance and the growth of the economic and natural systems. In more striking words, it is impossible that the economic system, as a sub-system, expands indefinitely in a finite world (Odum, 1973; Daly and Cobb, 1989).

In line with what was discussed when dealing with the Fourth Law of thermodynamics, the major constraint seems to be that of matching economic and ecological time scales. This is something that can be found in the ideas of Boulding (when arguing for reducing the material throughput), Georgescu-Roegen (when arguing for reducing population and material standard of living to one that could be maintained by organic agriculture), in Daly (1990) (when defending a steady state based on development[41] instead of growth[42]), or in Odum (2001) when talking about "the prosperous way down". The scale of the sub-system does matter.

2.4.5. Strong sustainability

Ecological economics deals, as stated before, with the interactions between the human system and the environment. In doing so, some relevant topics are tackled, such as the distinction between weak and strong sustainability. By weak sustainability (Pearce and Atkinson, 1993) we mean the keeping of welfare (understood as wealth or consumption) either constant or growing; this is based on the idea of complete substitutability between human-made capital and nature and perfect valuation of all goods and services. By contrast, strong sustainability (Noël and O'Connor, 1998) acknowledges the existence of a series of goods and services provided by nature (the so-called critical natural capital) that would be necessary for keeping and regulating systems and, therefore, that could not be substituted by human-made capital (Barbier and Markandya, 1990). Instead, there would be

---

[41] Qualitative improvement or unfolding of capabilities.
[42] Quantitative increase in physical scale.

complementarity. This complementarity allows for considerations of co-evolution between systems, as will be developed in Chapter 4. The idea is, then, to generate a set of biophysical indicators to let us know the quality of the systems to make proper diagnostics, and promote environmental policies, avoiding the economic reductionism when taking decisions.

This co-evolution of economic and natural systems is an expression of, and also enhances, complexity, which means that the new environmental problems are characterised by uncertainty. Thus, more research does not mean necessarily better understanding, but rather new questions. From that, three major implications derive. First, science can be no longer restricted to scientists. A popular or post-normal science that includes stakeholders' views is needed. Second, no single discipline can deal with these new problems, so the intervention of different disciplines is also needed, something that has been called 'methodological pluralism' (Norgaard, 1989). Third, science has to turn from trying to find eternal laws that govern systems (in a deterministic and deductive tradition that is only feasible for simple systems) to "understanding the past of existing system[s]" (Clark et al., 1995: 27), acknowledging their uncertainty, and trying to find regularities in the behaviour of variables in time in a more empirical tradition.

2.5. Conclusion

Summarising the arguments presented in this section, it has been shown 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 resource 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. 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.

Ecological economics is a multi-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, some concepts and tools developed by energy analysts or ecologists like Podolinsky, Lotka, and Odum are used. 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, which 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, as we have seen when dealing with scale.

CHAPTER 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 analysing 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[43]. In particular, the Second Law cannot be directly applied to open systems in its classical interpretation[44]. This is why '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 section presents complex systems' main characteristics in order to proceed, in Chapter 4, to a characterisation of human systems as complex self-organising systems.

3.2. Far-from-equilibrium thermodynamics

---

[43] See Chapter 2 for a definition of the different kinds of systems from a thermodynamic point of view.

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

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 *e*nvironment, while dS_i is the entropy change in the system due to the irreversible processes *i*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 be, by definition, 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 section. 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 larger 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 in *What is life?*, suggesting that all organisms need to import low entropy from the environment and to export high entropy, or waste, in order to survive.

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 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 needed at this stage of the dissertation. 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". This hierarchy of concepts is used to deal with the issue of structuring and organisation, that will be expanded in Section 3.6, after explaining what are complex systems in the next section.

Since very long scientists faced a 'contradiction' between the laws of thermodynamics and the appearance of life, as an expression of greater structuring of systems. 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 Martínez-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 VII) for more details and for the references of those authors mentioned above. 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 von Bertalanffy and Prigogine (after Boltzmann (1872) and Ostwald (1907)) solved the apparent contradiction. In the 1930's Bertalanffy formulated the "organismic system theory". His starting point was to deduce the phenomena of life from a spontaneous grouping of system forces. Following that aim, he postulated two biological principles, namely, the maintenance of the organism in the non-equilibrium, and the hierarchic organisation of a systemic structure. Later on, in the 1940's, he conducted his "theory of open systems" from a thermodynamical point – a similar approach as the thermodynamics of irreversible processes as developed by Prigogine at the same time. Open systems would tend to the steady state since that state corresponds to a minimum entropy generation enduring the systems conditions. Thus, the system will achieve the dissipative state that configures a structure since it maintains itself in a state far from equilibrium. From the combination of the former two theories, Bertalanffy introduced General Systems Theory (1949, 1950, 1968) as a new paradigm which should control the model construction in all the sciences. As opposed to the mathematical system theory, it describes its models in a qualitative and non-formalised language. In general systems theory, 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 (Prigogine, 1962; 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 (see Section 2.3.2), in which he related low entropy with order, and high entropy with disorder. Thus, non-equilibrium (i.e. non-maximum entropy states, $dS \neq 0$) 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 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[45], "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. 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.

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

---

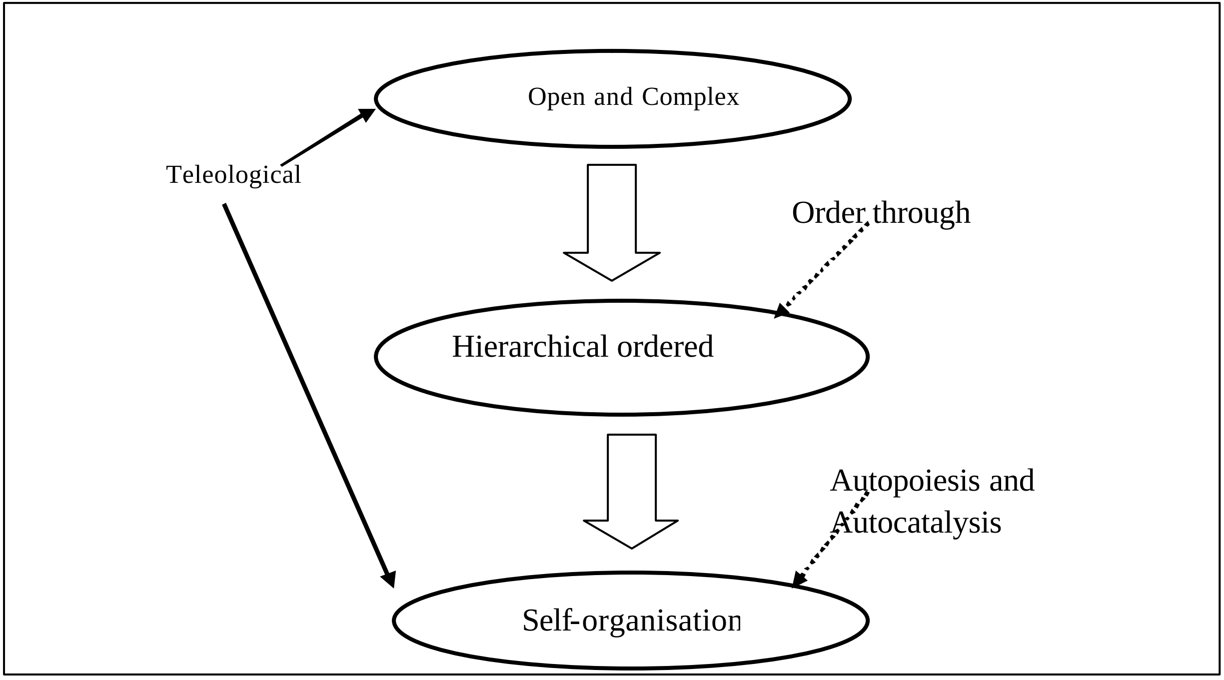
[45] See Schneider and Kay (1994) for a deep analysis on the Second Arrow of Time. The title of their paper says much about it: "Life as a manifestation of the second law of thermodynamics". A further exploration of their views is presented here in Section 5.3.2.

'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 (which might be called the throughput, or the metabolic flow, as mentioned above); 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 concept:

(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. 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[46]. 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

---

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

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.

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);
- holarchical 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 with more detail.

3.4.2. Teleological entities: 'natural' tele

The necessity of relating biological time scales to human time scales was emphasised above. This issue can also be understood by introducing teleology. 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 it is shown below. This telos can be termed a 'natural' telos. But they also have different tele for each hierarchical level of the system; that is, their respective role in the system.

This introduction of teleology has some advantages, since it allows, for instance, stressing the fact that human systems having 'social' tele; i.e. they are anticipatory and self-reflexive systems, as it will be discussed in the next section. Here, however, teleology for non-human systems is introduced following Faber et al. (1996, mainly Chapter 9[47]).

Faber et al. (1996) related teleology[48] with the idea of causation towards a

---

[47] 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).

[48] 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).

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 teleological organisms 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). Complex systems are well described this way, as stated above.

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.

Complex systems have the telos of self-maintenance and development. This telos is intrinsic to the system, and it 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[49] (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; that is, compatibility has to be achieved between the different goals, between human actions and the environment.

This teleological approach to complex systems undermines the use of mechanical-deterministic descriptions of such systems that are based in past causation 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

---

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

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)[50]. 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 ‘holarchy’ this kind of hierarchy. Complex systems are thus ‘nested hierarchies’ or ‘nested holarchies’ following Koestler. 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 by 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

---

[50] I am indebted to Mario Giampietro for introducing me to the work of Koestler.

levels to upper ones in the analysis of complex systems. Jantsch (1987) considers this relation as symptomatic of 'symbiosis' if it implies the exchange of *essential* products or services between the different parts of the system.

This hierarchy has not to 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* (Giampietro and Mayumi 2000a; Giampietro 2003); 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. Besides, the initial conditions, or the history of the system that is affecting the present behaviour, have to be accounted for, and it is one of the *descriptions* involved.

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.

This process of self-reproduction is more related with information than with the processing of matter (Jantsch, 1987). This relationship takes the form of knowledge about the structure, to control the structure and the dissipation of exergy (or available energy). But it is also related to the transmission of this information in the form of strategies of development to confront fluctuations or future changing boundary conditions.

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 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.

Thus autopoiesis can only take place when we have autonomous components of a system that interact with each other, i.e. the holons of a hierarchical system as discussed above. In this context, feedback loops link also outputs of some processes and convert them into inputs for not only the same processes themselves, but also other processes in the system, reflecting the interdependence of the different subsystems.

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. I say 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[51], 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 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.

This distinction between the hypercycle and the dissipative part of a system will be very useful when analysing the structure of economies, since both parts of the system can clearly be identified, allowing us to derive some conclusions on the relationships of dependence between different sectors of the economy.

3.4.5. Attractor points

The evolution of complex systems will be analysed in Chapter 5 in more detail. However, in order to understand better the narrative that follows, especially when dealing with self-organisation in section 3.6, it is necessary to introduce the concept of the attractor point. The hierarchical structure of complex dissipative systems, as well as the working of the feedback loops between the different hierarchical levels, induces non-linear 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,

---

[51] 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).

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[52].

Both non-linear behaviour, and far from equilibrium situations lead to the existence of a multiplicity of stables states (Proops, 1985) or attractors[53]. This situation leads to a series of 'bifurcation'[54] 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

---

[52] Holling (1996: 32) said, "*ecosystems are moving targets, with multiple potential futures that are uncertain and unpredictable*" (emphasis in the original).

[53] If there is a number of possible stable equilibria, these must be separated by unstable thresholds which represent the bifurcations (Dalmazzone, 1999).

[54] May and Oster (1976) first introduced the concept of bifurcation when analysing the behaviour of chaotic systems. They pointed out that in the middle of a cascade of bifurcations, stable cycles may return, giving support to the idea of the existence of structured disorder in chaotic systems.

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”. This is called path dependency.

The conclusion, thus, is “that a sufficiently complex system is generally in a 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, which always leave room for future development.

3.5. Complexity and environmental problems

As noted in the introduction to this section, as well as being dissipative structures, economies are also complex systems, so complexity is relevant for our analysis. Moreover, as discussed here, we can consider the present environmental problems as characterised by complexity. So, what is the relationship between environmental problems and complex systems? As presented in the last section, complex systems show teleological behaviour; they have tele, either ‘natural’ or ‘social’ for non-human and human systems respectively. This fact may lead to a contradiction between the tele when trying to implement them. This contradiction may lead to complex environmental problems. This is exactly what we see nowadays regarding the environment. As we stated earlier, when the human system was small as compared to the environment, the latter could absorb the impacts on it. However, once the system becomes much larger, this is no longer the case and we face environmental problems such as biodiversity loss and climate change that reflect the contradiction between the social and the natural tele mentioned above. In both cases, economic growth (via logging or increasing arable land in the case of biodiversity loss, or via consuming more energy in the case of climate change) implies that the satisfaction of social tele in the way that is done presently is in conflict with the goal of self-maintenance of natural systems. In fact, both biodiversity loss and climate change are characterised by their irreversibility. Once a species is lost, it is impossible to recover, and it may induce irreversible changes in the functioning of the ecosystem; "it is impossible or too difficult to come back to the initial state" (Muradian and Martinez-Alier, 2001: 284). The same is true in the case of climate change. Thus a hypothetical increase in global mean temperature may also induce irreversible changes in ecosystems. Another characteristic of environmental problems is that they are often long-term and global, implying that we have to account for different time and space scales when analysing them, thereby increasing the problem of their conceptualisation and modelling. Moreover, most of the consequences derived are, by definition, inconmensurables, so a simple economic account of benefits and costs is no longer possible[55]. Because of all of these characteristics, we can consider the new environmental problems as complex phenomena. This characterisation, however, is not enough to deal with environmental problems from a policy perspective, and this is why a new epistemology will be presented in Section 4.3.

As a consequence of this complexity, uncertainty and ignorance[56] are always present when dealing with such problems. In fact, the more research we apply the more uncertainty and ignorance are generated; new questions arise, and new relationships between variables are found. In the words of Faber and Proops (1998: 110), "by their nature, environmental problems are often global and long-run. As such, very often they involve the emergence of unpredictable events (novelty) (…) this implies that the simple sequence of problem → science → technique → solution is not necessary valid. On the contrary, we experience that our increasing knowledge may even impede the investigation for solutions". This is because the new knowledge allows us to realise the existence of these relationships between variables that make analysis and interpretation much more complex. If the traditional sequence of problem solving by applying more knowledge and research no longer works, a

---

[55] Most of the time it is not even desirable, since it implies the logic of monetary compensation for an induced damage. That is, it implies the acceptance of compensating for irreversible damages. This contradicts the concept of strong sustainability which asks for maintaining certain ecological functions above certain thresholds.

[56] Under ignorance, all of the outcomes of a process or decision are not known. Under uncertainty they are known, but not their probabilities, while under risk, even probabilities are known. For a clear taxonomy of surprise and ignorance, see Faber and Proops (1998), especially chapter 7.

new epistemology of complex systems is needed, as will be presented later.

3.6. 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', the 'transition'. 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".

Open complex systems (such as living systems) are dissipative structures that show a tendency towards increasing complexity, reflected in new structures developing that allow the processing of more energy and matter, in an increasingly effective way; that is, they are self-organising systems, reflecting the so-called Second Arrow of Time.

Open complex systems show order because a recognisable pattern is found in them. Moreover, as Proops (1979: 118) said, "the notion of 'structure' is rather stronger than that of 'order', implying some unity to the arrangement of components". Again following Proops, a system is organised if its structure is a realisation of some inter-relations of the components. This fact allowed Proops to distinguish between complexity and organisation. For him, a system is organised if it is complex and there exist strong inter-relations between its components. Complexity is viewed, thus, as a necessary but not sufficient condition for organisation, as was stated above.

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. They are, thus, teleological entities, as argued above. 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 (or available energy) 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). However, when the system is pushed too far away from the equilibrium, the system might face chaotic behaviour[57], instead of self-organising behaviour. In economic terms this is the equivalent to 'overheating' an economy. Too much investment (one means of dissipating energy) may lead to a fast capital accumulation of the economy, with two consequences. From a monetary point of view there is a push towards greater GDP growth rates, which may induce consumption increases, leading to inflationary

---

[57] As noted by Gleick (1987), Lorenz (1963) discovered the Butterfly Effect, later called 'sensitive dependence on initial conditions', by which small changes in some parameters of chaotic systems might lead to large consequences. This implies that there is (structured) disorder, so when trying to find regularities we should bear this fact in mind. As said by Dalmazzone (1999: 64) "sensitivity to initial conditions implies unpredictability; the system shows path-dependence, and although in principle it should be possible to predict future dynamics as a function of time, this is in reality impossible because any error in specifying the initial condition, no matter how small, leads to an erroneous prediction at some future time".

situations that may be out of control. From a biophysical point of view, that higher capital accumulation makes even more energy available for the system, in a clear example of the positive feedback characterising the hypercycle. This is always been one of the headaches of economy ministers, as nowadays the Chinese case exemplifies.

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 damp 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).

This generation of order through the dissipation of exergy has been called by Prigogine 'order through fluctuation', or 'order out of chaos'. 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 in which the system flips from one attractor to other, as was noted above) the deterministic aspects are dominant, since the system has reached, or it 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. This issue is analysed with more detail in Chapter 5.

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.

3.7. 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. As Binswanger (1993) said, 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 also are autopoietic; that is, self-reproductive, through autocatalysis, in which outputs of some processes are considered inputs of some others, showing the interdependence of the subsystems and processes within a system. It was also said that their evolution is step-wise, flipping from one attractor point to the next. This characterisation allows us to understand better the evolution of economic systems, as will be discussed later in this thesis.

Section 3.5 presented environmental problems as complex. This is so because they are long-term, they have global scale, and there is a great deal of uncertainty not only in their consequences, but also in their descriptions. For this reason, a new epistemology to deal with them is demanded, and this will be analysed in the next chapter.

Finally, Section 3.6 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.

Now the theory that describes open systems in thermodynamic terms and some of their characteristics have been given, the next chapter deals with the characterisation of human systems as open, complex, self-organising systems, and with the epistemology needed to analyse them.

CHAPTER 4: HUMAN SYSTEMS AS COMPLEX, ADAPTIVE, DISSIPATIVE, SELF-ORGANISING SYSTEMS

4.1. Introduction

The theory of dissipative structures, as well as the characteristics of open complex systems, has been the subject of the previous chapter. Moreover, it has been stated throughout the chapter that human systems are an example of open complex systems, organised hierarchically. Here, that statement is justified. It can be said that 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 also presented. This epistemology can be considered the foundations on which the argument of this thesis is built.

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 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, as this will be discussed in Chapter 6. The necessity for methodological pluralism in opposition to reductionism is also stressed. Finally, a conclusion summarises the relevant points.

4.2. Characterisation of human systems

When approaching the economic system from a thermodynamic point of view, which focuses on the production of goods instead of on their exchange, production can be seen as the process of upgrading matter into low entropy goods and services. This process, as was shown in Section 2.4.3, 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, as was also shown in Section 2.4.3. 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* exists between economies and other kind of organisms. In this same sense, Ulanowicz (1986) argued that increasing network ascendancy (i.e. self-organisation and structuring) also portrays development in economic systems. 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. That telos was the self-maintenance and development of the system itself, a telos which, as we said, can be approached from science to a certain extent. However, 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 Georgescu-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, with moral concerns, even with 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 it 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. As we shall see particularly in Chapte 9 and 10, these "rules" set by society regarding working and non working time are of especial relevance for determining not only the direction of development, but also the biophysical constraints associated to that path. That is, we shall see, for instance, how changing some social rules such as "working age" may affect the range of possible future scenarios for a particular system.

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 a new *elite* of 'supervisors' and 'regulators' and their activities, as we shall see in the next chapter. These regulatory activities might be considered as net dissipative systems, following Ulanowicz's distinction mentioned before between the hypercycle and the dissipative part of a system.

Regarding economic systems as anticipatory and their influence in defining the tele and in the overall behaviour of the systems, Jantsch (1987) argued that this capacity of anticipation makes the future effective in the present, when taking decisions, when regulating (i.e. organising) the behaviour of the system. Explicitly, Jantsch (1987: 256) said that "in self-reflexive systems, fluctuations may be anticipated and act in the mental constructs of the present even if only in a primitive form of fear (of the atomic bomb, of environmental pollution, or the 'limits to growth'). We may learn to 'defuse' the fluctuations, if not to suppress them".

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. As it was shown in Section 3.4.3, hierarchical systems can be defined as being composed of different holons. 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 them, reflecting the autocatalytic nature of those systems. That is, "downward and upward causation imply feedback between different levels of description in the hierarchy (…) [then], in mathematical terms it implies additional complexity and non-linearity such that an economic equilibrium is no longer evident and certainly cannot be easily calculated" (van den Bergh and Gowdy, 2003).

Ecological and human systems' dynamics are characterised by the presence of both positive and negative feedback loops, operating at different temporal and spatial scales, which stabilise the system around certain attractors, with an ordered configuration. In other words, processes undertaken at one moment in time or in one hierarchical level of the system do influence in positive or negative terms subsequent processes in time or at different hierarchical levels of the system. This reaction is what is called a feedback loop. Positive feedback loops play a special role in autocatalytic processes leading to system's 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 over the assimilative capacity of the system are a clear example of negative feedback loop, because it might imply even a regression in the development of the system.

Another form of viewing human systems' stabilisation is by autocatalytic loops (when dealing with economies, the output of one sector enters the process again as an input triggering the process to perpetuate). In economic terms, the autocatalytic loops represent the exchange of capital and human activity (labour), while in biophysical terms, they represent the stabilisation of the metabolism at two hierarchical levels, that of the individual human being, and that of the society as a whole (Giampietro and Mayumi, 2000).

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. However, as pointed out by Zeleny (1996), their individual goal or telos is not the same as the 'natural telos', that of the preservation of the system, the society. Rather it is motivated by their own purposes and value judgements, the social tele mentioned in the previous section.

Using Ulanowicz's 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.

Simon (1997: 226) relates autocatalytic loops with sustainable production by stating that "the general principle of a sustainable production process is that it functions as a never ending and self-regenerating [autocatalytic] loop. Products and by-products are 'final commodities'; they are needed to satisfy needs, but also to make the loop regenerate". However, this maintenance of the autocatalytic loop has entropic limits, and therefore that is why she also says that "the sustenance of the loop therefore relies on the openness of the system and on the efficiency of the 'entropy-use' in the system" (Simon, 1997: 229).

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. This is what explains increasing efficiency within systems being correlated with increasing organisation. 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. This is done in order to face the challenges of the future, in order to adapt to changing conditions, either due to external shocks, or because of internal causality within the system (Giampietro and Mayumi, 1997).

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, more usual nowadays. This metaphor stresses the fact that human societies use large amounts of materials and energy in a similar way to organisms.

In this sense, the 'exosomatic metabolism' of societies[58] 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.

This concept has a long history in biophysical analysis of the interaction of socio-economic system with their environment, and can be consistently found in the writings of those authors that see the socio-economic process as a process of self-organisation. Pioneering work in this field was done, among others, by Podolinsky (1883), Jevons (1865), Ostwald (1907), Lotka (1922, 1956), White (1943, 1959), and Cottrell (1955). Cottrell worked out the idea that the very definition of an energy carrier (what should be considered an energy input) depends on the definition of the energy converter (what is using the input to generate useful energy). The idea that metabolism implies an expected relation between typologies of matter and energy flows has been explored by H.T. Odum, (1971, 1983) (for studying the interaction between ecosystems and human societies); Rappaport (1971) (for anthropological studies); Georgescu-Roegen (1971) (for the sustainability of the economic process). Georgescu-Roegen, in exploring the relation between the economic process analysed in terms of energetic and material flows, coined a new term for such an integrated analysis namely "**Bio-economics**" (Mayumi 2001). Georgescu-Roegen (1971) called the flows associated to a given socio-economic structure 'metabolic flows'. This metaphor stresses the fact that human societies must use large amounts of materials and energy to sustain their structure and activities, exactly like organisms do. Within

---

[58] See Section 2.3.2. for a distinction between exosomatic and endosomatic energy.

this rationale, Georgescu-Roegen (1975) proposed the distinction - first introduced by Lotka (1956) – between exosomatic energy flows (i.e. use of energy sources for energy conversions outside the human body, but operated under human control, for stabilising the turn over of matter within societal structures) and endosomatic energy flows (i.e. 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). He proposed to use this distinction as an analytical tool for the energetic analyses of bio-economics and sustainability. In this sense, the 'exosomatic metabolism' of societies or 'societal metabolism' deals with the consumption of exosomatic energy (e.g. for the making and operation of tools and machinery) which is required for guaranteeing the set of useful activities associated with sustainability.

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 said (1971: 281), "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. That relationship is the subject of the next chapter, where it will be further analysed.

Therefore, in biophysical terms, the process of self-organisation of human systems, as identified in Section 3.6, 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 also showed that this fact has been confirmed by empirical evidence for a range of countries including both developed and developing countries.

Because economic systems share the characteristics of being teleological entities, of being anticipatory systems (with the novelty associated to that fact) and because they are hierarchical and thus show non-linear behaviour due to the feedback loops between the different levels, they are, by nature, contextual, depending on one particular space and time scale, and so they have to be analysed, taking one specific time and space scale for our analysis. Moreover, because of the same characteristics, and because being anticipatory systems means that they incorporate possible future states in the present background, there may be multiple equilibria.

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 trouble 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, which may be approached by means of the narratives used,

(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).

However, in this thesis we shall focus on the analysis of the energy throughput, which we shall assume as a proxy of an environmental impact indicator, and that this is indicative of the evolution of the system towards higher organisation. However, the methodology to be used later, MSIASM is not just an accounting system for the biophysical metabolism of economic systems. Rather, it helps better understanding systems' evolution and structuring information for having informed discussions on narratives (i.e. future tele).

4.3. 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 these complex systems and problems, 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[59].

4.3.1. The need for a new epistemology

The main characteristics of the new environmental problems, as we have seen, 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, which is our narrative; 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

---

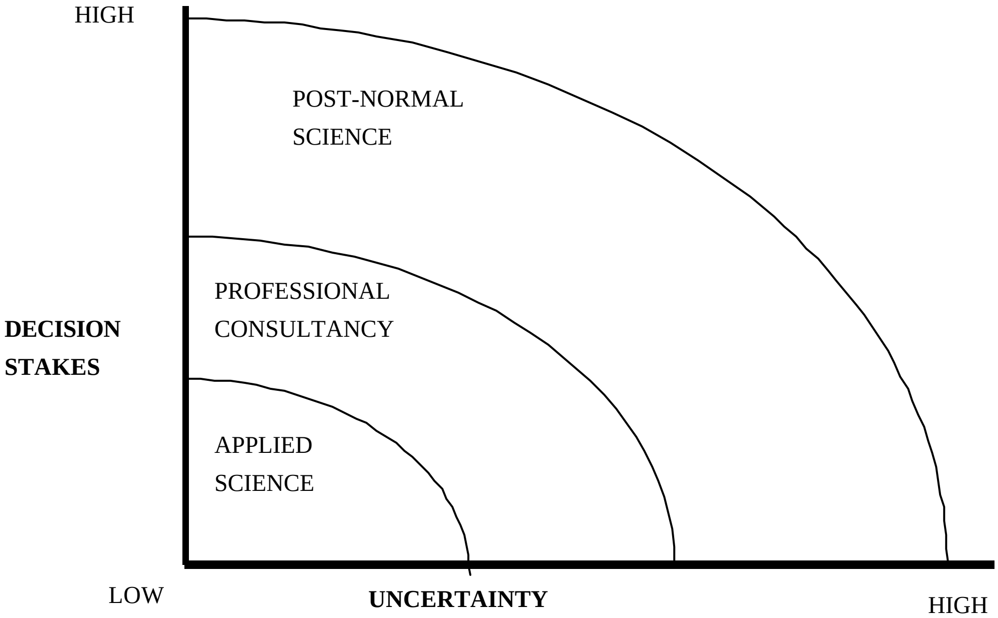
[59] Joan Martinez Alier introduced Neurath to me.

uncertainty[60]. 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' (Denzen, 1994), 'civic science' (O'Riordan, 1996), or 'post-normal science' (Funtowicz and Ravetz, 1991).

4.3.2. Post-normal science

Figure 4: Post-normal Science



Source: Funtowicz and Ravetz 1991

---

[60] See footnote 56.

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[61].

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. Finally, when even professional consultancy cannot deal with the high uncertainty, 'post-normal' science enters into 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 (Denzen 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 of 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,

---

[61] The sequence of problem → science → technique → solution (Faber and Proops, 1998) mentioned above.

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, to a new procedural rationality (Simon, 1983), in which the process of knowledge generation is the relevant issue[62]. 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 problems 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.

The implication of this approach for this thesis is that here the intention is just to provide guidelines of how to analyse the evolution of economic systems by analysing their exosomatic energy metabolism, in order to *understand* them better. Then quality information could be given to all agents involved in decision making for their use in the process of policy formulation. There is not the aim of providing an *explanation* that can be used either to forecast future behaviour or to recommend policies based on these results alone.

4.3.3 Methodological pluralism

---

[62] I am indebted to Giuseppe Munda for this point and for introducing me to Simon's work.

When we are dealing with complex systems that operate in different parallel hierarchical levels, there is no single explanation for their behaviour, as we will see in the next chapter. Rather, "the existence of contrasting 'correct' scientific assessments is unavoidable" (Munda, 2000: 5). That means that we need *parallel non-equivalent descriptions* (Giampietro and Mayumi 2000a) of the same phenomenon to comprehend it sufficiently. Therefore, even ecological rationality alone (e.g. when using the concept of carrying capacity[63] to human beings), is not the best way of dealing with complex environmental systems. Instead, the idea of an integrative holism[64] is more suitable to tackle the description and understanding of complex systems.

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, which are, at least in principle, legitimate. Each of them would be related to the specific set of parameters 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 Martínez-Alier, 1987:

---

[63] Carrying capacity refers to the maximum population of a given species that can be supported indefinitely in a given territory, without a degradation of the resources base that would diminish this population in the future. This concept, originating in biology, can be applied with success to other species in which endosomatic consumption of energy (for the internal metabolism) is predominant, but cannot be used for human beings, since exosomatic consumption is dominant. Thus exosomatic consumption must be specified before we apply the notion of carrying capacity to the human species. Then, applications of the concept like the 'ecological footprint' or 'environmental space' are incomplete, and they should be seen mainly as metaphors.

[64] 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).

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 bioeconomics, or ecological economics, as a post-normal science, advocates the use of the insights of different disciplines, as it is being done here.

4.4. Conclusion

Section 4.2 characterised human systems (i.e. economic systems) as open complex systems, or dissipative structures, hierarchically organised and teleological in their nature. They have been said to be also adaptive, self-reflexive and self-aware systems. In particular it was argued in favour of considering them as an isomorphism with other organisms, rather than an analogy. It was also said that their anticipatory nature makes them adapt to changing conditions and even influence future boundary conditions consciously, by changing their social tele. This distinction about the tele allows us to see the threats to environmental sustainability, since sometimes natural and social tele may be in contradiction, and one good way to analyse this contradiction is by using the throughput, or in a simpler form, energy dissipation of human systems.

Finally, Section 4.3 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’ solution. It was also argued that in this context, the role of empirical analysis changes, as we shall see in the next chapter. 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.

The next chapter goes one step further in this attempt to understand the energy metabolism of societies, by analysing the different explanations of the evolution in time of energy dissipation (our measure of the throughput or metabolism). This will be done by going from the traditional way used by neo-classical environmental economists, to an integrated approach under ecological economics, in which we shall use the tools developed in Chapters 2 to 4. Moreover, a justification for the 'integrated' analysis will be made in Chapter 6 by introducing the new role of empiricism when analysing complex systems.

CHAPTER 5: THE ENERGY METABOLISM AND THE EVOLUTION OF ECONOMIES

5.1. Introduction

In the last chapters some concepts from thermodynamics and complexity theory have been introduced in order to analyse sustainability, focusing on the relationship between exosomatic energy consumption and the evolution and development of economic systems. It has been also shown that economic systems, as the human systems that they are, are open complex systems, or dissipative structures, hierarchically organised and teleological in their nature. They have also been said to be adaptive, self-reflexive and self-aware systems.

This allowed us to say that economies, as complex systems, have the tendency towards an increase in order and structure through the dissipation of energy. This gives rise to self-organising behaviour to stabilise the inflow of low entropy energy from the environment, which can be understood as an emergent property of complexity itself. As we shall see, this process of self-organisation is translated into more regulatory activities, which for the case of economic systems might imply an increase in the services and government sector.

All of these characteristics pose a few problems that have to be tackled when analysing the exosomatic energy metabolism of these systems. Using the concepts from thermodynamics to link the views presented in this section, a first approach will be dealt with in the next section. This is a classical interpretation of how economies evolve in time and their relationship with energy consumption. Recently it has been called the environmental Kuznets curve, although it has been analysed for some (cf. Proops, 1988) before that name was applied to it. Some empirical results from this approach have led to the optimistic concept of dematerialisation, as we shall see later. This is an approach that can be criticised in the same way as deterministic models were when analysing neo-classical economics. This criticism is the reason why this approach is not satisfactory to deal with complex systems (it does not take into account their evolution, nested hierarchical structure or structural change).

On the other hand, a second approach will be also presented, in which 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 to be said that, while the former approach has been used mainly by economists and energy statisticians, the latter 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. This latter approach will lead to a specific kind of empiricism to deal with complex adaptive systems, as it will be developed in the next chapter. There a kind of blueprint indicating the relevant points to account for when analysing the exosomatic energy metabolism of societies will be presented.

5.2. Classical interpretation: the case of the environmental Kuznets curve

5.2.1. Introduction

Recently, the issue of the dematerialisation of developed economies (the reduction of material as well as energy intensities over time) has gained popularity in the field of ecological economics. For example, the hypothesis that the use of less energy and resources to produce the same economic output could represent a solution to the ecological compatibility of future economic growth was discussed in a special issue of the journal *Ecological Economics* dedicated to the so called Environmental Kuznets Curve (Vol. 25, 1998). This idea is strongly supported by technological optimists from the perspective of the industrial ecology (e.g. Von Weizsäker et al., 1997, Hinterberger and Schmidt-Bleek, 1999).

However, there are several problems – as we shall see later – with the studies which are used to support such a hypothesis:

(1) The results are based on the 'ceteris paribus' assumption applied to historic series and therefore are difficult to generalise into the future. They therefore do not take into account the basic characteristics of economic systems as complex adaptive systems as explained in the last chapter. For instance, these studies do not account for the possibility that economic systems may adapt to changes in the boundary conditions. This is what happens with the Jevons' Paradox (Jevons, 1990), that lessens the importance of improvements in (energy) efficiency for reducing total energy consumption, as we shall see.

(2) A reduction of consumption per unit of output does not imply a reduction in absolute terms. In fact, the trend of environmental impact will be determined by the different speeds at which the rate of consumption per unit of output is reduced compared to the speed at which the rate of production of output per capita grows.

(3) The variables considered in the historic series considered were reflecting only some of the relevant parameters determining the relationship between Gross Domestic Product (GDP) and the throughput of matter and energy of countries (they do not consider changes in the household sector[65]).

(4) They do not account for the entropic limits to efficiency, which can be improved to a certain extent, but not indefinitely.

From a sustainability point of view this debate is crucial, since this hypothesis is being generalised among policy makers as a progressive and green approach to economic development. For instance, most National Statistics Institutes now calculate the "energy intensity", that is Total Energy Consumption divided by GDP as an "indicator" of sustainability. However, the limitations mentioned above make us sceptical about the real possibilities of explanation of such a hypothesis and about the political implications that might be derived from it.

---

[65] Schipper (1996: 115), for example, said that "the sum of the recent changes in energy demand is essentially a shift in prominence from producers to individual consumers and to the collective consumption of the service industries".

5.2.2. The theory

The so-called hypothesis of "intensity of use" was first put forward by Malenbaum (1978) and states that income is the main factor that explains the 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 as growth in income, until one defined level of income is reached. Beyond that level, however, we have to expect a de-linking between 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[66]. This is the so-called inverted-U shaped curve or an Environmental Kuznets Curve (EKC)[67]. According to this hypothesis, developed countries should be 'dematerialising', meaning that they would be decreasing their use of materials per unit of output, because they have already reached the threshold value of income (or the 'peak' year in historic series). In contrast, developing countries would still be 'materialising', that is, increasing their materials and energy intensity.

The discussion on dematerialisation is specially relevant since the Environmental Kuznets Curve is believed to be able to link a measure of environmental impact (e.g. the requirement of inputs for the economy such as energy and the resulting pollution, i.e. CO_2) to a measure of wealth generation (e.g. the GDP). So, if the energy intensity of modern economies is actually reducing over time, the same will occur for the 'carbon intensity', and other variables reflecting pollutants.

Most of the studies on the intensity of use assume a quadratic relationship between the evolution of the (GDP) and the biophysical throughput. As observed at the beginning, the majority of these studies show:

(1) a growing throughput associated with growth in GDP in the early stages of

---

[66] One remark here is that this hypothesis is opposed to that of Odum, the Maximum Power Principle, explained in Section 2.4.2., since the latter requires that the increase in energy and materials will continue as long as systems develop.

[67] Stern et al. (1996) offers an introductory literature review of the EKC. See also de Bruyn et al. (1998), Opschoor (1997), Arrow et al. (1995), and Ayres (1997).

development, and

(2) a decreasing growth in the throughput compared with the growth of GDP, for the main developed countries (the so called phase of dematerialisation).

That latter phase would imply that economies become more and more efficient in their use of exosomatic energy, in their exosomatic metabolism, leaving room, therefore, for more growth and development in the future without the side effects occasioned by energy dissipation. This is a very optimistic view of the evolution of economies in energy terms.

Traditionally (Mielnik and Goldemberg, 1999; Opschoor, 1997), the de-linking has been explained by three factors:

1) Structural change in the economy, shifting from high energy intensity sectors to lower intensity ones;
2) improvement in energy efficiency;
3) changes in consumption patterns

This 'income determinism' (Unruh and Moomaw, 1998) implies, according to its defenders, that an increase in economic growth is a good policy for the environment[68]. In fact, it will bring, sooner or later, a de-linking from the consumption of energy and materials and wealth, which will lower the environmental impact of economic activity[69]. This result, found for some developed countries, is therefore applied in a deterministic way to the other economies, extrapolating (in time and in space). Thus the analysis gives the same kind of 'universal' advice to policy makers: growth has to be seen as something positive for the environment. Moreover, economic growth can be seen as decoupled from energy and material consumption and, therefore, from environmental degradation. This fact is in contradiction with the historical tendency of economies in the use of exosomatic energy, as we shall see in Section 5.3.

---

[68] Stern et al. (1996) said that one of the major problems of the EKC is this assumption of unidirectional causality from growth to environmental quality, which is assuming there is no feedback from the state of the environment to economic growth.

[69] As noted by Ayres (1995), this historical regularity is taken seriously by economists because it has an interpretation that fits economic theory, namely that as people get richer, they will value the environment more.

5.2.3. The criticism

Despite the optimism derived from the EKC hypothesis, there are several problems with it. In particular 2 points are related to the present analysis:

(1) The expected de-linking implies only a week dematerialisation (per unit of GDP) but not a strong or absolute dematerialisation (decrease in the metabolism of the system).

(2) The de-linking occurs only after the country has reached a certain threshold of income and consumption of energy and materials per capita. Looking at world values, such a threshold is a very high one for the majority of the world's population[70].

From an environmental point of view the second point is rather relevant. This is because the final size of the throughput of the world economy will be determined by *when* all countries will reach the expected threshold level (admitting that this will be possible).

To make things more difficult, three additional explanations should be added to the three presented above for explaining the dematerialisation of developed countries shown by the historical series.

The first explanation is linked to the idea of 'trans-materialization'. This is that the economies of many developed countries are using new resources (or old resources in a different way). This can imply that the changes we track using old indicators of pollution do not necessarily reflect the actual environmental stress induced by modern economies. In this case, therefore, EKCs simply *do not see* what is going on in reality.

The second explanation is similar, pointing again at a poor representation of the phenomenon when using EKC. More and more in the last decades a certain fraction of the economic activity required for sustaining societal metabolism of

---

[70] Here, for instance, as Agras and Chapman (1999) mentioned, too much attention has been paid to shift the turning point to the left (meaning start de-linking with lower levels of GDP), but reducing the overall level of pollution, which is more important, has been given too little attention.

developed countries, especially the most energy and resources intensive, have been shifted to developing countries (for a fuller explanation of this, including statistical data supporting their views, see specially Stern et al., 1996; Suri and Chapman, 1998; and Muradian and Martinez-Alier, 2001). In this case, we simply deal with an externalisation of the phase of possible re-materialisation of the economic process (the environmental impact linked to the production of capital goods is moved to developing countries). Put another way, we are not dealing with a real process of dematerialisation, but just an artefact generated by a sort of *epistemological cheating*. That is, it would be an example of the internationalisation of environmental externalities, or put in other words, an example of 'cost-shifting successes' from northern countries to poorer ones, allowed by social asymmetries in the distribution of (mostly de facto) property rights, income and power (Martinez-Alier and O'Connor, 1999). Damage to the environment due to 'externalised economic activities' simply does not show up in the analysis made at the national level. In fact, as empirical data shows (Muradian and Martinez-Alier, 2001: 289), "the North's economic growth goes together with: (a) increasing consumption of non-renewable resources coming from developing countries; and (b) worsening terms of trade for exporting countries specialized in non-renewable resources". As Stern et al. (1996) noted this strategy of specialising in low energy and resource intensity activities by rich countries is not applicable to the world as a whole; therefore not every country can experience a de-linking phase. In fact, when trade is incorporated into EKC studies (Suri and Chapman, 1998) the turning point of the curve for energy consumption is estimated to be about $224,000 per capita, which is a level unlikely to be attained by any country in the near future. Despite that evidence, even "when economic growth has made people wealthy enough (to clean up the damage done by growth) it may be 'too late to be green'" (Muradian and Martínez-Alier, 2001: 284).

The third explanation is related to the changes over time in the fuels used. Cleveland et al. (1984), Hall et al. (1986), Kaufmann (1992), and Cleveland et al. (1998) have studied in detail this aspect of the historical de-linking of some industrialised economies, leading to the conclusion that an important part of the reduction is due to the change in the fuel used, from low to high conversion efficiency, or quality (i.e. from coal to oil). The different qualities of the fuels (the capacity of doing useful work per heat equivalent unit) can influence energy efficiency (Hall et al., 1986). For instance, in the case of the USA, 69% of the change in the energy intensity since 1929 is due to the changes in the type of fuel used (Cleveland et al., 1984). More specifically, we can say that much of the decline in the energy intensity has been due to the ability to expand the use of higher quality fuels and convertors, and this has upper limits (the availability of scarce high quality energy resources). Nevertheless, this factor is usually forgotten when analysing the EKC hypothesis.

In fact, even admitting that some countries are in a dematerialisation phase (as shown by Jänicke et al., 1989), the entire debate may remain sterile according to the insight provided by De Bruyn and Opschoor (1997). Indeed, some developed countries are in a re-materialisation phase, after experiencing a phase of dematerialisation during the previous years. This, 're-linking hypothesis' implies that an inversion in existing trends could always occur also for those countries that at the moment are still in a de-linking stage. According to this hypothesis, the curve of the throughput versus the per capita GNP, would therefore not follow the inverted-U shaped curve, but rather an N-shaped one (depending on the time window used for observation). That is, the N-shaped curve implies 3 phases:

(1) The use of resources grows in parallel with income growth.
(2) The phase of capital accumulation is followed by a reduction in the rate of materialisation, in which the major increase in output is in the service sector.
(3) At this point a new materialisation phase can start at any moment (when introducing new activities in the economic process). This phase will continue until new technological innovations (increases in the efficiency for the new activities) will allow for a new de-linking.

As shown by these results about the re-linking phase, we have to bear in mind that the phenomenological explanations we can get from processes are always contextual in nature and not universal, depending on the time-space scale considered for the analysis.

Moreover, the hypothesis of dematerialisation considers the implications of the principle of matter-energy conservation, but seems to ignore the implications of other characteristics of complex adaptive systems. For example, changes in cultural identity, institutional changes, technological change and changes in individual preferences, occur in parallel but with different frequencies.

This implies that when making future scenarios reflecting changes occurring now, we should base our analysis not on the 'ceteris paribus' hypothesis, but rather on characteristics reflecting the evolutionary nature of the system considered. This is very important, since the studies that forecast dematerialisation are based on the extrapolation into the future of past historical series. Before using this type of analysis to recommend policies for the future one should, first of all, check whether or not patterns that occurred in the past (e.g. past trajectories of dematerialisation) can be expected to be repeated in the future. This implies understanding which is the right time scale to be used to recognise patterns and to extrapolate into the future.

As stated half a century ago by Schumpeter (1949: 58), "it is not possible to explain *economic* change by previous *economic* conditions alone" (emphasis in the original). One factor, which supports this warning against this extrapolation, is that efficiency implies a faster processing of information and knowledge. This leads, then, to a faster potential depletion of resources (more energy consumption to fuel an enlarged set of activities). This is the so-called Jevons' paradox (Jevons, 1990, another scholar with the same surname as W.S. Jevons). The Jevons' paradox (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 (Giampietro and Mayumi 2000a). 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). There are two relevant aspects to be considered here. One is the fact, well known in economics that improvements in efficiency lead to cheaper resources, encouraging their use. The second is the fact that societies, as complex systems, work at different hierarchical levels. Changes defined at one level (i.e. efficiency in the use of energy by households) cannot be extrapolated to upper hierarchical levels (i.e. total energy consumption in the whole society), because of the numerous feed-backs and relationships that are operating across these levels and among the compartments of the system (see Giampietro and Mayumi 2000a, and

Pastore et al., 2000).

This paradox, which holds in economic theory, has been tested many times. For example, Giampietro (1994) shows how "doubling the efficiency of food production per hectare over the last 50 years, due to a dramatic increase in "efficiency" (...) did not solve the problem of hunger, it actually made it worse, since it increased the number of people requiring food". Another example is brought by Herring (1999) who reports that increases in lamp efficiency in public lighting in the UK took the form of higher level of service, both in more miles illuminated and in higher illumination levels, not in the form of lower consumption.

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, 2000a). 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 (Ostwald, 1907, 1909). The conclusion is that we can be more energy efficient but still consume more energy! Therefore, from an environmental management point of view, one solution might be to remove from circulation resources gained through efficiency improvements (Sanne, 2000), as has been done over time by different civilizations (through wars[71], construction of memorials, religious buildings, palaces, etc.). Another way of dissipating the surplus could be by investing in natural capital or shifting towards more environmentally friendly productive activities. This would avoid the Jevons' paradox.

Another example against the extrapolation is given by Schipper (1996), who after acknowledging the fact that efficiency in households has increased, warns us about the fact that we might be losing these 'economies of scale' due to household size, because recently the size of households has been shrinking. That is, changes in

---

[71] Recently we have seen the US administration changing its policy of reducing public debt with budget surpluses and allocating them in fighting external theoretical threats.

customs have to be accounted for. For example, the tendency nowadays towards more single people and childless couples implies that there are more households, and therefore, greater energy use; “household growth could multiply energy use more than population growth” (Schipper, 1996: 130). The author gives some examples from the USA, Japan and West Germany to support his thesis.

Hall et al. (1986) give other kind of explanations to international differences in energy consumption (mainly in the household sector), based on the different characteristics of the societies (different weather, population density, etc.). These are contextual characteristics not taken into account when doing an EKC analysis looking for universal explanations.

Therefore, intensive variables (i.e. energy intensity in MJ/$) are useful for describing changes in relevant qualities of societal metabolism. However, they are not enough, since they do not reflect the evolution of the throughput and its environmental impact. We need to use parallel, additional variables reflecting the absolute evolution of the throughput (e.g. what is the final value of MJ when we calculate the product “MJ/$ of GDP” x “$ of GDP per capita”).

In conclusion, I agree with Stern et al. (1996: 1158) when they said that “we believe that the problems associated with both the concept and empirical implementation of the EKC are such that its usefulness is limited to the role of a descriptive statistic”. Therefore, a conclusion is that the EKC offers no basis for believing in economic growth as environmentally beneficial (Ayres, 1997).

If we are not happy with this approach, let us explore an alternative explanation of the relationship between economic development (and structuring) and the exosomatic energy metabolism of societies.

5.3. Complex-systems perspective

In contrast with what was presented in the last section, here alternative views on the development of societies are proposed. These views, defended basically by a group of ecologists and economists interested in evolutionary views and with some knowledge of physics and complex systems theory, offer an alternative explanation of the exosomatic energy metabolism of societies and the way they develop by dissipating energy. 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.

5.3.1. 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 (2001a; 2001b) and Krausmann and Haberl (2002), 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 (2002) 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 analysis 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.

In any case, regarding the environmental effects of economic activity and energy consumption, Perrings (1994) tells us that in standard economics there is the assumption of the absence of feedback effects due to the disposal of residuals, whereas they account for the positive feedback effect generated by investment. They are, therefore, not accounting for the changes induced in the system due to the disposal of residuals. This is not the case with the approach presented here, since we recognise that the disposal of residuals in any sector or level of the hierarchical system will induce feedback effects in that system/level, but it will also affect the rest of the sub-systems composing the whole system. Thus, in order to account for such effects (which can give us a picture of sustainability trade-offs), we have to have a clear idea of the size of the system (by using extensive variables), which we will relate to the potential adverse effects that economic processes have upon the environment. Therefore, the sustainability of human development would mean dealing with the compatibility of two interacting systems, the human economic system and the environmental system (Giampietro, 1991) described in non-equivalent terms. Here, the concept of 'environmental loading', as introduced by Odum (1996), is of great relevance, since it tries to account for human interference with the process of self-organisation of the natural system with which humans interact (Giampietro and Mayumi, 1997). Thus, a 'critical environmental loading' could be found (Hueting and Reijnders, 1998), expressing the maximum loading of any pollutant, or the maximum disturbance of the ecological functions of ecosystems which would be compatible with the self-organisation of the system. This is a powerful concept to be used for policy analysis. Indeed, energy consumption can be used as a variable defining the size of the economy and, therefore, the impact of economic activity upon the environment. This is why an analysis on the energy metabolism of economies is relevant for sustainability.

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 (Soddy, 1922), 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 hypothesise that fraction will increase over time, as the system grows. Here we can understand better the implications of the hypercycle as introduced by Ulanowicz (1986) and mentioned here in Section 3.4.4. The hypercycle would be delivering net energy to the system so that it can maintain itself and further develop. We can suppose that this fraction of exergy expended in maintenance will increase as the system does. Let's see now how economic systems use energy as they evolve.

5.3.2. On how economic systems evolve

As noted in Chapter 4, economic systems may be characterised as complex, adaptive, dissipative, self-organising systems. Therefore, it is argued here that the same explanations about how such systems evolve can be applied to the case of economies. 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[72]. 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 combination, yield *creativity* in economic evolution" (emphasis in the original). All of those characteristics will be discussed in this section.

---

[72] 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).

Over half a century ago, Schumpeter 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), something later called 'punctuated equilibrium'. 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, evolution and the maintenance of economic systems far-from-equilibrium is only possible through the irreversible dissipation of energy from the economy, which increases the entropy of the overall environment. Therefore, we can see energy dissipation as the driving force of evolution (Nicolis and Prigogine, 1977). Moreover, evolutionary changes towards more complex and structured systems happen in a discontinuous manner at the different bifurcation points, by some random fluctuations that may be caused either by alterations of the boundary conditions or by internal causes[73], as we shall see in Section 5.3.5. 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

---

[73] As Dopfer (1991) points, one basic distinction between neo-classical and evolutionary approaches to the development of economies is the fact that for the former change is 'caused from outside', whereas for the latter, change must be considered as generated 'from within'.

modified by the system's development itself" (Buenstorf, 2000: 127).

Taking these arguments into account, we can proceed briefly to describe the process of the evolution of a complex system (following Jantsch, 1987), which has been already explained in Section 4.2.4. When the system is far from equilibrium, due to the inflow of low entropy energy from the surrounding environment, a dissipative structure will emerge to stabilise the flows of energy with the environment. As long as more energy is entering the system, this will be pushed towards a critical threshold (the bifurcation point) beyond which a new regime or structure will develop[74]. In the bifurcation point there are several possible equilibria available for the system. Here is where a random fluctuation will drive the system towards one attractor or another. This is a qualitative change in the existence of the system which renews the capacity of entropy generation once the new meta-structure is achieved. This process may be understood as life. The system, therefore, also builds up through positive feedback, which are called 'evolutionary feedbacks' as we saw before. The further the system moves from equilibrium (due to the dissipation of available energy), the more numerous become the possible structures[75]. 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. This will be further analysed in Section 5.3.3.

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[76]. Therefore, as ecosystems develop they should increase their dissipation of energy, and they should also develop more complex structures with more hierarchical levels. They would be able to degrade more solar energy. This is a view which is influenced by Lotka's

---

[74] Once a bifurcation has passed, one choice has been made. Therefore, the other alternative paths of evolution are closed. There is irreversibility (Haken and Knyazeva, 2000).

[75] As Haken and Knyazeva (2000: 72) said, "the future is open and uncertain in our nonlinear world".

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

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

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. What Lotka said was "due to selection pressure on the species, at the system level both the energy efficiency processes and the total energy flow tend to increase". 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 and that is being followed throughout this dissertation. 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).

Following Schneider and Kay, Giampietro and Mayumi (1997) have a particular view on the development of societies. Specifically, when dealing with technological development, they said that it can be described as an acceleration of the energy throughput in the productive sectors, generating a decoupling between human time allocation and the exosomatic energy allocation, meaning that those activities that with development require less human time, require on the other hand a higher amount of energy (their exosomatic metabolism increases). As Proops (1979) noted, economies work because they are using 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. Therefore, a relationship between energy consumption and technological advance can be found, as we shall see later in Section 5.3.5.

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 authors who support and reject what is now called the EKC hypothesis. Among the latter we can find Costanza (1980) and Cleveland et al. (1984), who 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 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 a 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 relativise their results 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 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 the one defended by those who argue for the application of punctuated equilibrium to the development of the energy metabolism of societies, as we shall see in Section 5.3.5.

Thus, we can say that economic growth is related to energy consumption. 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. 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). If we take “self-reflexive” systems seriously, we could explain demographic transitions and improvement of technical efficiency like this. Until now, developed countries would have been following the maximum power principle, but, after realising the problems of energy and materials dissipation (i.e. waste), they would alter their behaviour in order to make them compatible with the maintenance of ecological cycles.

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[77], 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

---

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

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 in changing humanity's behaviour to meet our targets of pollution and system size. This means that we should stress demand policies to slow, and even reduce, population and/or energy consumption, not only in per capita terms, but also in absolute terms. That is, Odum's *prosperous way down* (2000). This reduction in the material standard of living would bring up distributional conflicts, since, as Hall et al. (1986: 531) put it in such explicit terms, "without a growing pie, one group's demand for a larger slice must be taken from another group's slice".

5.3.3. 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)[78]. Regarding this point, Proops (1983), when undertaking an empirical analysis of organisation and dissipation in 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 (hierarchy made of holons) 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,

---

[78] 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.

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.

Ulanowicz (1996) does not see increasing ascendancy (organisation) as something to be equated to the robustness or integrity of the system. One might think that as systems become more organised, they might also become more fragile. However, 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.

Holling (1996: 32) relates this 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 a different 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.

5.3.4. 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* to 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.

Before entering on the discussion of energy and technology, we have to remind ourselves of Ulanowicz's terminology introduced earlier in Section 3.4.4., since it will help to understand the autocatalytic character of technology. We can see in human society the two different compartments described by Ulanowicz: the hypercycle, a net producer of useful energy for the rest of society; and other dissipative, which is a net consumer of useful energy. The hypercycle can also be seen as an autocatalytic loop. 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 with 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. This result is not bad on 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[79]. 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. This would explain recent "oil wars" in which richer countries try to guarantee a cheap supply of this high quality energy carrier. 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. This link between energy dissipation and economic productivity of labour will be checked later in this thesis.

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

---

[79] Ostwald (1909) first advanced this ideas. Later, Cottrell (1955) 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" (quoted in Cleveland, 1987: 56).

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. One may think of the services sector as a proxy for this measure.

Giampietro and Pastore (1999) see the process of economic development as highly related to the dissipation of energy. They 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. This means that different patterns for energy dissipation between groups of countries can be found.

The fact that technological change is related to energy dissipation, and the fact that new technologies involve greater dissipation than old ones, implies that “in building up large amounts of capital goods and in generating the corresponding technical knowledge, irreversibility is created, which can be weakened or changed only in the very long run” (Faber and Proops, 1998: 79). That is, it implies lock-in and path dependency, as explained above in this section and later in Section 6.1.

Finally, for Georgescu-Roegen (1971), who also analysed this relationship, technological innovation has an impact upon the economic process in two ways. It induces an industrial rearrangement and it produces a consumer reorientation, implying therefore a structural change in the society, or the appearance of novelty. As noted by Faber and Proops (1998), the implications of the emergence of novelty and the environment are that we should look for flexible responses, in order to increase adaptability, as we shall see in the next chapter, in Section 6.6.

5.3.5. 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 (non-linear behaviour and the presence of attractor points, bifurcation points, novelty, etc.), 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.

For example, Gowdy (1994)[80] applies to the economy the vision, originated in palaeontology, of the evolution as a 'punctuated equilibrium' (Eldredge and Gould, 1972)[81]. This is the new name for something that has been studied before by

---

[80] See Gowdy (1994) for an application of 'punctuated equilibrium' to the evolution of economic systems, and Foster (1997) for an sceptical viewpoint of that use.

[81] Gould (1992: 12) when talking about the original idea said, "Eldredge and I argue that most species are stable for most of their geological life-times, often lasting many millions of years – the

Schumpeter, who 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). 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”. This translates in economic terms to the existence of a set of possible typologies of metabolic systems.

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

---

equilibrium – and that change does not usually occur by imperceptibly gradual alteration of entire species but rather by isolation of small populations and their geologically instantaneous transformation to new species – the punctuation”.

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, as it will be argued in the next chapter.

As van den Bergh and Gowdy (2003) say, “the punctuated equilibrium debate is relevant as a general lesson for the social sciences because it demonstrates the need for theory of evolutionary change incorporating hierarchies of causality”. No longer will evolution be seen as a matter only for the individual organism, but also we have to account for macroevolution in the upper hierarchical levels of the system. 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, is not a deterministic hypothesis, rather it has more to do with historical regularities (the frequencies).

5.4. Conclusion

Due to the fact that economic systems are in constant evolution, their structure is incapable of exact definition. The most we can say is that systems’ parameters change more slowly than their variables. Therefore, our estimates of the parameters have to be contextual or contingent (Clark et al., 1995). This result, as we shall see in the next chapter, is of special relevance when analysing which kind of empirical analysis to use to deal with open complex systems.

I agree with Prigogine (1987: 102) that “the universe has a history. This history includes the creation of complexity through mechanisms of bifurcation”. I would also add that a consequence of that complexity is self-organisation, which is fuelled by the tapping of energy and materials from the environment, in order to maintain complex systems far from thermodynamic equilibrium.

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 tells 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).

Particular care has to be taken to avoid that the de-materialisation of some countries (the developed ones) is obtained by an over-materialisation of some others (the developing ones). That is, we have to consider the current generalised internationalisation of environmental externalities, which Mielnik and Goldemberg (1999) have identified in the case of CO_2. The countries included in Annex I to the Framework Convention on Climate Change (developed ones) would be ‘de-carbonising’ (in relation to their GDP), while the countries not included in Annex I (developing ones) would be ‘carbonising’, basically due to ‘surrogate emissions’ (Kopolo, 1999). Surrogate emissions in developing countries are those generated by the production of goods and services that are going to be consumed in the North. As Machado et al. (2001: 422) show for the case of Brazil in 1995, “the total energy and carbon embodied in the exports of non-energy goods reached 831 PJ and 13.5 MtC, respectively". These figures are much higher than the embodied energy and carbon of imports. In other words "each dollar earned on exports embodies 40% more energy and 56% more carbon than each dollar spent with imports" (Machado et al., 2001: 422). Thus, the attitude of international agreements, and national governments, should be aimed at inducing structural changes to revert the tendency of the energy intensity as well as to reduce, later on, the exosomatic metabolism of the system. This implies that the throughput of the economy should be compatible with several environmental thresholds besides being compatible with the expectations of humans for a better standard of living. From a strictly environmental point of view, ecological constraints are independent from human wants.

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, i.e. Jevons' paradox).

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, as we shall see in the next chapter, asks for a new kind of empiricism and for a new epistemology of complex systems (which was presented in Section 4.3.).

CHAPTER 6[82]: EMPIRICISM IN ECOLOGICAL ECONOMICS: A VISION FROM COMPLEX SYSTEMS THEORY

6.1. Introduction

Ecological economics deals with, and is related to, policy generation and, in order to do this needs numerical data about both human and natural systems. It is the goal of this chapter to analyse the role of empiricism in the framework of neo-classical environmental economics and ecological economics. After doing that, the chapter defends a phenomenological and ex-post analysis to deal with the complexity of modern economies, by giving some examples of empirical work already done under this view.

The concepts underlying ecological economics and neo-classical environmental economics will be outlined, to emphasise that the latter makes some strong implicit assumptions about the working of systems under its analysis (i.e. economic systems). These assumptions are compatible neither with the main characteristics of present complex environmental systems nor with the nature of economies. This is why ecological economics deals with both the problems and the systems in an alternative way.

The structure of the rest of the chapter is as follows: Section 2 focuses on the conceptual structures in ecological economics and in neo-classical environmental economics from an evolutionary perspective based on the concept of time. Section 3 presents the debate about the role of policy for sustainability purposes. Section 4 presents the position of these two schools of economic thought on empirical analysis, focusing on time and evolution. With this background, Section 5 mentions some of the latest developments in empirical analysis that have been published in the field of

---

[82] This chapter builds on the paper of the same title published in the Journal *Ecological Economics*, Vol. 46(3): 387-398, 2003.

ecological economics, and that are an example of what could be empirical analysis when dealing with complexity in ecological economics. Finally, Section 6 reaches the conclusion that a predictive use of econometrics in ecological economics is not possible. This leads to presenting the way ahead regarding empirical analysis in ecological economics, and its relationship to policy formulation.

6.2 Conceptual structures in ecological economics and in neo-classical environmental economics

6.2.1. Neo-classical economics

Neo-classical economics focuses on the exchange of goods and services among the economic agents, such as consumers and producers, emphasising the role of consumer preferences and resources endowments, to guarantee the economy's equilibrium. 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 then the history of processes), linearity, and a consideration of the environment only as a given boundary. This means that the methodology developed by neo-classical economics, general equilibrium theory, guarantees the achievement of a solution in the allocation of scarce resources (Faber et al., 1996).

To understand better neo-classical economics we might think that it follows classical mechanics in its description of the economic process. That is, production, 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, p.319), it "is a mechanical analogue". As in mechanics, economists are seeking "universal laws" that can be applied everywhere and regardless time. Once laws are defined and basic principles or axioms are accepted, then this economics must be a theoretical science, deductive, and deterministic, capable of finding *unique optimal solutions*.

With its emphasis on allocation in markets, neo-classical theory cannot deal with the issue of the scale of the economy with respect to the environment (Daly, 1992). Rather, its analysis is supposed to be valid for any scale; that is, it is the same regardless of space and time. This is a key difference from ecological economics, as we shall see later, since it is precisely the issue of defining the boundaries of the system that is relevant for this discipline. As Hall et al. (1986, p.526) said, "nature no longer affords us the luxury of ignoring or downplaying the role of natural resources".

The same problem that is found with scale is present when dealing with time. Since neo-classical economics follows mechanics, where all processes are reversible, its equations and models are also 'time symmetric', where time is just a cardinal magnitude, which can, therefore, be added or subtracted (Beard and Lozada, 1999). At this point it is worth recalling Georgescu-Roegen's distinction between 'time' and 'Time' as we presented in Section 2.2.2. Using his own words (1971, p.135), "*T* represents Time, conceived as the stream of consciousness or, if you wish, as a continuous succession of "moments", but $\underline{t}$ represents the measure of an interval (*T'*, *T''*) by a *mechanical clock*" (emphasis in the original). Neo-classical economics claims the theory to be valid in all societies, that is, to be a-historic, because they are considering *time*, instead of *Time.*

Natural resources economics, or neo-classical environmental economics, deals with the environment by analysing the threats of scarcity and pollution using the traditional ideas described above. The methods developed have been: (i) optimisation in the case of managing natural resources (either renewable or exhaustible), and (ii) assigning property rights on pollution (or more generally externalities) in order to incorporate them into the price system, and thus, in the decision process under the market mechanism. This is 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, neglecting two basic things. On the one hand, there are services provided by nature that are not substitutable at all (like the water or the carbon cycles). On the other hand, “from a physical perspective substitution cannot replace energy completely (including the energy of labour) because each factor of production depends ultimately on an input of net energy for its own production and maintenance” (Hall et al. 1986, p.46). It could be added that we can interpret the relationship between energy and matter, or any kind of production factor, as largely that of complementarity rather than substitutability.

All of these characteristics of neo-classical economics, and its environmental branch, led to it being viewed as having difficulties dealing with new and complex problems, such as environmental problems. As Clark et al. (1995) pointed out, the mechanical character of economic models does not allow them to treat evolution or structural changes in the system. This fact led to the proposing of new approaches, such as those developed by ecological economics.

6.2.2. Ecological economics

Ecological economics takes production, or the transformation of energy and materials, as its focal point, as it was done by classical economic thought, but it uses in its analysis the insights derived from thermodynamics, i.e. the second law of thermodynamics that introduced the issue of irreversibility. It is, then, an evolutionary science. An evolutionary science deals with historical events, and the processes between the events; that is, it deals with the issue of time. Using Georgescu-Roegen’s distinction about time, 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.

Ecological economics also deals with new complex adaptive systems, as presented above. Ecological economics, thus, unlike neo-classical environmental economics, focuses, among other things, on evolution of economies, on the process of *becoming*, on structural change, and the emergence of novelty (in the form of technological change, for example), all features shown by complex adaptive 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. This is one reason to ask for a new epistemology, as it is done in the next section. In fact, the more research we apply, the more uncertainty is generated, new questions arise, and new relationships between variables are found. As we already have shown in Section 3.5., Faber and Proops (1998, p.110) when talking of environmental problems, put this way "very often they involve the emergence of unpredictable events (novelty) (…) this implies that the simple sequence of problem → science → technique → solution is not necessary valid. On the contrary, we experience that our increasing knowledge may even impede the investigation for solutions". This fact causes the issue of unpredictability, relevant for ecological economics, and especially for policy generation.

6.3. The role of policy

In economics, the role of policy is viewed differently depending on the school of thought taken. Neo-classical environmental economics conceives of the existence of policy based in economic analysis. It analyses market failures that induce environmental externalities, and tries to design policy to 'correct' these failures, and eventually give optimality. To do that, it uses the tools explained before in Section 6.2.1.

However, the new environmental 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). In this context, ecological economics defends a new epistemology to deal with complexity. So, 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). Ecological economics is said to be an example of post-normal science (Funtowicz and Ravetz, 1994), as it has been discussed in Section 4.3.2.

6.4. 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, inside 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, p.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 than the positivist one. It acknowledges that when dealing with human systems, these have the intrinsic characteristics of changing and evolving in time, of becoming, due to external factors (i.e. shocks) or to internal causes, such as changes in preferences, technologies, or institutions. This fact makes it impossible to consider them as uniform and unchanging, so, in order to explain them, we have first to understand them.

Neo-classical environmental economics defends a position favourable to the use of predictive analysis 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, neo-classical environmental economics supports an ex-post analysis for ex-ante predictions because is implicitly based in classical mechanics where that is possible. This is because the basic characteristics of physical systems are described by universal laws; that is, they are not subject to structural change (i.e. gravity is stable, and so on). But this is not the case with biological systems and, in particular, human systems, where the underlying characteristics of systems, and therefore the same occurs with the parameters that we use to describe those characteristics, are *constantly* evolving, making prediction much more problematic (Faber et al., 1996). So, neo-classical environmental economics would be extrapolating past results into the future by assuming two things; one, that the parameters defining both the system and the relationships between the different variables 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, these assumptions seem not to apply, since systems are constantly evolving and becoming, 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.

Ecological economics, therefore, can 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.

6.5. Recent empirical work in the field of ecological economics

With this background on how the conceptual structures of both neo-classical environmental economics and ecological economics can be defined, and with the different roles of policy and empirical analysis that each discipline defends, the next step is to proceed with an exemplification of the kind of empirical work to be carried out in ecological economics when dealing with complex systems.

Most of the work published in the field of ecological economics 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 in the genotypes. With this analysis, they can recommend policies based on the results of their projections, that is, based in the extrapolation of past results. Then we can say that 'science' seeks to 'model' the genotype so it can predict the phenotype. But, scientific data is only on the phenotype (the realisation or representation of the potentiality of that system). So, if the phenotype changes, observations on phenotypes are a poor basis for modelling and prediction. This is what is happening with an important portion of empirical work in ecological economics, that they are not matching the technique to the problem analysed. 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; that is, to their evolution or process of becoming.

There is, however, another way of understanding empirical analysis in ecological economics. Perrings and Walker (1997) use a model of resilience and empirical analysis to explain the importance of fire in the self-organisation of semi-arid rangelands, being 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. 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 (i.e. different types) 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 have an ex-post analysis for an ex-ante prediction about the future, recommending economic growth as a solution for environmental problems. But, on the other hand, there are some exceptions, like Rothman (1998), Suri and Chapman (1998), Unruh and Moomaw (1998) or De Bruyn and Opschoor (1997).

Recently, another group of papers dealing with societal metabolism have tackled the issue of complexity in economic systems. In particular, the papers use a new approach, called Multiple-Scale Integrated Assessment of Societal Metabolism (MSIASM), in relation to sustainability of human society. A detailed presentation of theoretical aspects, a numerical validation, and applications in the form of case studies have been presented elsewhere (Giampietro and Mayumi, 2000a,b; Pastore et al., 2000; Ramos-Martin, 2001a; Falconi-Benitez, 2001; Gomiero and Giampietro, 2001). In particular, Ramos-Martin (2001a), extending some research initiated before (Ramos-Martin, 1999, 2001b), dealt with the historical evolution of energy intensity in Spain to respond to the debate on the environmental Kuznets curve with a counterexample (see Chapter 7).

The relevant point here is that all of these papers took the phenomenological approach and dealt with an ex-post understanding on how systems work, by trying to find statistical regularities that reflect the underlying characteristics of economic systems, but without any aim of predicting the future using past parameters. On the contrary, the aim of these papers was to explain how the system 'got there', what were the mechanisms underlying the behaviour of some key variables, such as energy consumption. This is why I think they are an example of the kind of empiricism I understand should be applied when dealing with open complex economic systems.

6.6. 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. 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, which will drive the system towards one attractor or other. For example, internal causality may be caused by feedback loops between the different hierarchical levels of the system. We should bear in mind that when the 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).

So, if a basic characteristic of complex systems is that "they can only be approximated, locally and temporarily, by dynamical systems" (Rosen, 1987, p.134), but we still try to control them by using predictive dynamic models, we may face a "*global failure*" (Rosen, 1987, p.134, emphasis in the original) in the form of a growing discrepancy between what the system is doing and what the model predicted. This is one of the reasons why normal science is losing credibility among citizens, and why post-normal science, with its interest not in finding 'truth' but on giving good quality information for the decision-making process, is viewed as a way out of that difficulty.

When analysing data, in order to tackle complexity we can adopt the idea of triangulation (Ramsay, 1998) or parallel non-equivalent descriptions (Giampietro and Mayumi, 2000a). This idea consists of using more than one source for the data, analysing the data with different theories or models, or using different hierarchical levels, in order to gain robustness in our analysis and give more credibility to scientific analysis. This will bring redundancies, which are rather positive since they will reinforce the argument or the regularities that we may find. This is thus an argument in favour of a inter-disciplinary approach to sustainability, in which the different readings of the different disciplines are seen as compatible in generating the overall understanding of the structure of the system, and its development.

If we cannot use empiricism for prediction, as econometrics does, what kind of empiricism can we use? In ecological economics we are interested in evolution, the process of becoming, structural change and the emergence of novelty; therefore, first we have to bear in mind that since stochastic processes are dominant in nature, scientific theories should be more down-to-earth, based in direct observations. Then, we should use empirical analysis not to give the exact values of the parameters in 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, characterised by irreversibility and stochasticity, with their numerous possible trends, their uncertainty, the emergence of novelty, makes them largely unpredictable. That is, ex-ante modelling is often not possible. We have to admit that there are no deterministic explanations (universal and a-historical). Rather we can describe and understand these systems by finding historical and spatial, regularities, and by looking at the emergence of such systems' properties. This leads us to admit that the knowledge we can obtain from complex systems is context dependent (Clark et al., 1995); it is dependent on the time window considered and also on the spatial context. This is the reason why, as pointed out by Boulding (1987), the failure in our predictions are not the responsibility of human knowledge itself. Rather, it reflects an inherent property of complex systems, that of unpredictability. Therefore, our failure might come either because we do not know the parameters of the system (ignorance) or because they change very rapidly (emergence of novelty, evolution) reflecting structural or genotypical change caused by external shocks or by internal causality within systems (e.g. chaotic behaviour).

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). This is part of the process of guaranteeing transparency and fairness in the process of decision-making, by promoting a continuous dialogue with stakeholders and policy makers. 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;
- 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, p.728).

The implication of the argumentation presented before is that complex systems 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 (Martínez-Alier et al., 1998).

Thus, the fact that the future is open has some repercussions from a policy perspective. This openness asks for what has been called 'soft management' by Haken and Knyazeva (2000). This has to be understood as encouraging flexibility in response to changing boundary conditions. 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 the system.

In conclusion, in complex systems prediction is not possible not only because the parameters defining the relationships between variables may 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. Consequently, a predictive use of econometrics in ecological economics is not possible when dealing with complex systems. Rather, the phenomenological approach presented here, and exemplified by the papers mentioned in Section 6.5 dealing with an ex-post analysis, seems 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. This may also include, as stated above, the use of econometric analysis to account for *past* developments and trends. At the end, history *does count*.

CHAPTER 7[83]: HISTORICAL ANALYSIS OF ENERGY INTENSITY OF SPAIN: FROM A "CONVENTIONAL VIEW" TO AN "INTEGRATED ASSESSMENT"

7.1. Introduction

As presented in Section 5.2. the issue of dematerialization of developed economies has gained popularity in the field of ecological economics. However, from what was learned in that section we may not be happy with the explanations given so far. This is why, in this chapter, I present for Spain: (1) the conventional analysis of this relationship, using the definition of the concept of energy intensity used in these "conventional" studies; (2) a representation of changes based on an evolutionary approach; and (3) an integrated assessment, in order to generate non-equivalent descriptions of the same process.

The case of Spain is relevant since the development of its energy intensity over time, at the moment, is not following the hypothesis of the Environmental Kuznets Curve (EKC) or the inverted-U shaped curve. Therefore, trying to understand the reasons of this anomaly can also help to better analyse the robustness of the hypothesis of dematerialisation of modern economies.

In the following analysis I consider the economic process as the production and consumption of goods and services through the transformation of energy and matter. Daly (1991: 36) has called this transformation the 'throughput' (the entropic physical flow of matter-energy from nature's sources, through the human economy

---

[83] This chapter builds on two papers. The first, of the same title, published in the Journal *Population and Environment*, 22: 281-313, 2001. The second, a Spanish version of the article, "Intensidad energética de la economía española: una perspective integrada", *Revista de Economía Industrial*, 351 (III): 59-72, 2003 offers some of the data until year 2001.

and back to nature's sinks). This can also be described as the 'metabolic flow' of society following the ideas of Georgescu-Roegen.

The following analysis of changes in intensity of use in Spain is based on a simplification that implies considering the level of throughput of a country as an indicator of its environmental impact. Lack of detailed data upon different types of pollution and their location specificity prevents the possibility to perform, in parallel, different studies to track changes in different material throughputs linked to these pollutants. This is the reason why, in general, data of consumption of energy and resources use are used as a proxy of the consequent output. That is, assessments of the input side of throughput are used as indicator of environmental impact. Especially, when dealing with CO_2 this is a quite reasonable choice.

Evidence of the German case (De Bruyn, 1999) shows that sometimes such a relationship between material throughput and GDP is not continuous, but shows some 'jumps'. This kind of behavior is the one tested here for the Spanish economy in section three, after presenting data showing the increase of its energy intensity in section two. Non-linearity in energy metabolism of Spain can be explained by analysing its process of becoming more energy intensive. In order to do that, I apply here the methodology used by De Bruyn (1999), a phase's diagram, which represents the intensity of energy use of the year ***t*** and that of the year ***t-1***. This alternative view makes possible to check the validity of the hypothesis of a continuous trend of dematerialisation, or the alternative hypothesis of alternate phases of dematerialisation and re-materialisation around certain 'attractor points', the so-called theory of 'punctuated equilibrium' (Eldridge and Gould 1972; Gowdy 1994).

Finally, I use an integrated assessment of exosomatic metabolic rates of various economic compartments, to characterise economic development and energy metabolism of Spain. The model has been presented in Giampietro and Mayumi (2000a, 2000b), and also used by Falconí-Benítez (2001) to assess the recent history of economic development in Ecuador. The relevance of this additional non-equivalent analysis is determined by its ability to provide new insights for the same facts (the changes in economic development and energy intensity of Spain presented in Sections 2 and 3). This is obtained by: (1) focusing on the development of economic and energy productivity of different sectors of the economy and by including in such an analysis also the household sector, usually neglected in the analysis on EKC. (2) combining biophysical indicators (such as human time allocation related to energy consumption per unit of human activity) with economic indicators.

Therefore, the structure of the rest of the chapter is as follows:

* Section two presents briefly the theoretical explanations about the issue of dematerialisation found in the literature. Then, the evolution of energy intensity of Spain is compared with other countries, using the conventional approach.

* Section three deals with the 'evolutionary' perspective of dynamic systems, showing the phase diagram for Spain and the non-linearity that characterises its energy intensity.

* Section four presents an integrated assessment of exosomatic metabolic rates of different economic compartments, pointing at the special relevance of the demand-side (household sector). This section compares the behavior of Spanish economic development to that of Ecuador as presented in Falconí-Benítez (2001). When considering the dynamic of exosomatic energy metabolism of the various sectors linked to demographic changes, it becomes clear that Spain followed the other side of the possible bifurcation in economic development (a positive spiral in which surplus generated more surplus at a faster rate than population growth).

* Appendix – this section provides explanations for calculation and data sources.

7.2. The conventional representation of energy intensity

7.2.1. The Empirical Data on Changes in Energy Intensity of Spain

This analysis is focused only on the relationship between GDP and the consumption of commercial energy, considered as a proxy of an intensive indicator of throughput. The variable ‘energy intensity’ is “Total Primary Energy Supply” divided by “GDP” and it is expressed in MJ/US90$ GDP) – [1 MJ= 10^6 joules].

A set of countries following the hypothesis of dematerialisation is shown in **Fig. 5**, where we can see how energy intensity in the OECD, USA, Japan, and EU has been decreasing in the period 1960-1996. These curves can be used for a comparison with Spain.

As expected according to the theory, India, Malaysia, and Mexico (**Fig.6**), three developing countries, show, when analysed from 1970 to 1996, growing energy intensities. According to the hypothesis these developing countries are still increasing the energy intensity since they did not reach the “threshold value” yet. However, the problem comes with the curve of Spain (the lower curve in **Fig. 6**), that also shows a continuous growth in this variable, over the same time window considered for the other OECD countries in **Fig. 5**.

Figure 5: Energy intensity for the OECD, the USA, the EU, and Japan (1960-1996) in MJ/US90$

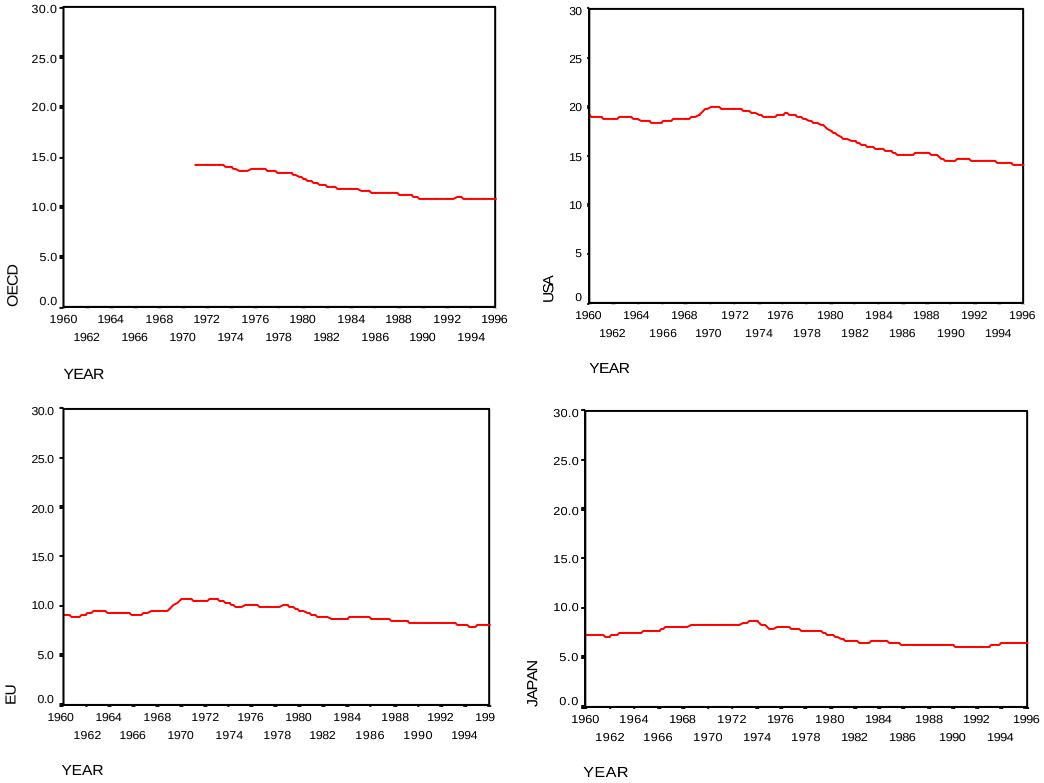


Figure 6: Energy intensity for India, Malaysia, Mexico, and Spain (1960-1996) in MJ/US90$

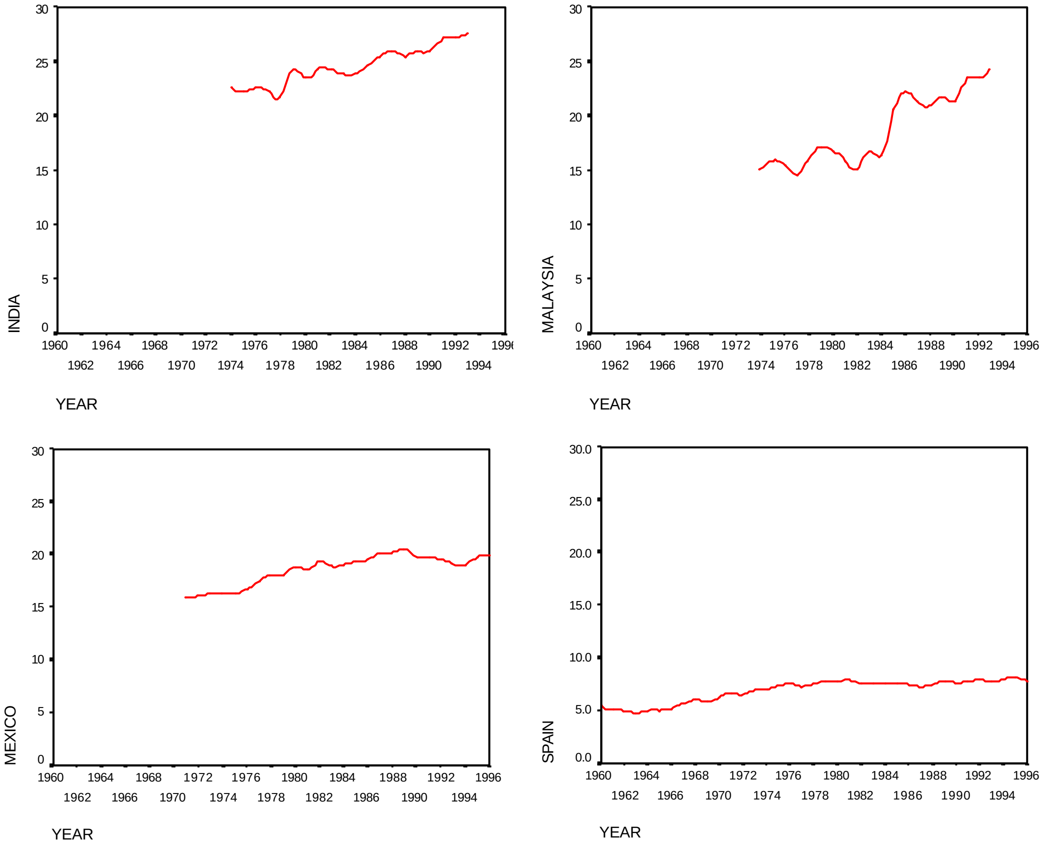
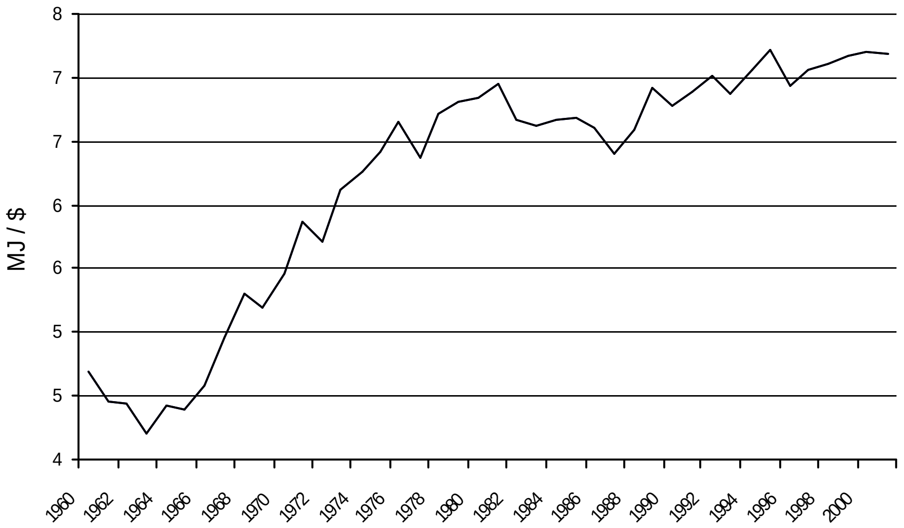


Figure 7: Energy intensity for Spain (1960-2001) in MJ/US95$



Two points from the graph of Spain in **Fig. 7** deserve attention. First, without doubts the Spanish economy is increasing the energy intensity over time. Second, this tendency is not continuous. In fact, we can see how energy intensity increased very quickly from 1963 to 1981 (from 4.2 to 7 MJ/US95$), remaining around the value of 7 MJ/US95$, with light ups and downs until 2001, when it reached 7.2 MJ/US95$. Therefore, according to this graph, we can say that Spain does not follow the hypothesis of the inverted-U shaped curve. However, someone can argue that this is due to the fact that Spain has not yet reached the inflection point or the 'peak' year. Put in another way, the economy of Spain is still not developed enough to start dematerialising. This objection can be rejected easily. As it is shown by Unruh and Moomaw (1998: 225), the majority of developed countries following the EKC hypothesis show their peak year for energy intensity in the 1970s. This year is linked to values of GDP per capita comprised in the range between: 9,000 US$ (Austria on the lower side) and 15,500 US$ (USA on the higher side). The majority of countries have their turning point at a value of about 11,000 US$ GDP p.c. in their peak year.

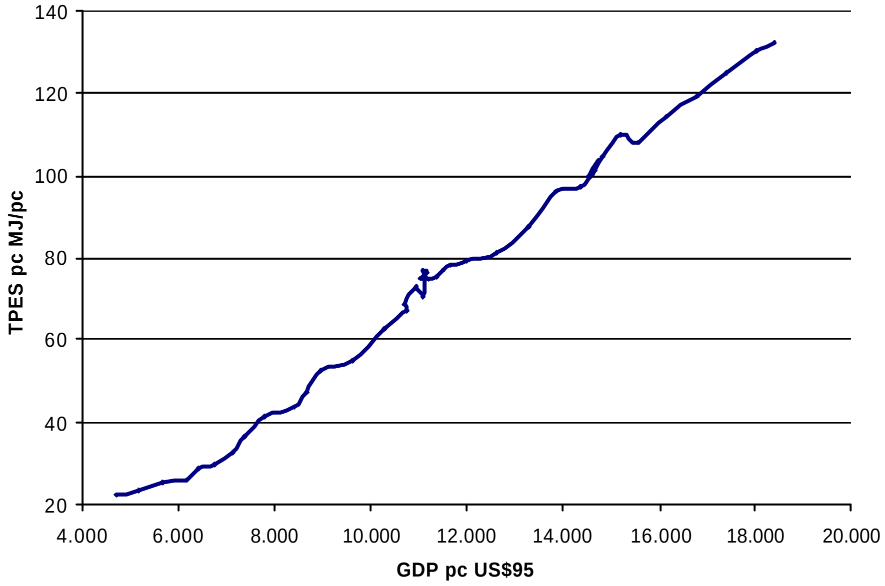
Spain, which is far from being a fuel-based economy like the USA or Canada and that, because of that, should show a behavior more similar to Austria, still shows a growing energy intensity in 1996 after having surpassed the13,500 US$ of GDP p.c. That is, if the hypothesis were true Spain should have shown signs of dematerialisation much earlier.

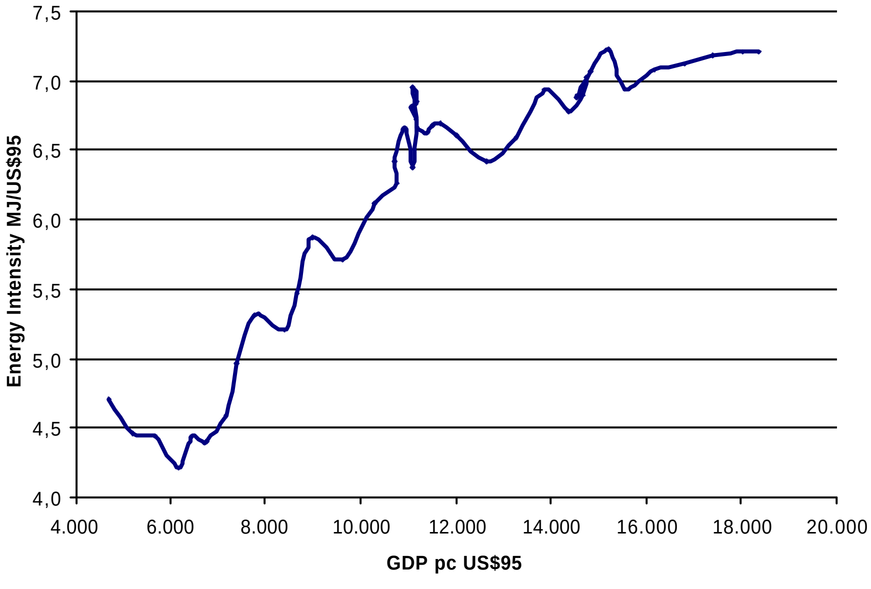
The same result (Spain does not follow the trend of other developed countries) is obtained if we graph the relationship between the indicator of throughput per capita (TPES per capita) and the GDP per capita (the famous EKC), or the energy intensity and the GDP per capita. These two curves are shown in **Fig. 8** with data from 1960 to 2001. The graphs shown **Fig. 8** confirm what already seen in the graph of **Fig. 7**: (1) Spain has not reached the peak year; and (2) the evolution of energy intensity is not continuous, but with ups and downs.

Figure 8: The Environmental Kuznets Curves for Spain.

A= Total primary energy supply per capita in Gj/year

B= Energy intensity in Mj/$





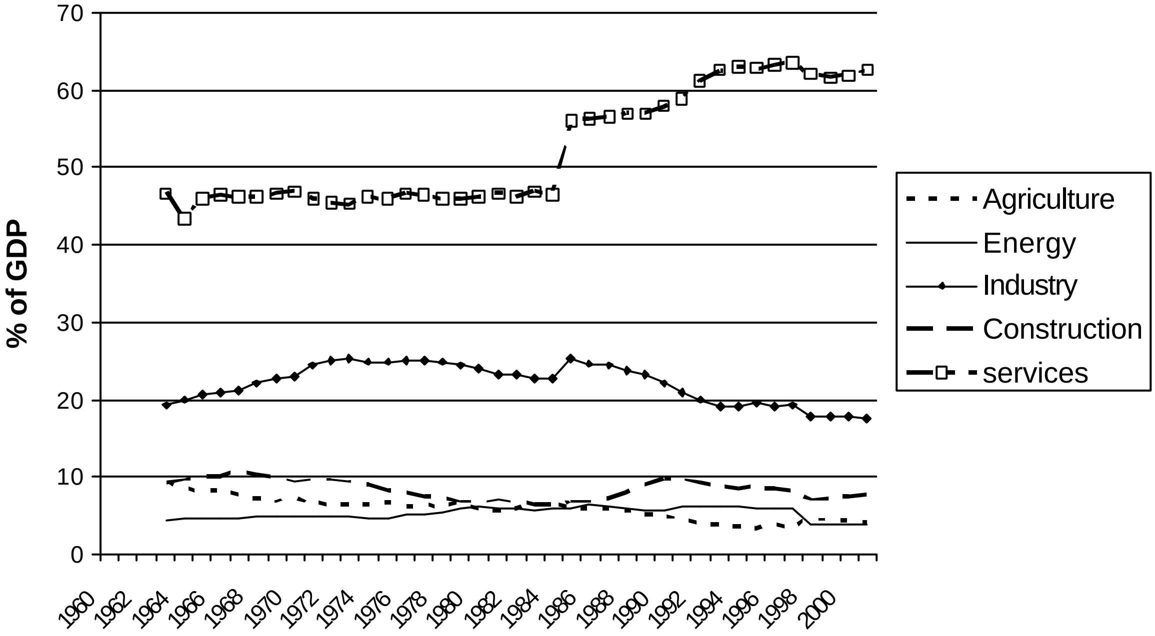
7.2.2. Possible Explanations of these Changes by Looking at Sectorial Changes

Some authors (Simonis 1989; Jänicke et al. 1989, quoted in De Bruyn and Opschoor 1997) state that technological and institutional change, or generically "structural change" (that includes changes in consumption patterns), are the main causes of the evolution of energy intensity. This fact can explain that after the first oil crisis in the early 70s, the energy intensity in Spain grew rather than decreasing as in other developed countries. In that occasion, the Spanish government (following the advice of the IMF) just compensated the rising prices with subventions, postponing the adaptation of the economy to higher prices. However, after the second oil crisis in the late 70s, the intensity of some economic sectors was finally decreasing due to two reasons: (1) the government did not use again subventions, allowing increases in prices. This fact made energy, a production factor, more expensive not only in absolute terms but also relatively when compared with capital or labor. Thus, most industries adapted to the new situation and improved efficiency as well as changed the mix of fuels. (2) a deep industrial restructuring, which started in the early 1980s, implied closing down many traditional factories, with high energy consumption levels, like shipyards and steelworks.

This is the main factor that seems to explain the changes in Spanish evolution. That is, local decreases in the variable "energy intensity" were reflecting structural changes (i.e. the economic restructuring mentioned before) rather than a smooth change in the evolution of the energy intensity.

Indeed, in the case of agriculture and construction, the energy intensity has been more or less stable after the pull up of the 1960s, whereas the relative importance of the sectors (as a percentage of the total GDP) has decreased over time (**Fig. 9**). The industrial sector shows a similar evolution, in which the contribution to GDP is decreasing since 1973 as well as the energy intensity (although not continuously) as we shall see later. This evolution is similar to that of some other developed countries that are shifting from industry to services.

Figure 9: GDP structure in Spain



However, the service sector has not grown very much. The energy sector grew only until 1980. All of the three sectors show, with some differences, growing tendencies in energy intensity. This fact is especially relevant for the service sector, due to its size.

From these data we can say that, it is true that Spain is shifting its economic activity to the service sector, but at the same time it is also true that this sector is increasing its energy intensity. This tends to compensate the reduction of energy intensity in industry and to increase the overall energy intensity of the economy.

Finally, an additional explanation of the peculiar evolution of the energy intensity of Spain is that the country has not yet shifted matter-energy intensive industries to the developing world, as some other developed countries that follow the inverted-U shaped curve have done. However, in order to check this hypothesis, we should have available data on the evolution of both the international trade and the internal consumption of these intensive goods, something that has been already done, for instance by Carpintero (2003a, 2003b) and Cañellas et al. (2004).

7.3. The evolutionary analysis based on a phase diagram

This section presents an alternative approach to deal with the study of energy metabolism of societies. This approach is used to investigate two relevant points emerged in the analysis presented before: (1) the hypothesis of dematerialisation does not apply to Spain (nor the EKC); and (2) changes in energy intensity do not follow a continuous smooth curve.

7.3.1. The Perspective of Dynamic Systems

From the criticism presented in Section 5.2.3., and the characterization of economies as complex, adaptive, self-organising systems developed in previous chapters, 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.

This idea might explain the ups and downs of energy intensity for Spain. That is, the results of "improvements in efficiency" can induce oscillations (decreases of consumption at one level followed by increases in consumption at a different level) in energy intensity.

Another relevant aspect of human systems (i.e. individuals, household, whole economies) is that they are 'dissipative systems'. When describing them in biophysical terms, we can say that they are open systems not in thermodynamic equilibrium that maintain their internal organisation by consuming constantly energy carriers (food in the case of humans and fossil fuels in the case of economies). The very concept of societal metabolism implies that the economic process can be described in biophysical terms as the stabilisation of matter-energy flows linked to the production and consumption of goods and services. Dissipative complex systems interact both with the environment and with each other continuously adapting to new circumstance. That is they co-evolve with their context. Due to the necessity of this continuous interaction and adaptation, it is impossible to expect that these systems will operate with success having accessible only a single state of equilibrium for their societal energy budget. Rather the most probable solution is that they have accessible a set of possible points of dynamic equilibrium.

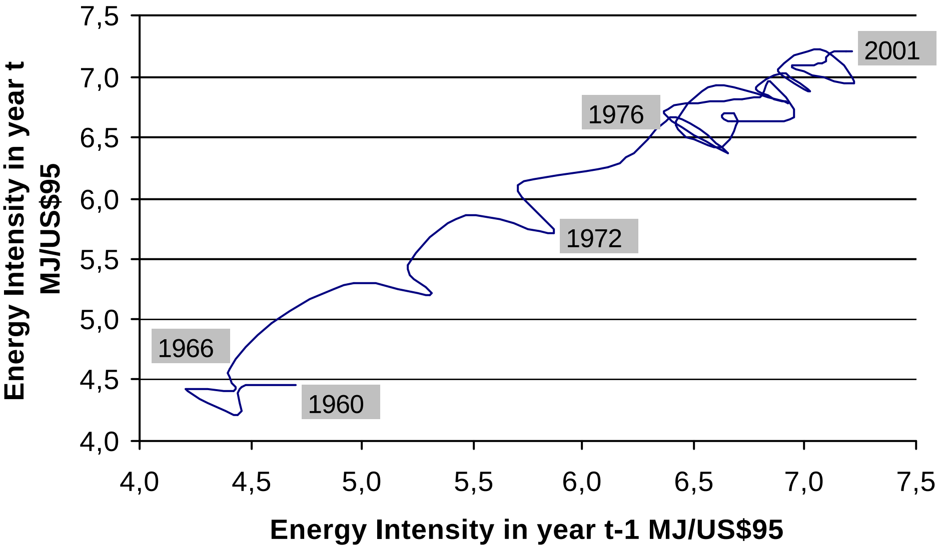
7.3.2. Representing Changes in Energy Intensity on a Phase Diagram

According to what discussed previously, it is difficult to describe the behavior of societal metabolism by adopting traditional linear techniques. Whereas non-linear dynamic techniques allow us to observe patterns of temporal behavior and intermittent changes in the set of considered variables.

In particular we may recall here the discussion developed in Section 5.3.5. on the discontinuity of economic evolution in time. 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 diagram for energy intensity for Spain is shown in **Fig. 10**. In the Y-axis the energy intensity in the year ***t*** is represented (expressed in MJ/US95$), and in the X-axis, the same variable in year ***t-1***. The various points obtained in this way are then joined by using a line. If the increase in energy intensity observed in figure 2 would be due to gradual changes in intensity of use (as claimed by the original hypothesis of the intensity of use), then the phase diagram in **Fig. 10** should show a more or less straight positive line, implying greater intensities over time. However, if we are facing a situation of "punctuated equilibrium", the phase diagram show different attractor points where the values taken by the variable "energy intensity" move around a given value. In the case of Spain we can see clearly two different attractor points, one between 1960-1966, and the second between 1976-2001.

Figure 10: Phase diagram for Spain



This second attractor point implies values of energy intensity, which move around the value of 7 MJ/US95$. Between these two points we can see a transitional period, which we would characterise as re-energisation. This graph indicates that when considering its energy intensity, Spain is following the dynamic behavior described by De Bruyn (1999).

This behavior can be linked to the peculiarity of complex adaptive systems discussed before. Important feedback effects of energy dissipation across different hierarchical levels affecting the characteristics of the whole system translate into strong non-linearity.

7.3.3. Discussing the Insight Provided by the Dynamic/Evolutionary View

The phase diagram shown in **Fig. 10** shows that in the considered time window the evolutionary trajectory of energy intensity went through phases of stability (when moving around the two attractor points) and a transitional phase (when moving from one attractor to the other). The values taken by the variable "energy intensity" are stagnant around attractor points, and increasing fast in the transitional phase.

The overall trend for energy intensity in Spain is that of grow over the time window considered, meaning that structural and/or institutional changes in this country did not generate the same effect of reduction on energy intensity as in other developed countries. But to better understand this peculiarity, we have to distinguish between analyses of the evolutionary trajectory at different scales. On a medium scale, structural changes can bring a period of stability (generation of a new attractor point), giving the impression of stability and in the case of the hypothesis of de-materialisation, the impression of a well established trend. On the other hand, when using a larger time window, we can appreciate the trajectory across different attractor points. In this case, when considering the various transitional phases in the movement across different attractor points, it is the relative position of the various attractor points that will determine the overall trend (on a larger time window).

To understand the mechanisms generating these changes on different levels (and at different scales) implies studying in parallel the evolution of the energy metabolism of the whole country and that of different sectors of the economy. As soon as we do that, in the case of Spain, it becomes evident the crucial role of changes that are still occurring in the household sector (in the demand side of the economy).

Finally, before closing this analysis of the implications of the evolutionary perspective I have to reiterate two points crucial for this analysis:

(1) intensive variables (i.e. energy intensity - MJ/$) are useful to describe changes in relevant qualities of societal metabolism. However, they are not enough, since they do not reflect the evolution of the throughput and its environmental impact. We need, to use in parallel additional variables reflecting the absolute evolution of the throughput (e.g. what is the final value of MJ when we calculate the product "MJ/$ of GDP" x "$ of GDP per capita").

(2) the existence of feed-backs between different hierarchical levels of a complex adaptive system implies that we cannot extrapolate a trend observed at one level as generating another trend at a different level using linear extrapolation. In these cases, we have to address the dynamic nature of the system, by using new tools, like

phase diagrams, to represent the non-linear behaviour of the variables considered. Equally useful is the parallel analysis of changes on different scales and the study of their reciprocal effect.

7.4. Integrated Assessment of Exosomatic Metabolism across levels

In this section I introduce the approach of integrated assessment of the exosomatic metabolic rates of economic compartments presented by Giampietro and Mayumi (2000a, 2000b), and used by Falconí-Benítez (2001). Integrated means economic development and energy metabolism of societies are described in parallel, by using economic variables and biophysical units such as human time allocation and energy consumption, and across different hierarchical levels.

With this analysis I explore the same issues explored in section 2 using only economic variables. Here I use additional variables and a different perspective, obtaining different interpretations. In this way, I hope to show to the reader that we can gain in robustness and usefulness of the analysis.

This section has the goal of: (1) providing additional explanations for the peculiar behavior of Spain, a developed country with an increasing energy intensity. In order to do that I explain the role of the different sectors in determining the overall increase of energy intensity over time. In particular, this analysis points at the special role plaid by the household sector. (2) providing explanations about the mechanism generating Spain's development trajectory. The combined effects the characteristics of its societal metabolism (changes in endosomatic flows - linked to demographic variables - and changes in exosomatic flows - linked to economic variables) imply that Spain, in contrast to the case of Ecuador presented by Falconí-Benítez (2001) got into a positive spiral of development. This is leading to an increase in the exosomatic metabolic rate of its various compartments, especially the HH sector. Before presenting this analysis I provide in the next section some definitions of the relations used there.

7.4.1. The Relations Used in the Analysis

The parameters used here are those presented and discussed in Appendix 1 and Appendix 2 of Giampietro and Mayumi (2000b).

In this analysis, the economy of Spain has been divided into two main sectors: the paid work sector (PW) and the household sector (HH). The paid work sector of the economy is the one that generates added value (or GDP), and the household sector of the economy is the one that consumes that value. Both of them, however, consume energy for their maintenance and development. The paid work sector can be divided into three major sub-sectors, the productive sector (PS), services and government (SG), and agriculture (AG).

$$PW = PS + SG + AG \qquad (1)$$

Energy intensity (EI) is total energy consumption, or total energy throughput (TET) divided by Gross Domestic Product and, in this study, it is measured in MJ/US90$.

$$EI = TET / GDP \qquad (2)$$

Some useful ratios that will be used later are defined as follows.

The exosomatic metabolic rate average of the society (EMR_{SA}) is the total exosomatic energy throughput (TET) divided by the total human time (THA) of the society. This ratio gives us the rate of energy use of the society in megajoules (MJ) per hour. The interpretation of that ratio is that this is an intensive variable that reflects the rhythm at which society dissipates energy for its maintenance and development per unit of human activity.

$$EMR_{SA} = TET / THA \qquad (3)$$

By analogy, we can derive the same kind of ratio in the case of the household sector and the paid work sector. That is,

$EMR_{HH} = ET_{HH} / HA_{HH}$ (4)

Where ET_{HH} is the energy consumption in the household sector and HA_{HH} is the non-working human time in the society - for calculation of this see Giampietro and Mayumi (2000a). In this study ET_{HH} is calculated as residential energy consumption plus 50% of transport energy consumption. This later assumption is derived from the average energy consumption of cars and the number of circulating cars that suggests that 50% of energy in the transport sector can be attributed to households (see assessments and data source in the Appendix of this chapter). The other 50% of energy in the transport sector can be allocated to the services and government sector. In fact, even if this is used to carry items used by manufacturing, this transport will generate an added value within the service sector.

An increase in EMR_{HH} reflects an increase in the standard of living (see Pastore et al. 2000) and a higher consumption in the empowered HH sector.

By using the same procedure used in relation (3) and (4) we have:

$EMR_{PW} = ET_{PW} / HA_{PW}$ (5)

Where ET_{PW} is the energy consumption in the sectors that generate added value and HA_{PW} is the human working time (I use a flat value of 1,840 hours per year for employed people, which is consistent with ILO statistics for that period).
As discussed below, EMR_{PW} can be taken as a proxy for investments in the PW sector. The same holds for EMR_{PS}, EMR_{SG}, and EMR_{AG}.

The last ratio used in this analysis is the economic labour productivity (ELP) that can be defined as GDP / HA_{PW} in dollars per hour. Again, we can also calculate ELP_{AG}, ELP_{PS}, and ELP_{SG}. By dividing a sectorial GDP (e.g. GDP_{AG}) by its relative amount of working time in hours (e.g. HA_{AG})

For example, when using the economic reading, we can define TET = EI * GDP (from relation 2), but from this integrated assessment, due to the fact that HA = $HA_{HH} + HA_{PW}$, and TET = $ET_{HH} + ET_{PW}$, we can define TET as follows,

$$TET = (HA_{HH} * EMR_{HH}) + (HA_{PW} * EMR_{PW}) \qquad (6)$$

Using data for 1990, in the case of Spain, we obtain:

$$TET = EI * GDP = (HA_{HH} * EMR_{HH}) + (HA_{PW} * EMR_{PW})$$

$3.79*10^{12}$ MJ = 7.65 MJ/\$ * $494.794*10^{9}$ \$ = ($3.17*10^{11}$ h * 2.72 MJ/h) + ($2.32*10^{10}$ h * 125.89 MJ/h) = $3.79*10^{12}$ MJ

We can do the same for ET_{PW}. From relation (1) we know that PW = PS + SG + AG, so we can define ET_{PW} as follows,

$$ET_{PW} = (HA_{PS} * EMR_{PS}) + (HA_{SG} * EMR_{SG}) + (HA_{AG} * EMR_{AG}) \qquad (7)$$

Again, when using Spanish data for 1990, we have that the previous identity becomes:

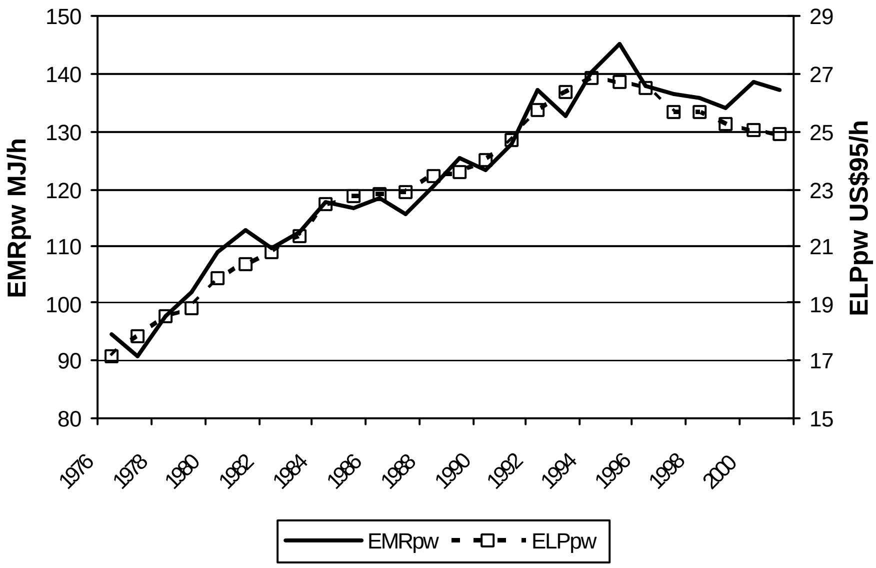
ET_{PW} = $2.92*10^{12}$ MJ = ($7.74*10^{9}$ h * 287.55 MJ/h) + ($1.29*10^{10}$ h * 48.66 MJ/h) + ($2.61*10^{9}$ h * 26.99 MJ/h) = $2.92*10^{12}$ MJ

For a discussion of the usefulness of writing identities containing redundant information that can be retrieved by using non-equivalent data sources see Giampietro and Mayumi (2000b). Very quickly, these examples show that it is possible to define the same variable (i.e. TET or ET_{PW}), using an economic reading (energy intensity and GDP) or using an integrated assessment (using exosomatic metabolic rates and human time allocation referring to the characteristics of lower hierarchical levels). This fact gives our analysis a wider scope and more robustness, and allows us to give different explanations to the same facts.

7.4.2. Describing Changes of ELP and EMR in the Various Sectors

The various data sources and methods for calculating the figures presented in this section are given in the Appendix. By calculating these ratios for Spanish economy, we obtain relevant information that would be lost otherwise.

Figure 11: Exosomatic Metabolic Rate and Economic Labour Productivity in paid work sectors



One major hypothesis that can be used in integrated assessment is the correlation between empowered productive sectors (assessed by their exosomatic energy consumption = fixed plus circulating) and their ability to produce GDP. Accepting this hypothesis implies that EMR_{pw} and ELP_{pw} are correlated (Cleveland et al. 1984; Hall et al. 1986). The good correlation obtained by Cleveland et al., in their historic analysis of US economy (see Section 5.3.4.), is confirmed by the curves shown in **Fig. 11** for Spain. When representing changes of EMR_{pw} and ELP_{pw} we find a similar shape or tendency in the considered period. That is, exosomatic energy consumption per unit of working time in the paid work sector follows the GDP trend.

The same finding has been obtained in the historic analysis of Ecuador (see **Fig. 6** in Falconi-Benitez, 2001).

If we accept the validity of this correlation during the considered time window, it follows that changes in the energy intensity of Spain are generated by: (1) differences in the speed at which the two parameters EMR and ELP adjust in relation to each other. (2) changes occurring outside the paid work sector. This second option points at the possibility that important changes, in Spain, are taking place in the household sector.

Changes in the PW sector

The EMR_{pw} increased from 94.7 MJ/hour in 1976 to 137.11 MJ/hour in 2001), which is reflecting the accumulation of capital in the sectors of the economy producing added value. This change has been reflected in a relative increase in the economic productivity of labor (ELP_{pw}) (from 17.17 $/hour in 1976 to 24.93 in 2001). As a side effect, this allowed the relative decrease of the human time allocated in activities that generate added value. In fact, more exosomatic energy used per worker implies the existence of more exosomatic devices per worker (technology) linked to the ability to buy more oil to perform the given economic activity. The two things, *fixed investment* – the exosomatic devices needed to dissipate fossil energy in an useful way by workers – and *circulating investment* – fossil energy consumed – combined together can be considered as an indicator of a larger empowerment of the economic activity considered. That is, an increase in EMR leading to an increase in ELP is linked to more technology involved in production.

Changes in the HH sector

If the changes in the PW sector led to an increase of non-working time, how this was reflected in the level of exosomatic energy metabolism of the household sector? In the example of the analysis of Ecuador, Falconi-Benitez (2001) shows that a sharp increase in HA_{HH}, translated into a sharp reduction of EMR_{HH} since the increase in ET_{HH} could not keep the pace of growth of HA_{HH}.

Contrary to what happened in Ecuador in the last decades, the exosomatic metabolic rate of the household sector (EMR_{HH}) in Spain almost doubled. It went, from 1.54 MJ/hour in 1976 to 3.9 MJ/hour in 2001.

Combining the two

When combining changes in intensive variables (EMR_i) and extensive variables (HA_i) and when considering sectors dealing with both production and consumption, we obtain a different picture of changes of energy intensity in Spain from what obtained in the first analysis. Even tough industry is decreasing its energy intensity, the overall energy intensity of the economy is increasing, due to the behavior of the household sector, which is increasing energy consumption also in absolute terms, from 449 PJ in 1976 to 1,260 PJ in 2001 (1 PJ = 10^{15} J).

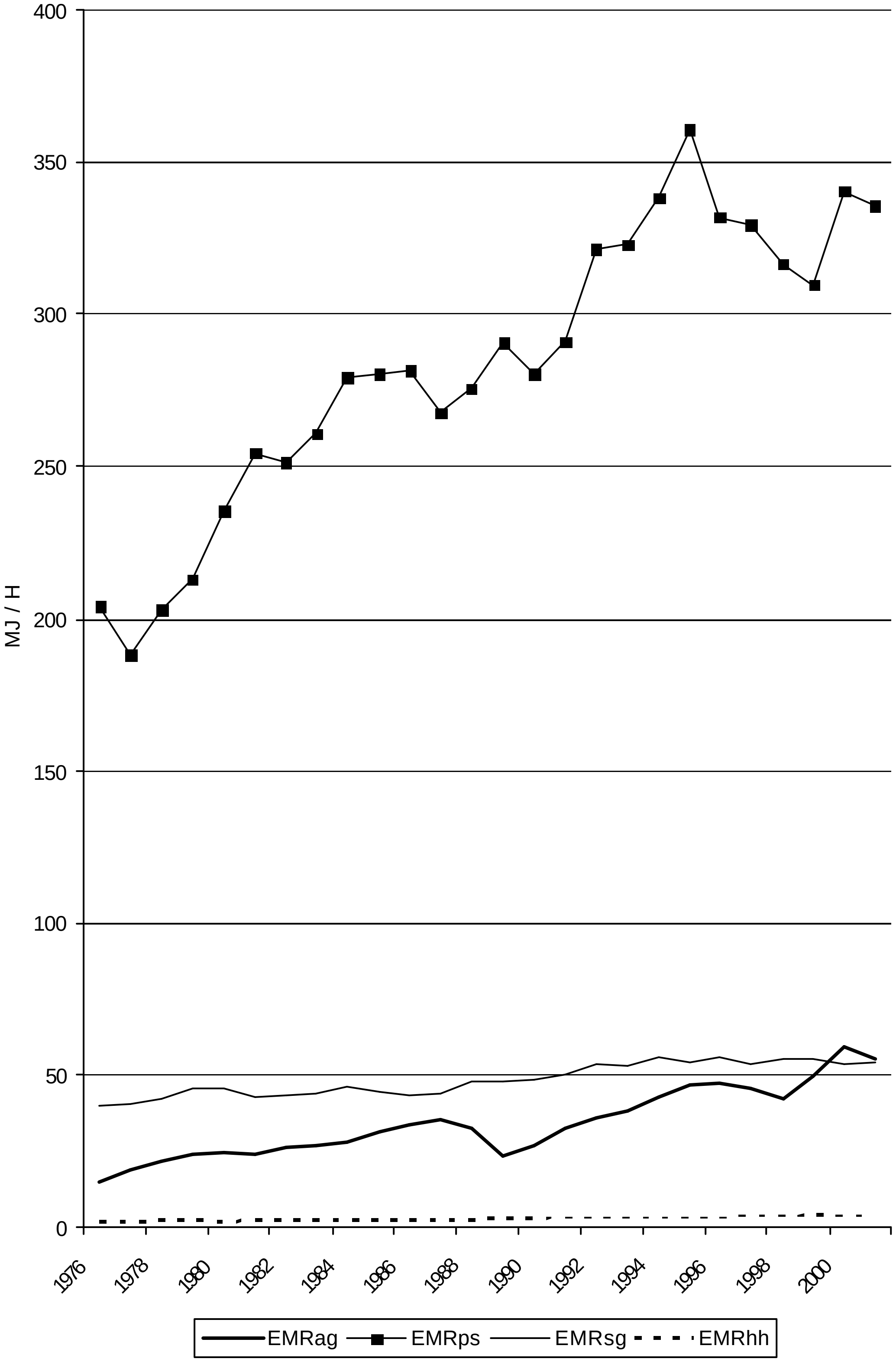
This fact is usually neglected by the studies on the EKC or energy intensity that focus only in the supply side of the economy (= on changes in the paid work sectors). However, the demand side, the household sector, can be a relevant factor explaining the development of energy intensity, and should be taken into account carefully. That is, using an analysis based on human time allocation provides new insights to the Spanish anomaly energy intensity increase.

7.4.3. The Crucial Role of Changes in Investments of HA Among the Various Sectors

When representing the different exosomatic metabolic rates of the economy (**Fig. 12**) we obtain important information. That figure shows that $EMR_{PS} >> EMR_{SG} > EMR_{AG} > EMR_{HH}$.

This sequence is very important since from that we can realise that when studying changes in the rate of consumption of exosomatic energy per capita in a country (EMR_{SA}), we have to look at the changes in the profile of human time allocation between these different sectors.

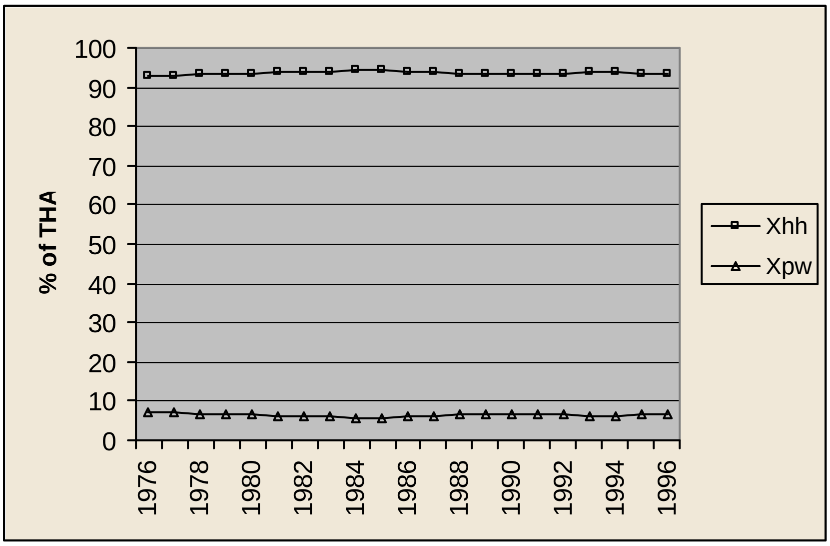
Figure 12: Exosomatic Metabolic Rates of PS, SG, AG, and HH

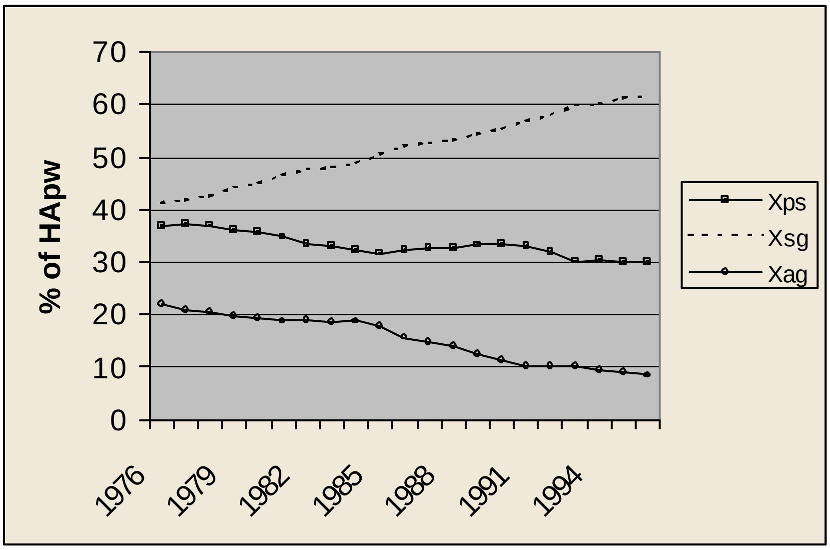


This is what shown in **Fig. 13**. In the upper part (**A**) we find that both HA_{HH} and HA_{PW} maintain approximately the same percentage of THA over the time window considered. In the lower part of **Fig. 13** (**B**) we can see the evolution of the different HA_i as a percentage of HA_{PW}, a variable that we call X_i.

Figure 13[84]**:** Distribution of working time between sectors

A: HA_{pw} and HA_{hh} as a % of THA **B:** HA_{ps}, HA_{sg}, and HA_{ag} as % of HA_{pw}





The real value of EMR_{PW} and therefore its curve in time not only depends on the level of capital accumulated and technological efficiency of each one of the

---

[84] Please note: only until 1996.

various sectors (the value take by EMR_i) but also on the profile of distribution of "working time" over the three different sectors, PS, SG, and AG. The percentage of working time in PS and AG is decreasing, while the same percentage for SG is increasing (post-industrialisation of the economy).

When combining this result with the relative value of the different EMR_i considered, we can conclude that the decrease in energy intensity in PS has been contrasted by: (1) an increase in EMR_{SG} linked to a growing size of the SG sector, and (2) the increase in EMR_{HH}, occurring in a sector which is much larger than the others (**Fig. 13 A**). That is, to explain the overall increase in energy intensity of Spain we have to combine (using extensive and intensive variables) different changes in the characteristics of the various sectors.

7.4.4. The Dynamics Associated to Economic Development

The relation between EMR_{PW} and ELP_{PW} would indicate that there is a quantitative link between GDP and energy consumption growth. However, the growth of total economic output can be explained by: (1) increase in population (dTHA/dt); (2) rise in the material standard of living ($dEMR_{HH}/dt$) or (3) increase in the exosomatic energy metabolism of economic sectors included in PW ($dEMR_{PW}/dt$). Whenever performance of the economy generates a surplus (an extra added value spare from what is used for its maintenance) this can be used for increase these 3 parameters.

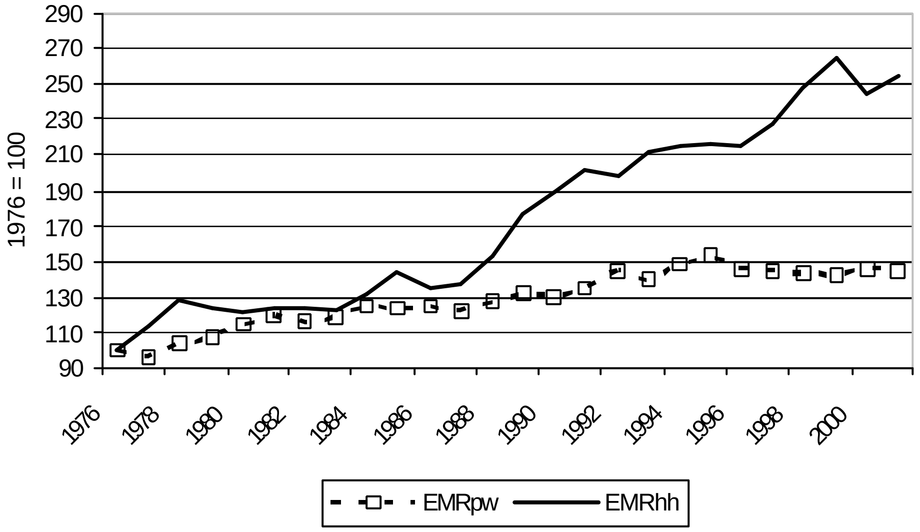
What are the implications, then, of the link between EMR_{PW} and ELP_{PW}, shown in **Figure 11**? In order to have economic growth ET_{PW} has to grow faster than HA_{PW}, this will be reflected in an increase in EMR_{PW}, which will be reflected into a larger availability of investment for producing GDP. Clearly the priority among the possible end uses of available surplus [= (1) increasing THA; (2) increasing EMR_{HH}; or (3) increasing EMR_{PW}] will depend on demographic variables, political choices (e.g. the ability and the willingness of compressing increases in the consumption of HH to favor quicker investments in PW), and historical circumstances (e.g. existing level of capital accumulated of the various sectors).

In opposition to what happened in Ecuador (see Falconí-Benítez, 2001), the surplus generated by the economic development of Spain was enough to absorb both new population (due to internal demographic growth) and the exodus of workers from AG sector. In fact, in the last decades Spain has still been absorbing a large fraction of workers moving away from the agricultural sector. This process of economic development was speeded up by a compression of the increases in material standard of living (increases in EMR_{HH}) – under Franco regime – which made possible to dedicate a larger fraction of this surplus to the empowerment of PW. Finally, the demographic stability of the country made possible to get into a positive spiral very quickly.

The very low levels of EMR_{HH} (when compared with those of other developed countries) indicate that in the early stages of industrial development Spain experienced a certain compression of consumption. However, once EMR_{PS} reached values comparable to those of other developed countries (i.e. 300 MJ/h) and the political situation changed, the surplus was allocated mainly to boost the SG sector (increasing X_{SG}, by absorbing workers from agriculture and increasing at the same time EMR_{SG}) and to improve the material standard of living (by increasing EMR_{HH}). In particular, the empowerment of the Household sector is implying the sharp increase in EMR_{SA} observed before.

When comparing the growth of EMR_{HH} and that of EMR_{PW} - as shown in **Fig. 14** - we can actually see the lag-time reflecting the choices made in the process of economic development. Indeed, when Spain was still focusing on a fast capital accumulation of the economy EMR_{PW} was growing parallel to EMR_{HH}. However, in the past 10 years, when the paid work sectors are loosing share of GDP, and therefore activity, EMR_{PW} is growing faster. However, the lower growth rate for EMR_{HH} is compensated by its huge size, resulting in the increase of energy intensity of Spain – **Fig. 7**.

Figure 14: Growth in Exosomatic Metabolic Rate (Household Sector and Productive Sectors) in Spain



When comparing this trajectory of development with that presented by Falconi (2001) for Ecuador, it can be said that in the case of Spain, low population growth and low debt service allowed getting into a positive spiral. Available surpluses were first invested to increase EMR_{PW} ($dET_{PW} > dHA_{PW}$). This fact led to an increase in ELP_{PW} that allowed the increase in the surplus (due to the temporary holding of EMR_{HH}). When a sufficient level of capital accumulation was reached in the PS sector (EMR_{PS} = 300 MJ/h) the surplus was allocated to expand the SG sector (by absorbing the workers in AG with a reasonable amount of investment – since $EMR_{SG} < EMR_{PS}$) and to increase EMR_{HH}. It has to be stressed that the dramatic difference in demographic trends between Spain and Ecuador is crucial to explain the different side of the bifurcation taken by Spain in its trajectory of development.

7.5. Conclusion

We have used in this paper three different approaches to study the issue of dematerialisation of the Spanish economy. The first approach has been the conventional one, focusing on the energy intensity reflecting an economic reading. The second approach described the non-linear behavior of the variable using a phase diagram. The third one has used in a combined way economic and biophysical variables when looking for explanation of the same fact. The major results are as follows.

In Relation to Spain

Spain does not follow the intensity of use hypothesis that suggests an inverted-U curve for energy intensity, since the variable is increasing over time. Then, it follows that also the Environmental Kuznets Curve hypothesis does not hold for Spain.

The behavior of the variable energy intensity is not linear, but shows some ups and downs, jumping from one 'attractor point' to the next. Thus, changes in energy intensity are basically due to structural change (as explained in section 7.3) and to the evolution of the characteristics of the various sector (especially HH), as it follows from section 7.4.

When considering the dynamic of economic development, Spain was able to take the other side of the bifurcation (when compared to Ecuador), thanks to the different characteristics of its energy budget. In particular low population growth was crucial in setting the trajectory into a positive spiral.

The increase in the rate of exosomatic energy metabolism of the household sector ($dEMR_{HH}/dt$) is one of the factors explaining the increase in energy intensity of Spain. Belonging to the demand side of the economy, this sector is usually not considered in conventional analyses of changes in energy intensity. On the contrary, this analysis shows that, when designing policies to reduce the environmental impact of the economy, we should take into account what is going on at the household sector. Changes in the set of activities linked to consumption are the ones that can provide clues about the possibility of movements toward new attractor points (following the theory of punctuated equilibrium).

In Relation to EKC and other Hypotheses of De-materialisation

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 the 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 behavior of the total throughput. For example, using the example of Spain, we can see in **Fig. 12** that the overall curve of TET is the result of changes in an intensive variable (the curve of EMR_{SA}) and an extensive variable (the curve of THA). From 1960 to 2001 population has grown from 30.5 million to 40.2 million, whereas EMR_{SA} from 2.52 MJ/h to 15.11 MJ/h. Reflecting these changes TET went from 675 PJ to 5330 PJ. Let us imagine that this process of increasing the metabolism of the economy had occurred with a growth in population of 100% (as in the case of Ecuador considered by Falconi-Benitez 2001). 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 dematerialisation hypothesis does not hold in conditions of continuous growth. As both the example of the Spanish economy presented here and the re-materialisation phases found by De Bruyn and Opschoor (1997) indicate developed countries can be on a trajectory of growth going across different attractor points. Rather than studying the trajectory followed when entering into the basin of attraction of a given attractor point (what seen now by the curves "seeing" dematerialisation), it would be more interesting to study what possible future attractor points we can imagine.

Finally, the use of integrated models to characterise changes in economies based on the use of different variables to generate parallel descriptions of the same facts at different level seems to be essential when dealing with issue of sustainability. That is when the effects of changes have to be assessed using different academic disciplines in parallel and in relation to events describable only on different levels. The generation of a "mosaic effect" among the various pieces of information improves the robustness of the analysis and the possibility of getting new insights generating synergism in the parallel use of different disciplines.

Appendix

Energy intensity has been calculated by dividing the Total Primary Energy Supply (TPES) expressed in joules by the Gross Domestic Product (GDP) expressed in 1995 US dollars, using the OECD data shown below.

The disaggregation by sectors for the Spanish economy has been done taking the disaggregated OECD data for energy consumption by sectors, as well as the aggregated GDP, and applying the evolution of the GDP structure by sectors found in the Spanish National Accounts (in the reference list).

Data on population comes from the OECD, while data on employed people can be found on the Spanish National Statistics Institute web site http://www.ine.es. We assume 1840 hours for working time that is 46 weeks times 40 hours per week. The distribution of the working time between the different sectors of the economy can also be found in the same web site.

When allocating the energy of the transport sector between the different sectors we make the following assumption: 50% of energy in the transport sector can be attributed to households. The other 50% can be allocated to the services and government sector. This later assumption is derived from the average energy consumption of cars and the number of circulating cars for developed countries, using the following sources:

1. “Transportation energy data book: edition 17”, prepared by the Oak Ridge National Lab. (http://www-cta.ornl.gov/data/tedb17/tedb17.html)
2. “Transportation energy and the environment: chapter 4”, US Bureau of Transport Statistics (http://www.bts.gov/ntda/nts/NTS99/data/chapter4/content.pdf)
3. Statistical Compendium Europe’s Environment from Eurostat (http://europa.eu.int/eurostat)

CHAPTER 8[85]: MULTI-SCALE INTEGRATED ANALYSIS OF SUSTAINABILITY: A METHODOLOGICAL TOOL TO IMPROVE THE QUALITY OF NARRATIVES

8.1. The challenge implied by Multi-Scale Multi-Dimensional analyses of sustainability

8.1.1 The epistemological predicament entailed by complexity

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

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

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

---

[85] This chapter builds on the paper of the same title published with Mario Giampietro in the Journal *International Journal of Global Environmental Issues* (Giampietro and Ramos- Martin, in press). Even though this Chapter is basically theoretical, I preferred including it after the example on Spain since it introduces concepts not discussed there and that are rather tackled in the last two chapters of this dissertation. I tried to skip redundancies, however sometimes, for the sake of fluent reading and comprehension, some concepts may be repeated.

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

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

(1) when making models of living systems it is unwise to look for "the model" which addresses all relevant aspects of a living system by using a large number of variables and very sophisticated inferential systems. It is meaningless to look for *the true formal identity* of an observed system or for *the right model*. Complexity, on the contrary, requires the ability of handling the open and expanding set of non-reducible perceptions and representations of the interactions of non-equivalent observers/agents. This process cannot be fully captured by any formal information space no matter how big or sophisticated is the computer and/or how smart and lucky is the analyst (see also Rotmans and Rothman, 2003).

(2) any observer must be a part of the reality which is observed. Scientists, no matter how hard science their background is, cannot escape this predicament. This means that the scientific endeavour should be viewed as a continuous challenge. The task is

to maintain a set of meaningful relations which evolve in time within an observer/observed complex. An observer/observed complex in which both the observed and the observer are becoming "something different" in time. Complexity, according to the narrative suggested by Chaitin (1975), implies the impossibility of compressing the information space required to represent a given object/entity without losing relevant information about it. This is to say that the essence of complex systems cannot be fully captured by formal models. This explains why it is impossible to have a full anticipation of their behaviour using algorithms.

In relation to this predicament, the approach of Multi-Scale Integrated Analysis (Giampietro, 2003) represents an attempt to deal with the analysis of sustainability in a different way. This approach, as explained below, can only be applied to the study of metabolic systems organised in nested hierarchies. However, this includes all living systems, ecosystems and socio-economic systems.

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

The capital sin of reductionism, in this case, is to ignore that before getting into the step of developing and using formal models there is always a crucial pre-analytical step to be made. This pre-analytical step is associated to the selection of useful narratives. Formal models can only be developed within a given narrative about the reality. A narrative can be defined as "a series of elaborate scaling operations that allow different processes occurring at different paces, and events describable at different space-time domains, to be made commensurable in our organization of perceptions and representations of events"[86]. The choice of a narrative therefore is a pre-analytical step which has to do with an "arbitrary" characterisation of "*what the system under analysis is and does*". This characterisation, always depends on the specific goals of the analysis, and therefore is closely related to the characterisation of "*what should be considered as relevant in relation to an improvement to be achieved*". Simple systems can be dealt with in terms of models, but complex systems must have a narrative (Allen, 2003). This is a crucial point whenever the observer is a part of the observed whole. A narrative is something about which scientists have to take responsibility (Allen et al., 2001).

8.1.2 The peculiar characteristics of Multi-Scale Integrated Analysis

The approach of Multi-Scale Integrated Analysis is based on the initial acknowledgment that any representation of a complex system must be necessarily arbitrary and incomplete. Therefore it is an analytical approach that adopts: (a) a set of epistemological assumptions; (b) a set of criteria for defining the quality of the analysis; and (c) a set of expected characteristics for the observed systems, which is totally different from those adopted within the reductionism paradigm. The new meaning given to the MSIA analytical tool derives from the acknowledgment that: (1) it is impossible to reduce to a single system of accounting information that refers to non-equivalent descriptive domains, i.e. different views of the same reality, which are generated by the choice of either adopting different criteria of observation or focusing on different scales of analysis]. This means that when handling data referring to a picture of a microscope, or to a picture taken by a telescope, or to an ultrasound scan, we should not expect that it is possible to reduce these data to each other using an algorithm. This is not possible, no matter how smart the analyst. The phenomenon of non-reducibility of patterns expressed (perceived and represented) at different scales is often referred to as "emergence" or "bifurcation in a system of mapping" (Rosen, 1985; 2000). When dealing with non-equivalent descriptive

---

[86] T.F.H. Allen, personal communication.

domains and non reducible models the task should be, rather, that of developing the ability of handling in a coherent way the resulting heterogeneous information space (Giampietro, 2003). This predicament in relation to Multi-Criteria Analysis has been called **Technical Incommensurability** by Munda (2004);

(2) it is impossible to rank and weight in a substantive way contrasting values and aspirations found in social interactions [= incommensurability of values within relevant social actors]. When dealing with legitimate but contrasting perspectives in relation to goals, fears and taboos, the task is rather to develop fair and transparent procedures to handle contrasting definitions of what is relevant [to be included in the analysis] and what is irrelevant [to be neglected]. A substantive definition of "the best course of action" is simply not possible when dealing with reflexive systems, such as human systems (Martinez-Alier et al., 1998). This predicament in relation to Multi-Criteria Analysis has been called **Social Incommensurability** by Munda (2004).

(3) non-equivalent descriptive domains are associated to different typologies of data. The difference in type of data can be related to the required time lag to be gathered, to the cost and effort required to be gathered, to their degree of reliability and accuracy. The implications of these differences have to be carefully evaluated when deciding the profile of investment of analytical resources to characterise an investigated system in relation to different dimensions of analysis (e.g. ecological, technical, economic, social, cultural). For example, if there is a clear taboo regarding a potential activity to be implemented in a given socio-economic system, it does not make sense to invest a lot of resources to gather empirical evidence about its technical feasibility (e.g. studying how to improve the efficiency of pig production for internal supply within Israel).

(4) when dealing with sustainability, future scenarios and evolutionary trends, there is always an unavoidable degree of uncertainty and ignorance on both the ability to detect in time relevant signals of change, and characterise, predict and simulate future scenarios (Funtowicz and Ravetz, 1991).

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

(1) Keeping clearly separated the descriptive from the normative aspect. This is an important departure from the hidden strategy adopted by reductionism to deal with sustainability. Analyses developed within the paradigm of reductionism try to collapse the descriptive side (characterisation of performance) and the normative side (definition of best course of action) into a single step (e.g. cost/benefit analysis, and optimising models looking for the best solution). Moreover, reductionism assumes that uncertainty and ignorance can be dealt with in substantive way by sound practices of science (e.g. more data, bigger computers and more sophisticated sensitivity analyses). Without recognising it, many researchers adopt only a limited set of narratives for their analysis. MSIA on the contrary has the goal to represent in an integrated way changes in the performance of an investigated system in relation to different criteria, on different scales and in relation to different narratives. No attempt is made to establish a ranking of importance or priority among contrasting or non-equivalent indications. The existence of uncertainty and ignorance is explicitly acknowledged as an additional input to the process of analysis. Obviously, this implies that MSIA has to be used within a participatory process of integrated assessment. That is, it requires a simultaneous process of Societal Multi-Criteria Evaluation (Munda, 2004) to deal with all the inputs of this process that refer to the normative side.

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

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

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

Section two of this paper provides an example of the power of integration of this approach. It illustrates, using a hypothetical case study, how this holographic process of representation across scales and descriptive domains makes it possible to frame the issue of sustainability in a coherent way across disciplinary fields. In this example it is possible to appreciate how this particular system of integrated accounting is not based on a substantive definition of a protocol to be used to do the accounting. In spite of this characteristic, the mechanism of accounting is still very effective and rigorous in handling the integrated set of data and assessments.

8.2. Studying the dynamic budget of metabolic systems across scales

8.2.1 Societal Metabolism of an isolated society on a remote island

8.2.1.1 The goal of the example

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

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

In general terms, we can say that in a metabolic system organised in nested compartments, it is possible to establish a relation between: (a) relative size of compartments (parts and whole) and (b) relative intensities of metabolised flows of parts and whole. This can be done according to typical values that can be associated with the identity of parts and the whole – e.g. expected technical coefficients or expected levels of consumption. This analysis can be extended to include both typologies of compartments: (i) those responsible for the *production* (the parts generating the required inputs); and (ii) those responsible for the *consumption* of various metabolised flows (the parts contributing to the consumption at the level of the whole). Large size parts do influence the value of the whole more than small size parts. In this way, it becomes possible to study the existence of constraints and bottlenecks in relation to different typologies of flows occurring within parts of different sizes and to establish benchmark values (e.g. economic compartments which are more or less capital intensive than the average). Constraints can be detected when finding incongruence between the relative requirement and supply of a given metabolised flow in its dynamic budget over different compartments at different levels. Biophysical constraints imply that if there are some compartments which have a throughput much higher than the average, we must find other compartments with a throughput much lower. This inverse relation in the relative value of throughputs is mediated by the relative size of the various compartments.

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

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

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

8.2.1.2 Theoretical assumptions and basic rationale

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

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

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

(B) an extensive variable characterising the size (for assessing the size of parts and wholes). In the following example, in our socio-economic system, we can define the size of the whole (**THA** = Total Human Activity) in hours; and the size of the parts

(**HA_i** = Human Activity in the element i). "Hours of Total Human Activity" is a variable directly related to population size and is affected by demographic changes.

In this simplified example, we deal with an endosomatic autocatalytic loop (= only human labour and food) referring to a hypothetical society of 100 people on an isolated, remote island. The numbers given in this example are not the relevant part of the analysis *per se*. We are providing numbers - which are familiar for those dealing with this topic - just to help the reader to better grasp the mechanism of accounting. *It is the forced relation among numbers (and the analysis of the mechanism generating this relation) which is the main issue here*. The same mechanism of accounting can be applied to exosomatic energy (e.g. fossil energy and technical capital, as can be seen in Chapters 9 and 10), monetary flows (e.g. added value generation and human activity), water (e.g. water flows and human activity). Two points are crucial in this example:

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

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

8.2.1.3 Technical assumptions and numerical data

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

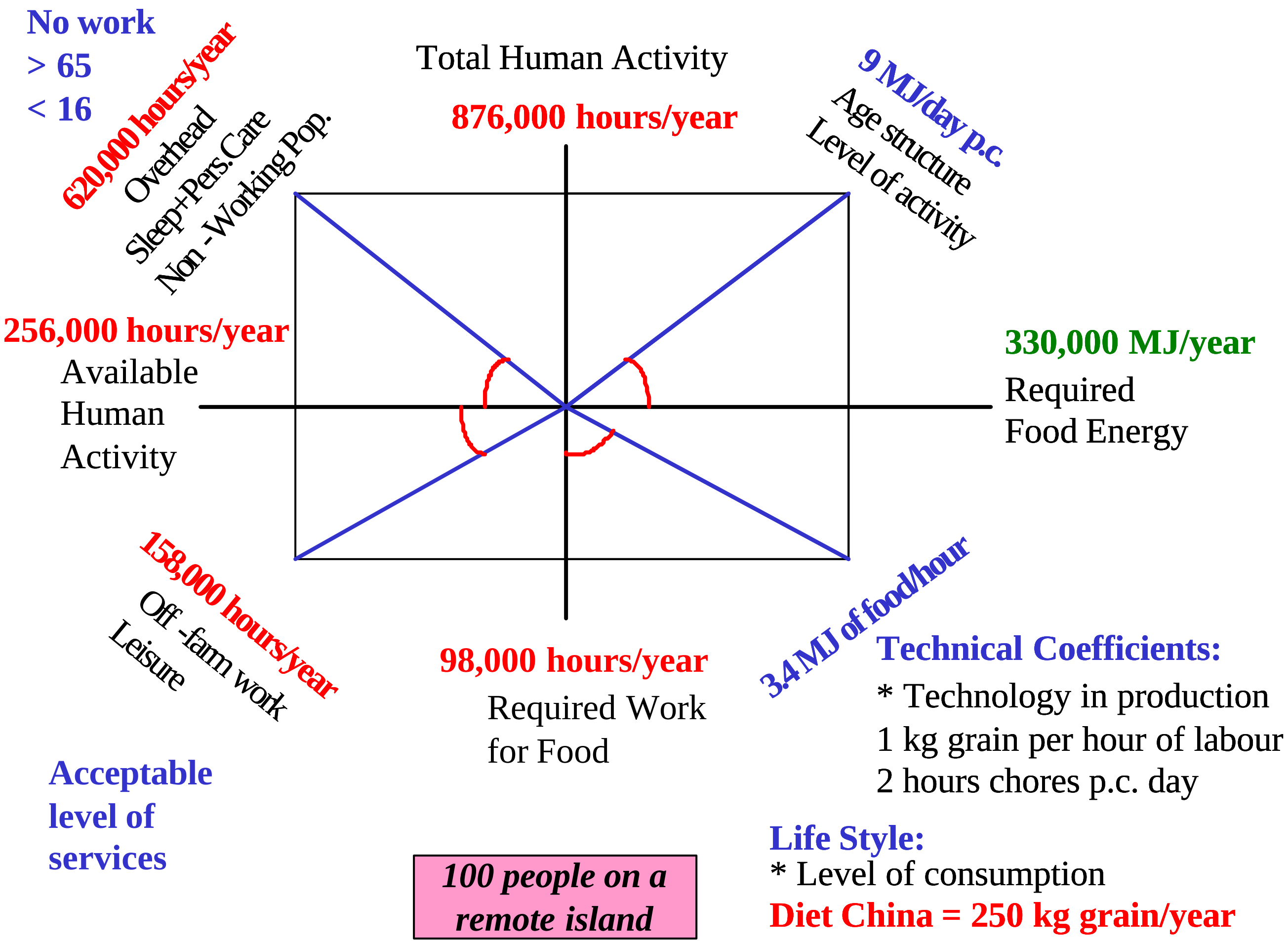
*** Basic requirement of food**. Using standard characteristics of a population typical of developed countries, we obtain an average demand of 9 MJ/day per capita of food, which translates into 330,000 MJ/year of food for the entire population.

*** Indicator of material standard of living**. We assume that the only "good" produced and consumed in this society (without market transactions) is the food providing nutrients in the diet. In relation to this assumption we can define, then, two possible levels of material standard of living, related to two different "qualities" for the diet. The two possible diets are: ***(1) Diet A***, which covers the total requirement of food energy (3,300 MJ/year per capita) using only cereals (supply of only vegetal proteins). With a nutritional value of 14 MJ of energy per kg of cereal, this implies the need of producing 250 kg of cereals/year per capita. ***(2) Diet B***, which covers 80% of the requirement of food energy with cereals (190 kg/year p.c.), and 20% with beef meat (equivalent to 67,5 kg of meat/year p.c.). Due to the very high losses of conversion (to produce 1 kg of beef meat you have to feed the herd 12 kg of grains), this double conversion implies the additional production of 810 kg of cereals/year. That is, Diet B requires the primary production of 1,000 kg of cereals per capita (rather than 250 kg/year of diet A).

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

*** Indicator of environmental loading**. A very coarse indicator of environmental loading used in this example is the fraction "land in production/total land of the island", since the land used for producing cereals implies the destruction of natural habitat (replaced with the monoculture of cereals). In our example the indicator of environmental loading is heavily affected by: (a) population; (b) the type of diet followed by the population (material standard of living) and (c) the technology used (recalling the I = PAT equation proposed by Ehrlich (1968). Assuming a total area for the island of 500 hectares, this implies an index of EL = 0.05 for Diet A and EL = 0.20 for Diet B (EL = Environmental Loading = hectares in production/total hectares of available land in the island).

Figure 15. One hundred people on a remote Island. Integrated representation of human activity and food energy requirement



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

*** Profile of investment of human activity of a set of typologies of "end uses" of human activity** (as in **Fig. 15**). These are: ***(1) "Maintenance and Reproduction"*** = As observed in the previous point, in any human society the largest part of human activity is not related to the stabilisation of the societal metabolism (e.g. in this example producing food), but rather to "Maintenance and Reproduction" of humans (HA_{MR}). This fixed overhead includes: (a) sleeping and personal care for everybody (in our example a flat value of 10 hours/day has been applied to all 100 people leading to a consumption of 365,000 hours/year out of the Total Human Activity available). (b) activity of non-working population (the remaining 14 hours/day of elderly and children, which are important for the future stability of the society, but which are not available – according to the social rule established before – for the production of food, now). For our budget of THA this implies the consumption of 255,000 hours/year (14 x 50 x 365) in non-productive activities. ***(2) "Human Activity Disposable for Society"*** (HA_{DS}). This is obtained as the difference between "Total Human Activity" (THA = 876,000 hours) and the consumption related to the end use "Maintenance and Reproduction" (HA_{MR} = 620,000 hours). In our example the amount of Human Activity Disposable for tasks of self-organisation is HA_{DS} = 256,000 hours/year. This is the budget of human activity available for stabilising societal metabolism. This budget of human activity, expressed at the societal level has to be divided between two tasks: (1) guaranteeing the production of the required food input (for avoiding starvation now) - "Work for Food" (HA_{WF}); and (2) guaranteeing the functioning of a good system of control able to provide adaptability in the future and a better quality of life to the people - "Social and Leisure" (HA_{SL}).

At this point, we can get into the circular structure of the flows associated with the autocatalytic loop as shown in the lower part of **Fig. 15**. The requirement of 330,000 MJ/year of endosomatic energy input (food at time [t]) entails the requirement of producing enough energy carriers (food at time [t+1]) in the following years. In the higher graph the same structure of relations among values taken by intensive and extensive variables is obtained using an intensive variable defined as "kg of cereals per capita" rather than "MJ/year". Obviously, the two assessments can be reduced to each other. Actually, this makes it possible to look for a biophysical constraint at the level of productivity of labour in the element HA_{WF} (the hours of HA invested in "working for food"). That is, if we want to preserve the characteristics of the whole (the total consumption of the society) it is necessary to invest a given not-negotiable fraction of "Total Human Activity" in the end use "Work for Food" (HA_{WF} = 98,000 hours/year). The seriousness of this constraint will depend on technology and availability of natural resources. This implies that the fraction of "Total Human Activity" which can be allocated to the end use "Social and Leisure" (the value taken by HA_{SL}) is not a number that can be decided only according to social or political will. The circular nature of the autocatalytic loop – lower **Fig. 15** - entails that numerical values associated to the characterisation of various identities defining elements on different hierarchical levels (at the level of individual compartments – extensive – segments on the axis: HA_i - and intensive variables – wideness of angles: throughput in HA_i) may be changed. However, changes must respect the constraint of congruence among flows over the whole loop. These constraints are imposed on each other by the characteristics and the size – extensive - and intensive variables – used to characterise the various elements across levels (the parts in relation to the whole and the whole in relation to the parts).

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

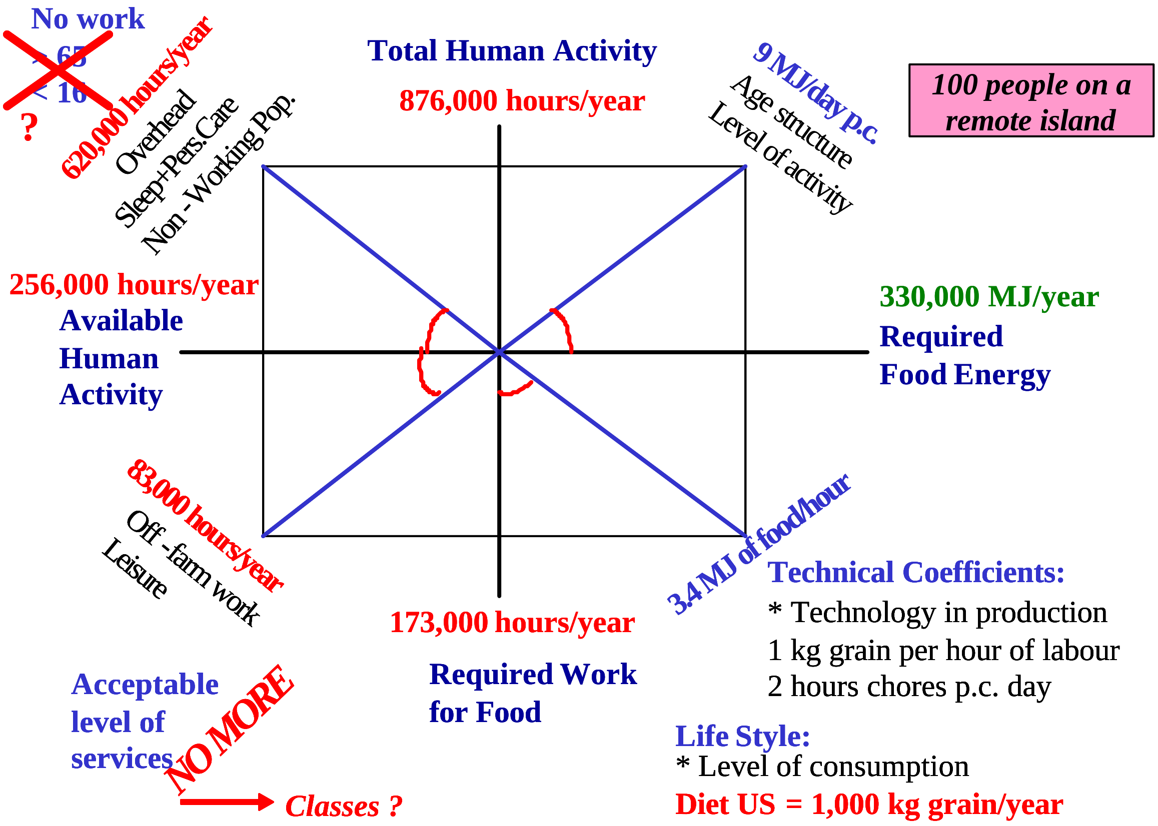
Different formalisations of the budget within the same meta-model

Let us imagine now to change, for example, some of the values used to characterise this autocatalytic loop of energy forms. For example let us change the parameter "material standard of living", which - in our simplified model - is expressed by the relevant attribute "quality of the diet" (formalised in the two options Diet A or Diet B). The different mix of energy vectors in the two diets (vegetal versus animal proteins), imply a quantitative difference in the "biophysical cost" of the diet expressed both in terms of a larger work requirement and in a larger environmental loading (higher demand of land). The same 330,000 MJ/year of food, with this diet requires the production of 1,000 kg of grain per capita (due to the conversion of grains into meat). As a consequence of this fact, whereas the production of cereals for a population relying 100% on diet A requires only 25,000 hours of labour and the destruction of 25 hectares of natural habitat ($EL_A = 0.05$), the production of cereals for a population relying 100% on Diet B requires 100,000 hours of labour and the destruction of 100 hectares of natural habitat ($EL_B = 0.20$). Moreover, to this assessment of work hours required for producing the agricultural crop used as input for the whole system, we have to add a requirement of work hours for fixed chores. Fixed chores include preparation of meals, gathering of wood for cooking, fetching water, washing and maintenance of food system infrastructures in this primitive society. In this simplified example we use the same flat value for the two diets = 73,000 hours/year (2 hours/day per capita = 2 x 365 x 100). This implies that if all the people of the island decide to follow the Diet A, they will face a fixed requirement of "Work for Food". The relative size of the HA_{WF} compartment would be 98,000 hours/year. Whereas, if they would all decide to adopt Diet B, they will face a different requirement of "Work for Food". That is, the relative size of the HA_{WF} compartment would be 173,000 hours/year. At this point, for the two options we can calculate the amount of "Human Activity" that can be allocated to "Social and Leisure". The size of the compartment HA_{SL} can be obtained by considering the difference (HA_{DS} - HA_{WF}). It is evident that the number of hours (HA_{SL}) that the people living in our island can dedicate to: (a) running social institutions and structures (schools, hospitals, courts of justice); and (b) develop their individual potentialities in their leisure time, is not only the result of their free choice. Rather, it is the result of a compromise between competing requirements of the resource "Human Activity Disposable for Social Self-Organization" in relation to different tasks of the economic process.

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

With the term internal biophysical constraints we want to indicate the obvious fact that the amount of human activity that can be invested into the end uses "Maintenance and Reproduction" + "Social and Leisure" [(HA_{MR} + HA_{SL}] depends only in part on the aspirations of the 100 people for a better quality of life in such a society. The survival of the whole system in the short-term (the matching of the requirement of energy carriers input with an adequate supply of them) can imply forced choices. An example of this is given in **Fig. 16**. Depending on the characteristics of the autocatalytic loop, large investments of human activity in "Social and Leisure" – a large value of the size of HA_{SL} expressed in hours - can become a luxury. For example, if the entire society (with the set of characteristics specified above) wants to adopt Diet B, then for them it will not be possible to invest more than 83,000 hours of human activity in the end use "Social and Leisure". On the other hand, if they want together with a good diet also a level of services typical of developed countries (requiring around 160,000 hours/year per 100 people), they will have to "pay for that". This could imply resorting to some politically important rules reflecting cultural identity and ethical believes (what determines the Societal Overhead of Human Activity for Maintenance and Reproduction). For example, to reach a new situation of congruence they could decide either to introduce child labour, or increase the work load for the economically active population (e.g. working 10 hours a day for 6 days per week) – lower part of **Fig. 16**. In alternative, they can accept a certain degree of inequity in the society (a small fraction of people in the ruling social class eating diet B and a majority of ruled eating diet A). We can easily recognise that all these solutions are operating in these days in many developing countries and were adopted, in the past, all over our planet.

Figure 16. One hundred people on a remote island. Possible scenarios for adjustments between human activity and food energy requirement



8.2.3 Lessons from the example

The simple assumptions used in this example for bringing into congruence the various assessments related to a dynamic budget of societal metabolism are of course not realistic (e.g., nobody can eat only cereals in the diet, and expected changes in the requirements of work are never linear). Moreover, by ignoring exosomatic energy we do not take in account the effect of capital accumulation (e.g. potential use of animals, infrastructures, better technology and know-how which can affect technical coefficients). Capital and flows of exosomatic energy are always relevant for reaching alternative feasible dynamic points of equilibrium of the endosomatic energy budget. That is, there are other options to reach alternative points of equilibrium, beside those linked to changes in population structure and size. Actually, following this approach, it is possible to make models for pre-industrial societies that are much more sophisticated than the one presented in **Fig. 17**. Models that take into account different technologies, quality of natural resources, landscape uses, detailed profiles of human time use, as well as reciprocal effects of changes on the various parameters, such as the size and age distribution of society (Giampietro, 1997, Giampietro et al., 1993, 1997). These models, after entering real data derived from specific case studies, can be used for simulations, exploring viability domains and the reciprocal constraining of the various parameters used to characterise the endosomatic autocatalytic loop of these societies. However, models dealing only with the biophysical representation of endosomatic metabolism and exosomatic conversions of energy are not able to address the economic dimension. Economic variables reflects the expression of human preferences within a given institutional setting (e.g. an operating market in a given context) and therefore are logically independent from analysis reflecting biophysical transformations. This is why a Multi-Scale Integrated Analysis has to include and handle simultaneously the representation of economic and biophysical flows.

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

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

A technical discussion of the sustainability of the dynamic energy budget represented in the lower graphs of **Fig. 15** and **Fig. 16** in terms of potential changes in characteristics (e.g. either the values of numbers on axis or the values of angles) requires considering non-equivalent dynamics of evolutions reflecting different perceptions and representations of the system. That is, the characteristics of the whole society (at **level *n***) in terms of size (THA) and throughput (total food per year) and the characteristics of the various elements (at **level *n-1***) in terms of size (HA_i) and throughput (total food per year either produced or consumed by the various elements) can be related to other relevant characteristics referring to different hierarchical levels of analysis.

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

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

To make another hypothesis of perturbation within the ILA shown in **Fig. 15**, let us imagine the arrival of another crashing plane with 100 children at board (or a sudden baby boom in the island). This perturbation translates into a dramatic increase of the dependency ratio. In this system of accounting this is translated in doubling the size of THA and increasing the value of SOHA = HA_{MR}/THA. That is, the system will face a larger food demand, for the new population of 200 people, which has to be produced by the same amount of 256,000 hours of “Human Activity Disposable for Society” (related to the disposable activity of the same 50 working adults). In this case, even when adopting Diet A, the larger demand of work in production will force such a society to dramatically reduce the consumption of human activity in the “end use” related to “Social and Leisure”. The size of HA_{SL} =158,000 hours/year was feasible in a society of 100 “vegetarians” (adopting 100% Diet A). But after the new crash of the second plane full of children, that size for the compartment “Social and Leisure” can no longer be afforded. This could imply reducing the investments of human activity in schools and hospitals (in order to be able to produce more food), at the very moment in which these services should be dramatically increased (to provide more care to the larger fraction of children in the population). A similar forced choice could appear an “uncivilized behaviour” to an external observer. This value judgment, however, can only be explained by the ignorance of such an external observer of the existence of biophysical constraints which are affecting first of all the very survival of that society.

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

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

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

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

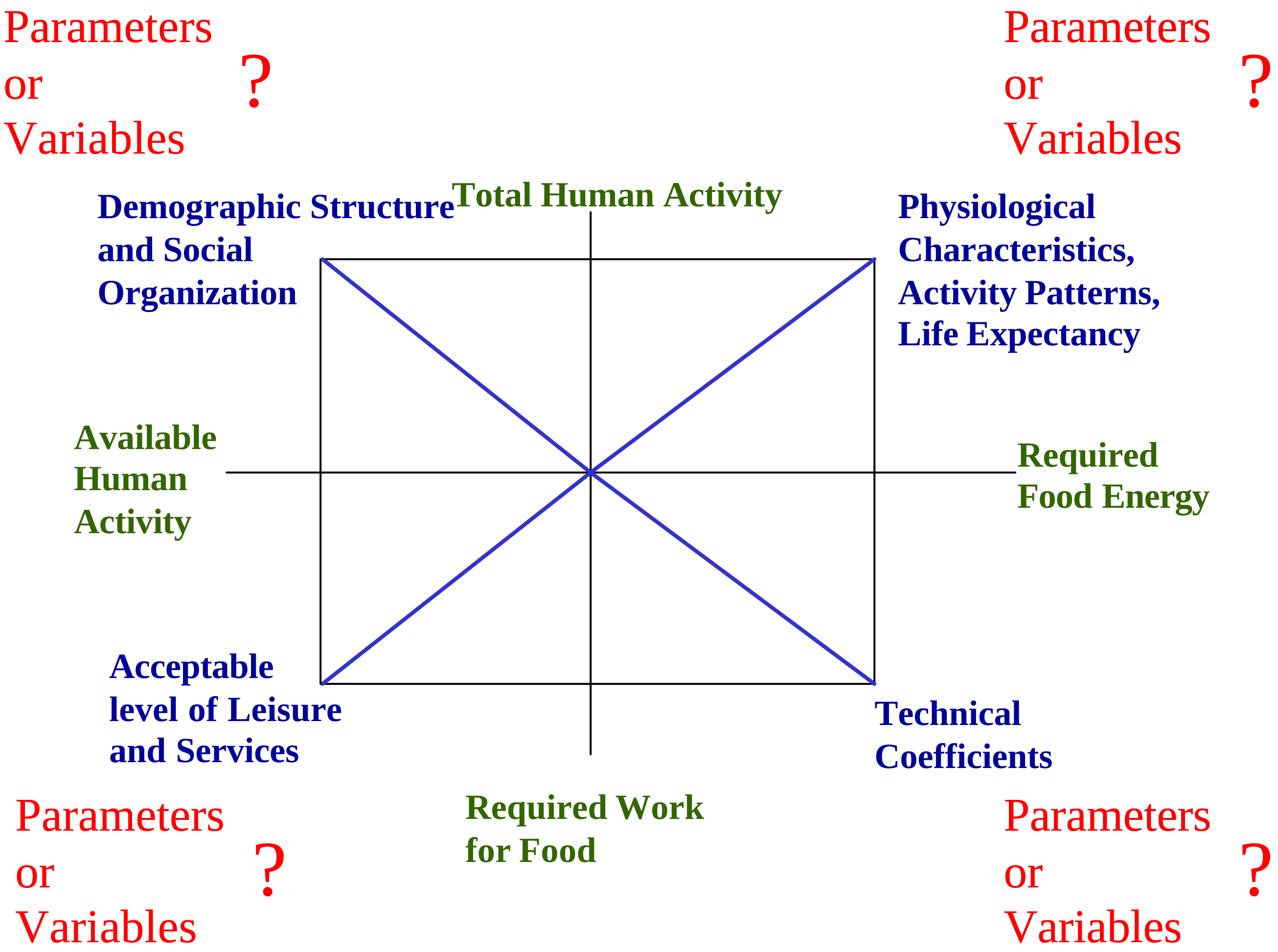
8.2.3.3 It enables to deal with the implications of non-equivalent narratives

Whenever humans are facing the need of adjusting the set of characteristics of an impredicative loop, they tend to go for the most popular idea introduced by the era of Enlightenment to obtain congruence. They always look for the silver bullet able to provide a win-win solution. To this respect the Enlightenment can be seen as a remarkable hegemonisation on the possible narratives that can be used in a debate over sustainability. The 'gospel' of western civilisation implies that the standard solution to all kinds of dilemmas about sustainability has to be obtained by looking for better technical coefficients. This solution, in fact, makes it possible to avoid facing conflicts among the various identities making up an impredicative loop. However, any solution based on adding more and better technology (a change in the characteristics related to intensive variables) does not come without side effects. It necessarily implies an adjustment all over the Impredicative Loop, and finally the requirement of the loop on its environment. Well known is the fact that improvements related to a given characteristic defined in terms of an intensive variable (e.g. more efficiency in using a given resource for a task) entail a worsening in relation to another characteristic defined in terms of an extensive variable (e.g. the given resource will be used more for the original task and for other). This is the well known Jevons' paradox ((Jevons, 1865) developed in Section 5.2.3. For the relative analysis within the MSIA approach see Giampietro (2003) Chap. 1 and 7). The counterintuitive side effect of expressing more efficient activities is the boosting of the size of the relative compartments. This tends to translate into an increase in the environmental impact of societal metabolism. In our example, this could be the amplification of agricultural practices based on monocultures (a typology of land use associated with the highest productivity per hour of labour and per hectare) associated with the elimination of poly-cultural systems. Framing the discussion about future options, within the framework of MSIA over an impredicative loop, implies that the various analysts are forced to consider, at the same time, several distinct effects (which require the simultaneous use of non-equivalent models and variables to be represented) belonging to different descriptive domains.

There are characteristics of the autocatalytic loop that have a very short typical lag time for change, for example when adopting economic prices in the analysis. Other characteristics may have a lag time of changes of a few years, as in the case of analysis based on laws and technical coefficients, which can refer to a very location specific space-time scale (e.g. the yield of cereals at the plot level in a given year) or a large space-time domain (e.g. the efficiency of a gas turbine). Other characteristics, such as the dependency ratio (the ratio between non-working and working population) may reflect slower biophysical processes (those associated to demographic changes) having a time horizon of 20 years. Finally there are other factors – e.g. regulations for compulsory schooling for children or religious taboos – which reflect values related to the specific cultural identity of a society, which have an even slower pace of change (values and taboos tend to be very resilient in human systems). If we admit this fact, when do we consider possible ways of obtaining congruence over a MSIA of an impredicative loop associated to a societal metabolism, how to decide what is a variable and what is a parameter? Which is the time horizon to be used as reference when making this decision? The very definition of what is a variable and what is a parameter in this type of analysis is associated to the pre-analytical selection of a narrative within which to frame the analysis - see **Fig. 17**.

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

Figure 17. Arbitrariness associated with a choice of a time differential



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

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

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

8.3 Conclusions

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

By adopting a set of innovative concepts developed within the field of complex system thinking MSIA can provide:
(1) an organised procedure for handling a set of useful representations of relevant features of the system reflecting stakeholders views - e.g. definition of a set of models which use non-equivalent identities and boundaries for the same system. In this way it becomes possible to represent over different descriptive domains different structures and functions – a multidimensional, multi-scale analysis;
(2) a definition of the feasibility space (= range of admissible values) for each of the selected indicators of performance. A definition of feasibility should consider the reciprocal effect across hierarchical levels of economic, biophysical, institutional and social constraints;
(3) a multi-criteria representation of the performance of the system, in relation to a given set of incommensurable criteria. This requires calculating the value for each indicator included in the package selected by social actors. In this way it becomes

possible to represent: (i) Targets - what should be considered an improvement when the value of the relative variable changes, (ii) Benchmarks - how the system compares with appropriate targets and other similar systems, (iii) Critical non-linearity - what are possible critical, threshold values of certain variables where non-linear effect can be expected to play a crucial role.

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

Chapter 9[87]: Multi-Scale Integrated Analysis of Societal Metabolism: learning from trajectories of development and building robust scenarios

9. 1. Introduction

In the past decades, analyses aimed at economic development (both in the scientific literature and in the discussions in policy agencies) have focused mainly on representations based solely on economic variables. This strategic choice has lessened attention to biophysical variables (such as energy conversion, human time allocation, materials use, or land use). We happen to believe that an integrated analysis of the economic and biophysical dimension of development, able to put back into the picture these neglected variables, is crucial for an effective description of the evolution of societies and their technological development, as well as for understanding possible constraints for further development.

Accounting for both economic and biophysical variables requires a wider focus than that adopted by neo-classical economics. It calls for a methodological approach able to link the various relevant dimensions of analysis associated to the economic process within a holistic view of the evolution of socio-economic systems interacting with an ecological context. To achieve this goal, traditional economic reading should be complemented by an analysis of flows of both matter and energy going “into the society”, “through the society” and “out of the society” according to the metaphor of metabolism. In the field of Ecological Economics this integration is associated with the concept of “societal metabolism” (Martinez-Alier, 1987; Fischer-Kowalski, 1997; Schandl et al., 2002), as it has been explained in Section 4.2.4.

Let us, at this point, summarise in a couple of pages how all the theory developed before, including the description of MSIA, fits together. This exercise of repeating already introduced concepts is considered necessary for fully

---

[87] This chapter builds on the paper of the same title published with Mario Giampietro in the Journal *International Journal of Global Environmental Issues* (Ramos-Martin and Giampietro, in press).

understanding the interconnectedness of all the pieces of work included in this dissertation, as well as for better following what comes here and in Chapter 10.

When considering the societal metabolism of economies, one has to acknowledge the fact that economies are complex, adaptive, dissipative systems. They are composed of a large and increasing number of both components and relationships between them. Economies are also teleological systems (they have an aim or end, a *telos*). Moreover, they are capable of incorporating guessed consequences of their possible actions into their actual decisions. That is, they are anticipatory systems (Rosen 1985) and because of this property they can even update their own definitions of goals and models. That is, they learn from past mistakes and from present developments, and they react, by changing both current and future actions. They are thus self-reflexive. Because of this they have the option of either adapt to new boundary conditions or consciously alter boundary conditions they do not like. Therefore, an economy can be understood as a complex, adaptive, self-reflexive, and self-aware system (Kay and Regier, 2000).

In terms of structure, economic systems are nested hierarchical systems. That is, they consist of elements defined on different hierarchical levels (the whole is made of parts, each part is made of sub-parts, the whole belongs to a larger network). In the case of a national economy, we can distinguish several subsystems such as economic sectors within it. Every sector may be split into different sub-sectors (e.g. industrial 'types' sharing common features) and so on. The various hierarchical levels of an economy do exchange flows of human activity and energy (i.e. among them at the same level, and across levels and scales). The resulting network of flows reflects the interconnected nature of those systems (the output of one sector enters another sector as an input, and vice versa). The feed-back of flows across scales implies a kind of chicken-egg behaviour that may be analysed by means of impredicative loop analysis.

Ecosystems and human systems (as open complex systems) are autopoietic systems. Autopoiesis (Varela et al., 1974; Maturana and Varela 1980) refers to the ability that living systems have to renew themselves and maintain their structure. In this frame, their capacity for self-reproduction has to be understood in relation to the fact that they are teleological (end-oriented) entities. They hold the essential characteristics of: (a) openness to energy and matter flows; (b) presence of autocatalytic loops (closed to the system) which maintain the identity of the system; and (c) differentiation of organisational structure and functions for different parts, that allows the systems to adapt to the changing boundary conditions, by becoming something different in time.

This process of self-reproduction and adaptation is therefore related to their ability to process both information and energy/matter (Jantsch 1987). In this context, the usefulness of information can be related to the ability: (i) to develop and transmit strategies of development useful to confront fluctuations or future challenging boundary conditions; and (ii) to generate and select different narratives useful for describing and representing the interaction with their context. The usefulness of energy and matter flows can be related to the ability to maintain compatibility of structures and functions against thermodynamic constraints.

Two other useful concepts for the analysis of self-production are: (1) "autocatalytic loop" (i.e. activities which affect themselves through an interaction with the context – a positive autocatalytic loop implies a reinforcement and amplification of an activity); and (2) "the key role of hyper-cycles" (i.e. the special role autocatalytic loops play in the evolution of dissipative systems) (Ulanowicz 1986). When describing ecosystems as networks of dissipative elements, Ulanowicz (1986) distinguished between two main parts: (a) a part responsible for generating the hyper-cycle (i.e. the subset of activities generating the surplus on which the whole system feeds), and (b) a part representing a pure dissipative structure. That is, a hyper-cycle (those processes taking primary energy from the environment - e.g. solar energy for ecosystems - and converting it into available energy for other processes - e.g. supply of different energy carriers – biomass for other ecological agents) must always be associated with a purely dissipative part (e.g. herbivores and carnivores feeding on net primary productivity). The same analogy can be applied to economies.

The role of the hyper-cycle is, therefore, "to drive and keep the whole system away from thermodynamic equilibrium" (Giampietro and Mayumi 1997: 459). Whereas the dissipative part is required to stabilise the system by avoiding an excessive take over of the hyper-cycle (without a complementing part damping their effect positive autocatalytic loops just blow up!).

As soon as we undertake an analysis of socio-economic processes based on energy accounting we have to recognise that the stabilisation of societal metabolism requires the existence of an autocatalytic loop of useful energy. That is a certain fraction of the useful energy invested in human activity must be used to stabilise the input of energy carriers taken from the environment. In the example used in this chapter, we characterise the autocatalytic loop stabilising societal metabolism in terms of a reciprocal "entailment" of two resources: (1) "human activity used to control the operation of exosomatic devices" and (2) "fossil energy used to power exosomatic devices" (Giampietro 1997). The two resources, therefore, enhance each other in a chicken-egg pattern (human activity enhances the use of fossil energy, the use of fossil energy enhances the generation and expression of human activity).

All the above characteristics of economies analysed as complex systems make them difficult to be understood and comprehended when using the drastic simplifications associated with reductionism (= the use of a single level of analysis, a single scale and a single dimension). This is why we need a methodology that combines information coming from different disciplines (e.g. economic, demographic and biophysical variables), and from different hierarchical levels of the system (scales) in a coherent way. The methodology used here is Multi-Scale Integrated Analysis of Societal Metabolism (MSIASM), which is described in detail in Giampietro and Mayumi (2000a, 2000b) and Giampietro (2003).

After having selected a useful narrative in relation to the research goal, MSIASM provides a representation of the performance of the given system in terms of a finite set of attributes by using 'parallel non equivalent descriptive domains' (economic reading, demographic reading, technical reading, and biophysical reading). In so far MSIASM should be considered as a 'discussion support tool' that may be used, as we shall show, for both historical analysis and scenarios analysis. In the latter case the intention is not to forecast the future behaviour of variables and the exact value they may take. Rather the goal is to improve the quality of the narratives adopted for building scenarios. That is, MSIASM can provide hints on future trends of key variables, and possible biophysical, or economical constraints for future development scenarios, pointing at those attributes of performance that should be considered when selecting and evaluating scenarios. The basic idea is that when dealing with the future it is better to be aware of possible attributes of performance that will be relevant - even if this implies not guessing with accuracy the value taken by the relative variable – rather than guessing with accuracy the future value taken by variables that can result irrelevant.

The rationale of the approach is based on the three concepts discussed at length in the previous chapter:

> (a) '***mosaic effects across levels***', obtained by using redundancy in the representation of parts and whole of the system using non-equivalent external referents (data source) across non-equivalent descriptive domains.
>
> (b) '***impredicative loop analysis***', obtained when addressing, rather than denying, the existence of chicken-egg paradoxes in self-organising adaptive systems. This analysis is required whenever the identity of the whole defines the identity of the parts and vice versa.
>
> (c) '***the continuous search and the updating of useful narratives for surfing in complex time***' based on the acknowledgement of the fact that the observer/observed complex requires the simultaneous consideration of several non-reducible relevant time differentials: (i) the 'time differential' at which the system evolves; (ii) the 'time differential' adopted in the set of differential equations used in models; (iii) the 'time differential' at which the observer changes its perception of what is relevant about the observed.

The structure of the rest of the chapter is as follows: Section 2 presents a historical application of MSIASM for analysing the bifurcation in the development trajectories between Spain and Ecuador. Section 3 presents an example of scenarios analysis in Viet Nam. Finally, the conclusion will make a few theoretical considerations about the advantages of using the MSIASM approach to analyse the exosomatic evolution of societies. As explained in the following text, we do not claim that the scenarios and numbers used in this paper according to the narratives we selected are 'the correct ones'. The opposite cannot be proven in substantive terms by anyone. What is relevant, therefore, is the illustration of the potentials of this approach when applied for an integrated analysis of scenarios. Such an analysis can be improved, by increasing the degree of overlapping across different types of data (using simultaneously more external referents) and bridging descriptions referring to different hierarchical levels. A last observation, in this paper, the MSIASM approach is applied to the level of 'national economy' as the focal level (**n**) of analysis, but other levels of analysis are possible (e.g. using the village or the household as the focal level of analysis – (Giampietro 2003)).

9.2. Learning from development trajectories: biophysical constraints to economic development in Spain and Ecuador 1976-1996

A methodological note

Carrying out a MSIASM always requires following three basic steps:

(A) Choosing a set of variables able to map the size of the system (i.e. economic system) as perceived from within the black-box (variable # 1, required to generate a multi-level matrix for the analysis). Typical examples are: "hours of human activity" and "hectares of land".

(B) Choosing a set of variables able to map the size of the system as perceived by its context in terms of exchanged flows (variable # 2, required to be able to use external referents, i.e. different sources of data at different levels). Assessing the exchanged flows makes it possible to describe the interaction of the system with its context at different levels. Examples are: "specific flows of exosomatic energy" (e.g. MJ of exosomatic energy – for the whole country, for an economic sector, for a particular plant), “specific flows of added value” (e.g. $ – for the whole country, for an economic sector, for a particular plant), “specific flows of other key material” (e.g. kg of water or kg of nitrogen – for the whole country, for an economic sector, for a particular plant).

(C) Mapping the nested hierarchical structure associated to the metabolic system using in parallel the two variables # 1, # 2, and the ratio of the two (variable # 3). The resulting family of intensive variables # 3 will result in an integrated biophysical accounting (e.g. exosomatic energy flows per unit of human activity or exosomatic energy flows per unit of land area) and economic accounting (flows of added value per unit of human activity or flows of added value per unit of land area). The resulting assessment MJ/hour of human activity, MJ/ha of land use, $/hour of human activity or $/ha of land use can be related to different hierarchical levels (the whole country, an economic sector, a particular plant or household) and can be used to define typologies through benchmarking.

When representing the system in this way we achieve coherence in the resulting information space (e.g. economic and biophysical readings referring to different levels of the nested holarchy that are related to each other) using equations of congruence. Such an integrated analysis allows seeing underlying constraints, problems and relations associated with economic development, which are difficult to see when applying traditional analytical tools from economics.

9.2.1. Goal of the example

This Section presents an application of the Multi-Scale Integrated Analysis of Societal Metabolism to the recent economic history of Ecuador and Spain. The main goal of this comparison is to understand the relationship between changes in Gross Domestic Product (GDP) and related changes in the throughput of matter and energy over time. Understanding this link is crucial for studying the sustainability of modern societies. MSIASM applied to historical analysis of development is based on the identification of different "types" of parts (sub-sectors, sectors) and whole (countries at different levels of development) that can be used for characterising trajectories of development.

The analysis of historic changes of Spain and Ecuador is based on the relative values taken by the characteristics of parts (various economic sectors, which are characterised in terms of typologies, using a set of expected values for a given set of variables – benchmarks) in relation to the characteristics of the whole (the national economy, which is characterised in terms of typologies, using a set of expected values for a given set of variables – benchmarks). This makes it possible to explain the different paths taken by these two countries over the period considered.

In this example, when considering the dynamics of economic development, Spain was able to take a path different from that taken by Ecuador thanks to the different characteristics of its energy budget and the relative values taken by other key variables such as population structure [affecting the profile of human time allocation] and the pace of population change. The integrated set of relevant changes is described using a mix of economic and biophysical variables (both extensive and intensive). The representation of these parallel changes (on different levels) requires the use of different variables, which can be kept in coherence by adopting the frame provided by MSIASM. In particular, the integrated representation based on a mix of extensive and intensive variables kept in congruence over a 4 angle figure, is based on the approach presented in Giampietro and Ramos-Martin (in press, and the basis for Chapter 8). A deeper analysis of both cases – Ecuador and Spain – using MSIASM and other more conventional approaches can be found in Falconi-Benitez (2001) and Ramos-Martin (2001, which is the basis for Chapter 7) respectively.

In the text below we present an example of mosaic effect and an impredicative loop analysis applied to the process that stabilises the metabolism of a society both in the short-run and the long-run. In a metabolic system, what enters as an input to be consumed is then used to carry out several activities. A fraction of these activities must be directed to guaranteeing the (re)production of what is later consumed as input (short-run stabilisation referring to the concept of efficiency). On the other hand, those other activities not aimed at the stabilisation in the short term of the various inputs (because they are purely dissipative) are still important, since they guarantee reproduction and adaptability in the long-term by means of other activities such as education (Giampietro 1997).

The representation of the metabolism across scales and hierarchical levels, this process can be represented using a set of different identities for:

(a) energy carriers (**level *n-2***; that of the individual members of the system);
(b) converters used by components (on the interface **level *n-2*/level *n-1***);
(c) the whole metabolic system seen as a network of parts (on the interface **level *n-1*/level *n***);
(d) the whole seen as a black box interacting with its context (on the interface **level *n*/level *n+1***).

The need of achieving a dynamic budget implies a mechanism of self-entailment among the various definitions of identity for sub-parts, parts, wholes and context describing this interaction across levels. The way to deal with such a task is illustrated in the example given in Chapter 8 – we refer the reader to **Fig. 17** given there. The impredicative loop analysis based on the 4 angle representation refers to the forced congruence among two different forms of energy flowing in the socio-economic process: (1) Fossil energy used to power exosomatic devices, which is determining/ is determined by (2) Human activity used to control the operation of exosomatic devices.

9.2.2. Analysis based on the mapping of flows against the multi-level matrix: Human Activity

9.2.2.1. The relations used in this analysis

The variables used in this example are the same ones described in Section 7.4.1. As a reminder, they are:

THA = Total Human Activity of the whole socio-economic system considered (hours/year).

The value of this variable (the size of the economy in terms of human activity is obtained by multiplying human population by 8760 (the hours per capita in one year).

HA_i = hours of Human Activity invested in Sector **i**

(SOHA+1) = Societal Overhead of Human Activity, THA/HA_{PW} where PW indicates the hours of work in all the sectors generating added value; that is, Productive Sectors (PS) and Services and Government (SG)

TET = Total Exosomatic Throughput of the whole system considered (Joules/year) expressed in primary energy equivalent as done in UN statistics of national energy consumption.

ET_i = Joules of exosomatic energy consumed per year in Sector **i**

(SOET + 1) = Societal Overhead of Energy Throughput, TET/ET_{PW} where PW indicates the amount of primary energy invested in all the sectors generating added value; that is, Productive Sectors (PS) and Services and Government (SG)

$ExMR_{AS}$ = Exosomatic Metabolic Rate (Average Whole System) the rate of consumption of exosomatic energy per unit of human activity (EMR_{AS} = TET/THA)

$ExMR_i$ = exosomatic metabolic rate per hour of human activity in Sector **i**

GDP = Gross Domestic Product, measured in constant dollars

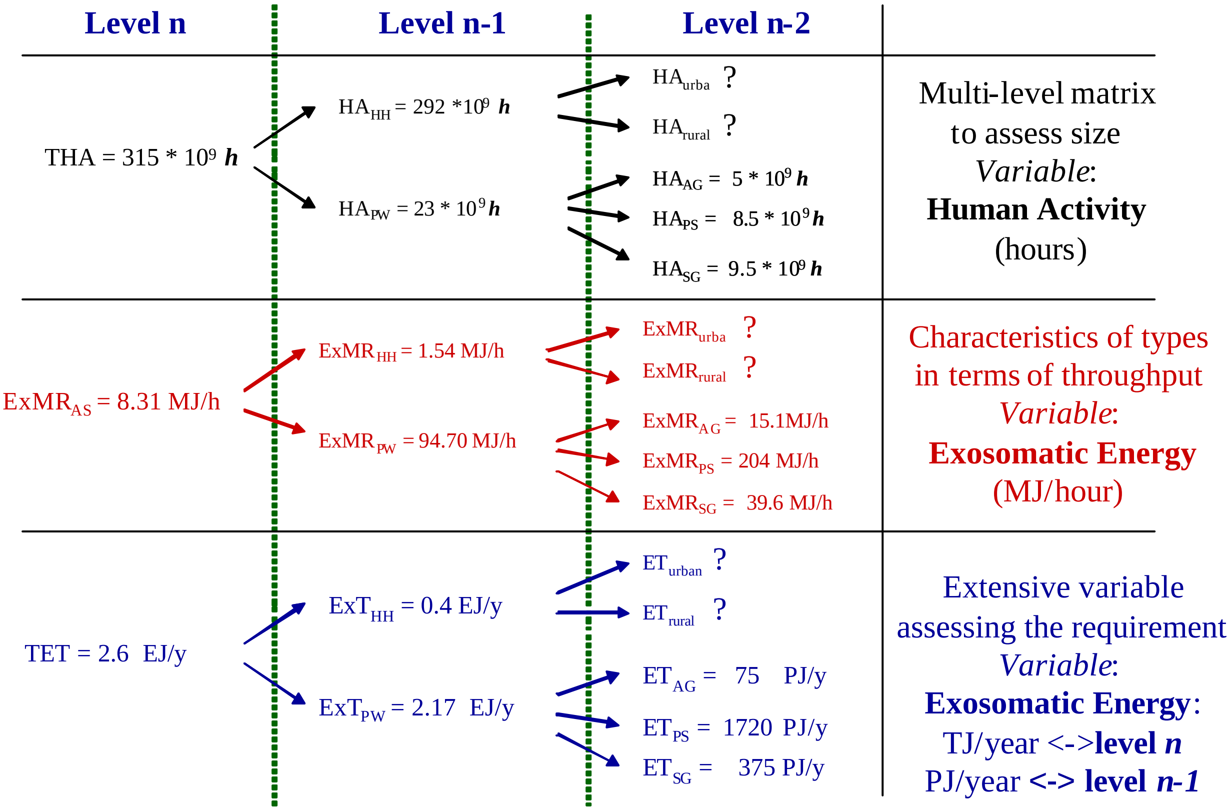
ELP_i = economic labour productivity in Sector **i,** that is, GDP_i/HA_i in dollars per hour of activity

For a more detailed explanation of the formalisation used in the 4-angle figures see (Giampietro 1997, 2003; Giampietro and Mayumi 2000a, 2000b; Giampietro et al., 2001).

9.2.2.2. Dendogram of $ExMR_i$ (relevant flow - extensive variable#2 - “Exosomatic Energy” versus a variable defining size - extensive variable#1- “Human Activity”)

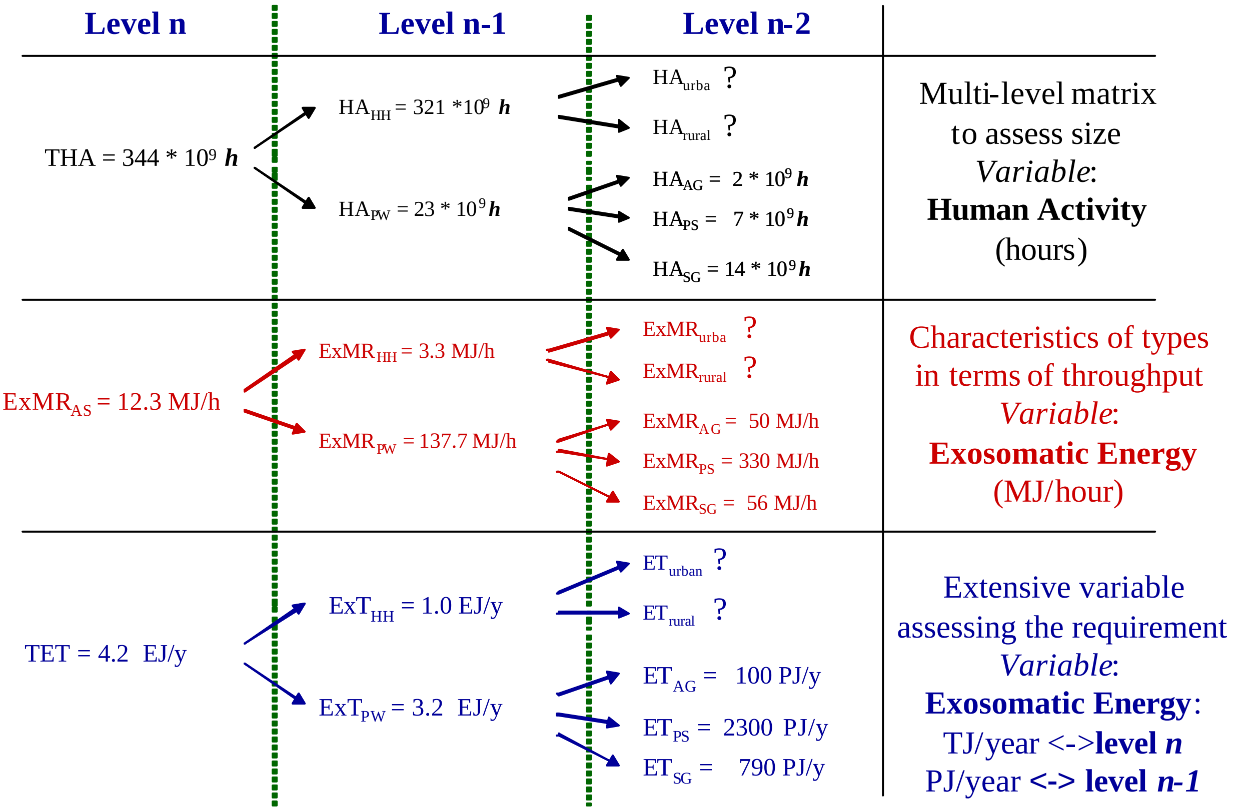
Fig. 18 and **Fig. 19** represent the dendograms of exosomatic metabolic rates, $ExMR_i$, for Spain in the years 1976 and 1996. We start our analysis by identifying two extensive variables that are defining the size of the system, in this case Total Human Activity (THA, extensive variable #1) and Total Energy Throughput (TET, extensive variable #2). In our representation of the hyper-cycle of the economy (**Fig. 20**), this would be the right-hand side of the graph. In our 4-angles representation (**Fig. 21**), this would be the upper right quadrant. It represents the **level *n*** of the analysis, that of the national economy.

Figure 18: Dendogram of ExMR in Spain in 1976



In **Fig.18** and **Fig.19** the first disaggregation distinguishes between investments of both "Human Activity" and "Energy Throughput" either in the "Household sector (HH)" or in the "Paid-Work sector (PW)". In other words this represents the split between the consumption side and the production side. In our analysis represented at **level *n-1***. A second disaggregation may imply splitting the performance of the household sector into different household types at the **level *n-2*** (such as *urban and rural*, or different household types depending on income level). Since we do not have data for the household sector at this level of disaggregation (**level *n-2***), we do not present data for this level, as done for the paid-work sector. The MSIASM mechanism of accounting, however, is robust insofar, as this does not affect the possibility of obtaining relevant information about different characteristics of the socio-economic systems outside the household sector. In fact, we do split the paid-work sector, at the **level *n-2***, between the different sectors: Productive Sector (PS, including industry and mining), Services and Government Sector (SG) and Agriculture (AG). In our analysis is **level *n-2***. In the 4-angles representation adopted in this chapter, this would represent the left lower quadrant, where the productive sector is the focus for analysis. Obviously, a different goal of the analysis could have included any of the other two sectors (SG or AG) instead.

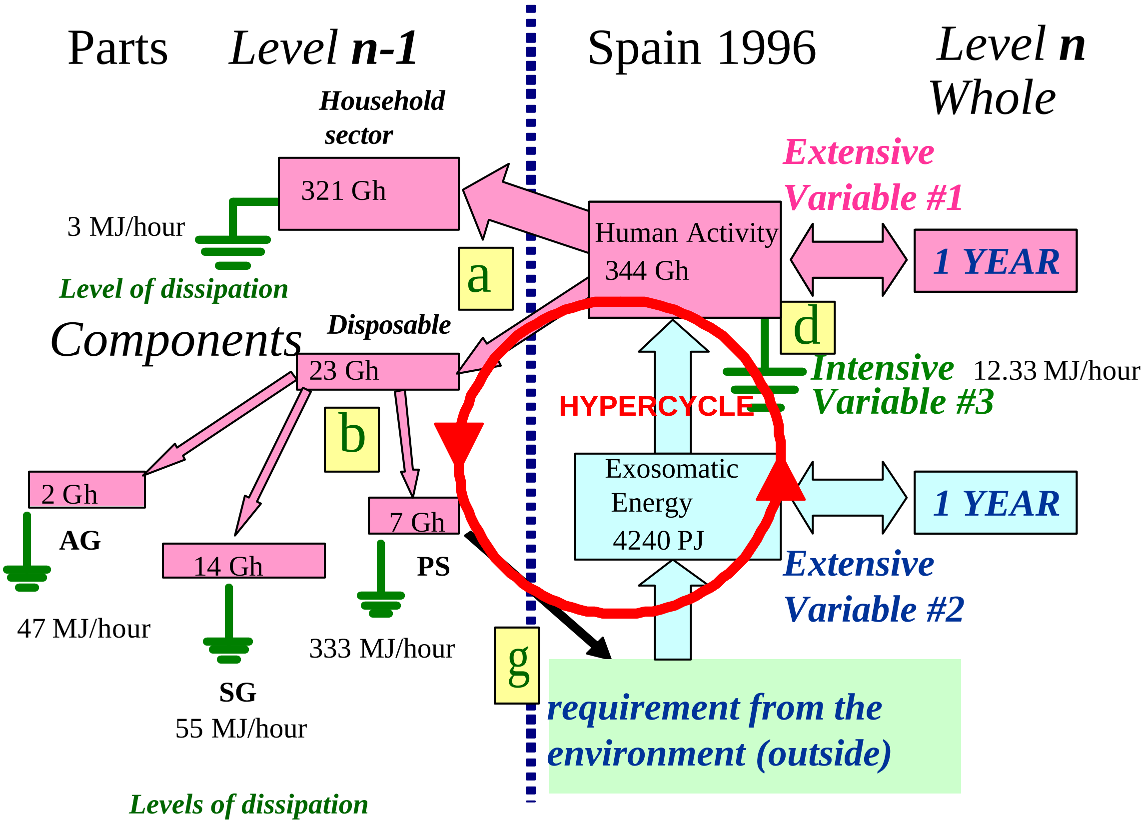
Figure 19: Dendogram of ExMR in Spain in 1996



The ratio between extensive variable #1 and extensive variable #2 (assessed over different elements at different levels) determines the value of the intensive variable #3, which in our case is $ExMR_i$. This variable reflects a biophysical accounting of the system. In the 4-angle representation, intensives variables are those found at the corners of the quadrants, whereas the length of the axis would represent the total size of the system or compartment (extensive variables, as perceived from the inside – extensive variable #1 – or from the outside – extensive variable #2). The value of the intensive variable#3 can be determined: (a) from the congruence of the value of extensive variables defined at a given level (e.g. **level *n***); and (b) from the typology (e.g. technical coefficient or economic characteristics) describing the component of the system at **level *n-1***.

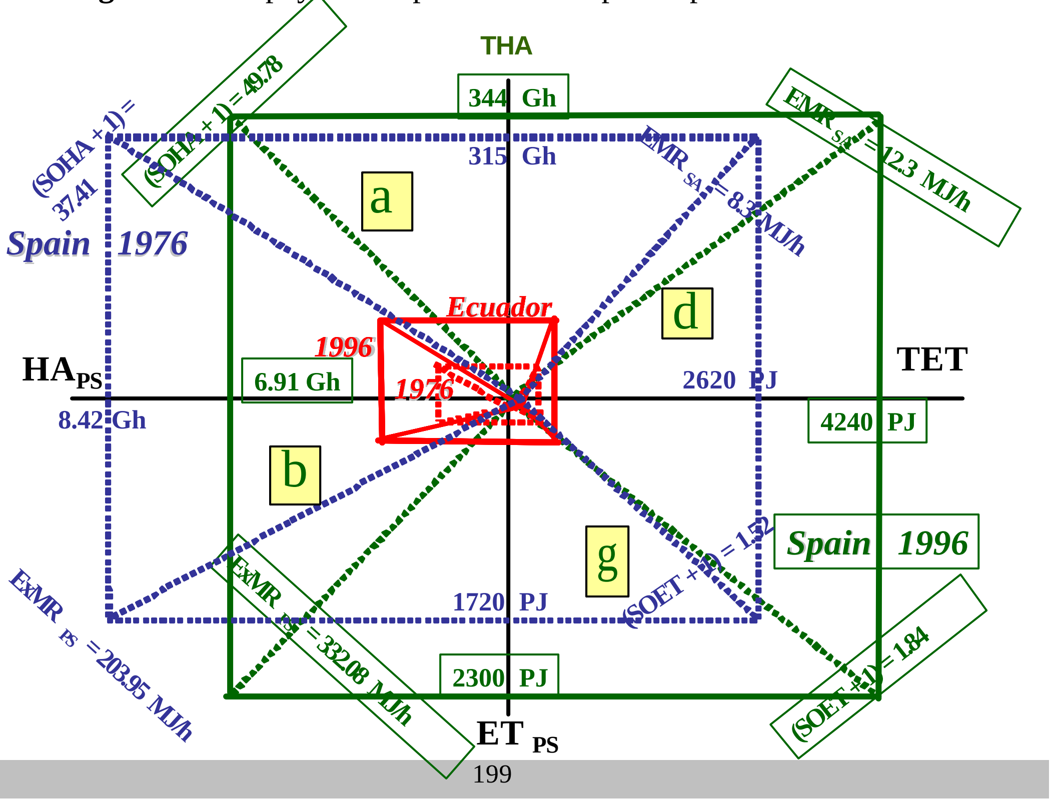
The representation of the characteristics of elements belonging to different hierarchical levels by using a dendogram makes evident an important characteristic of MSIASM: the ability of simultaneously handling a set of values taken by key variables on different hierarchical levels. That is, a given value of an intensive variable can be seen as being determined by: (a) relations of values taken by variables belonging to a higher level, or (b) the aggregation of values associated with typologies defined on lower levels. This feature is crucial when analysing scenarios of future development. In fact, the analysis presented in **Fig. 18** and **Fig.19** implies a representation of past trends. This is a case in which all data can be known in retrospect. However, in case of scenario analysis, we *would not need* all the data, because of the forced congruence across scales and the possibility of establishing mosaic effects missing data can be complemented. In other words, the value of some of the variables can be obtained using different methods of “guesstimation”. Future characteristics can be guesstimated by extrapolating into the future expected changes in typologies on the lower levels (scaling up), or guesstimating future characteristics of types on the higher levels (scaling down). For instance the value taken by the variable EMR_{HH} can be used as a proxy for the level of material standard of living of the household sector (average for the whole country). This value can be found using a bottom-up approach if we know: 1) the set of households types existing in the country - i.e. urban/rural, income levels, household size; 2) the profile of distribution of these households types over all households; and 3) the different EMR_i of these household types (observed using a ‘consumption survey’, for instance). On the other hand, if we approach the assessment of the value of EMR_{HH} with a top-down procedure, we will just need to look at the values of ET and HA found at **level n** of analysis. The value of EMR_{HH} is the ratio between ET_{HH} and HA_{HH}. Obviously, the same rationale applied to the assessment of EMR_{HH} can also be used for other intensive variables #3, in this case, for the other EMR_i.

Figure 20: Hypercycle of exosomatic energy in Spain 1996



A similar disaggregation as shown above for human time and energy use can be done for other key variables, such as added value, and land use. A useful feature of MSIASM is that it becomes possible to link non-equivalent representations of the economic process within a common frame. The same multi-level matrix represented by extensive variables #1, allows for mapping the size of the system (e.g. "hours of human activity" and "hectares of land area") across levels (e.g. whole society, components, sub-components) against a set of extensive variables #2 describing the interaction of the system with its context ("flows of exosomatic energy", "flows of added value", "other flows of key material inputs") at different scales. In this way, it becomes possible to see how a change in the value taken by a given variable, at a particular hierarchical level, does affect the value taken by the other variables defined on the same and/or on different hierarchical levels. The fact that several levels and several typologies of variables have to be considered simultaneously in this mechanism of accounting has important consequences. It implies that the constraint of congruence does not translate into a deterministic relation among possible changes. Over and above, the same change in the value taken by a given variable at a given level (an increase of energy efficiency at the level of a sub-sector) can generate different re-adjustments of the values taken by either the same variable on different levels (a different use of energy in the other sectors) and/or on different variables (a different profile of distribution of human activity across sectors). This insight demonstrates the impossibility of formalizing within reductionist analytical concepts such as "Kuznet's environmental curves" or the famous "I = PAT" equation proposed by Ehlrich. Using the mosaic effect we can look for congruence of flows across different scales and dimensions of analysis. The problem, however, is that multi-level systems may react to the very same change by adjusting in a different way the variables determining congruence. That is, there are different combinations of values for extensive variables [changes in 'size'] and intensive variables [changes in typical ranges of metabolic flows] – defined at the **level *n-1*** – which can generate the same set of characteristics at the **level *n***, as is shown in **Fig. 20**.

Figure 21: Biophysical impredicative loop for Spain and Ecuador



This is why, in order to understand the relation between changes and effects in different variables (extensive and intensive) on different levels, one needs to apply an impredicative loop analysis, as the one shown in **Fig. 21**. The 4 angles given in **Fig. 21** (which are labelled using Greek characters) are the same 4 angles indicated in **Fig. 20.**

This denotes that **Figure 20** represents a bridge between the dendograms presented in **Fig. 18** and **Fig. 19** and the 4-angle-impredicative loop analysis given in **Fig. 21**. Here we have a representation of the hyper-cycle of exosomatic energy (the autocatalytic loop of useful commercial energy) for Spain in 1996. In the right part of the graph we represent the system at the **level *n*;** that is, it combines an extensive variables #1 (Total Human Activity) and an extensive variables #2 (Total Exosomatic Throughput) into the resulting intensive variable #3 (Exosomatic Metabolic Rate, average for the society). On the left-hand side of the graph we show the representation of the system at **level n-1;** that is, the distribution of the human time among the set of different types of activities considered in this analysis, as well as the dissipative rates, assessed in Mega-joules per hour of human activity.

This kind of representation focuses on possible internal constraints in the energy budget. For instance, one can see that in terms of human activity a rather small Productive Sector (with only 7 Gh of human time over a total amount of 344 Gh) must be able to guarantee a sufficient inflow of exosomatic energy to the overall system. The Productive Sector has to guarantee the metabolism required for the structural stability of the overall system (and its components) in the short-run. This explains why its metabolic rate is the highest among the different systems components (333 MJ/hour). The large hyper-cycle associated with fossil energy, on the other hand, requires a very high level of capitalisation of the productive sector for its handling. In this context the idea proposed by Georgescu-Rogen of using the Exo/Endo ratio to describe a system can be useful to explain our data. A flow of 333 MJ/hour of exosomatic energy handled by one hour of human activity in the PS sector, implies an amplification of the energy controlled by humans there of 833 times! (since the rate of endosomatic energy is about 0.4 MJ/hour). The rate of exo/endo in different sectors therefore can be considered as a proxy for the level of capital accumulation of that sector and implies huge differences compared with the average values found for a country. For example, whereas the average value for Spain in 1996 is an exo/endo of 32/1, the biophysical constraint of technical coefficients associated to the ability of stabilising the energy budget requires an exo/endo of 833/1 in the PS sector (let alone if we would consider the exo/endo of the energy sector in which the amount of exosomatic energy controlled by one hour of work is in the order of GJ!).

After presenting the disaggregation of the different variables required to generate the mosaic effect, we can now proceed with an impredicative loop analysis using the 4-angles framework as shown in **Fig. 21**. The only difference is that “the set of activities required for food production” within the autocatalytic loop of endosomatic energy considered in the example of the 100 people confined on a remote island, has been translated into “the set of activities producing the required input of useful energy for machines” (energy and mining + manufacturing)” in the analysis of Spain and Ecuador.

There are two sets of 4-angle representations shown in **Fig. 21**. Namely formalisations of the impredicative loop generating the energy budget of Ecuador and Spain for the years 1976 and 1996 (smaller quadrants represent Ecuador, larger ones represent Spain). To allow for comparison we adopt the same protocol for the formalisation of these 4 impredicative loops. This figure clearly shows that by adopting this approach it is possible to address the issue of the relation between: (i) ***qualitative changes*** (related to the re-adjustment of reciprocal value of intensive variables within a given whole, represented by a change in the value shown at the angle) and (ii) ***quantitative changes*** (related to the value taken by extensive variables – that is the change in the size of internal components and the change of the system as a whole, represented by the length of the segments on the axes). Please note that when using this representation in **Fig. 21** we are not ‘normalising’ values, therefore a given ratio among two extensive variables (e.g. TET/THA) can be related to the cotangent of the angle determined by the length of the two segments – TET and THA. There are cases, though, in which representing differences in extensive variables without rescaling the relative values on the axes can imply graphs very difficult to read. In these cases it can be useful to adopt different scales for the different axes (for more detail see section 7.3.2 of Giampietro 2003).

Economic growth is often associated to an increase in the total throughput of societal metabolism and therefore to an increase in the size of the whole system (when seen as a black box). When studying the impredicative loop over the relative integrated set of changes in the identities of various elements (e.g. individual economic sectors and sub-sectors), we can better understand the nature of the constraints and the relative effects of these changes. That is, the mechanism of self-entailment of the possible values taken by the angles (intensive variables), reflect the existence of constraints on the possible profiles of distribution of the total throughput over lower level components.

The examples given in **Fig. 21** represent the set of variables for both Ecuador and Spain. In particular in the upper right quadrant we have an extensive variable #1 (THA), an extensive variable #2 (TET) and the ratio between them, the intensive variable #3 ($ExMR_{SA}$). In the upper left quadrant we have the loss associated with the societal overhead on human activity. This is the fraction of human activity which is invested in leisure, education, personal care and cultural interactions. These activities can be regarded as aimed at boosting the adaptability of the system in the long-term, and this explains the term societal overhead on human activity. In the lower left quadrant we have the representation of the characteristics of the Productive Sector based on the use of the same set of 3 variables defined before applied to that component in particular (i.e. HA_{PS}, ET_{PS}, and $ExMR_{PS}$). In this application of impredicative loop analysis, the PS sector is used in this position since it is linked with the stabilisation of the structure of the overall system in terms of operation of exosomatic devices, a short-term activity. Finally, in the lower right quadrant we can see the fraction of exosomatic energy associated with the value taken by the societal overhead on exosomatic energy. This fourth angle reflects the split of the Total Exosomatic Energy Throughput between those activities required and used by the PS sector for its own operation, and those activities included in the HH and SG sector. Therefore, there is a certain fraction of TET which is required to run the hyper-cycle, which is included in the total consumption, but not available as disposable energy to support long term activities. The term Societal Overhead on exosomatic energy indicates, on the contrary, the fraction of the total throughput which is required for final consumption and therefore not accessible to the PS sector. The PS sector operates over the interface of three levels: **level n** (supplying flows to the whole), **n-1** (processing flows at its own level), and **n-2** (using energy carriers – e.g. fossil energy fuels - defined at the lower level). Basic differences between the dynamic energy budget of Spain and Ecuador can be characterised in terms of: (i) profile of allocation of human activity over different sectors; and (ii) different levels of exosomatic metabolic rate.

As shown in **Fig. 21**, Spain changed, over two decades, the characteristics of its metabolism both in: (a) **qualitative terms** (***development*** – different profile of distribution of the throughput over the internal components – changes in the value taken by *intensive#3 variables – exosomatic metabolic rates of various sectors*); and (b) **quantitative terms** (***growth*** – increase in the total throughput – changes in the value taken by *extensive#2 variables*).

On the other hand, Ecuador, in the same period of time, basically expanded the size of its metabolism (the throughput increased as result of an increase in redundancy, i.e. more of the same – increase in *extensive variable#2*), but maintaining the original relation among intensive variables (the same profile of distribution of values of *intensive variables#3*, reflecting the characteristics of lower level components). In a nutshell, Ecuador's economy operated at the same level of exosomatic energy metabolism over two decades thereby experiencing growth without development.

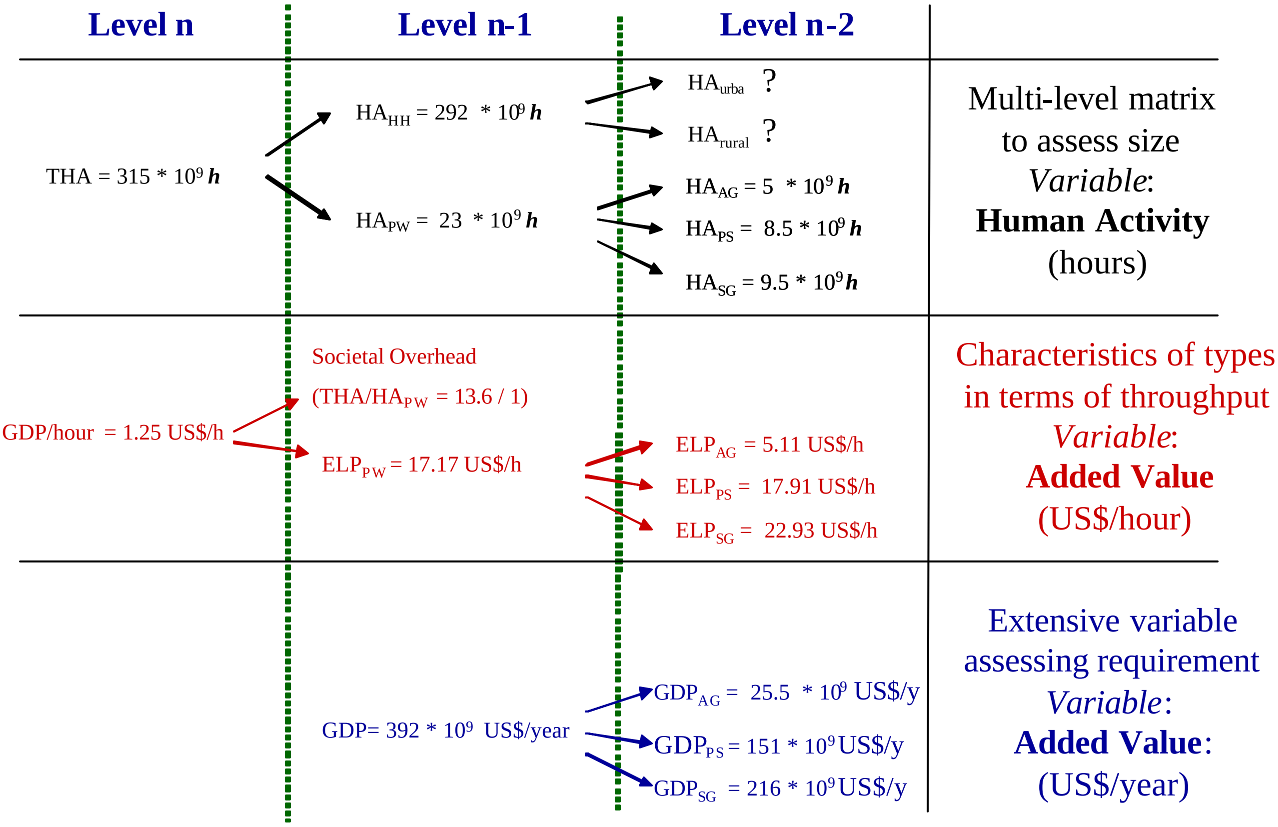
In more detail, when comparing the Spanish trajectory of development with that presented for Ecuador, it can be said that in the case of Spain, low population growth and low debt service allowed for entering a positive spiral (as explained in detail in Chapter 7). Available surplus was initially invested to increase EMR_{PS} ($dET_{PS} > dHA_{PS}$), as seen in **Fig. 21** shifted from 203 MJ/h to 332 MJ/h. This fact led to an increase in the economic labour productivity that allowed the increase in the surplus (due to the temporary holding of EMR_{HH}, that is, the rate of exosomatic energy metabolism in the household sector). When a sufficient level of EMR was reached in the PS sector the surplus was allocated to expand the Services and Government (SG) sector and to increase EMR_{HH}, which may reflect improvements in the material standard of living, which is represented in **Fig. 21** by the change in EMR_{SA} from 8.3 MJ/h to 12.3 MJ/h. It has to be stressed, however, that the dramatic difference in demographic trends between Spain and Ecuador, as documented by the change in the variable THA ($dTHA_{Ecuador} > dTHA_{Spain}$) is crucial to explain the different side of the bifurcation taken by Spain in its trajectory of development. In fact, the rate at which new human activity was entering in the work force in Spain (+ dHA_{PS}) was smaller than the rate at which Spain could generate additional capital (+ dET_{PS}). This made possible a dramatic increase in the level of exosomatic metabolism in that sector (++ $dEMR_{PS}$).

In contrast to Spain, the lack of development experienced by Ecuador can be seen as generated by two factors: (1) the necessity of a fast capital accumulation of the economy of the country (both in the productive sectors and in building infrastructures) in that decades due to the very low values of these variables when considering it as a benchmark (need of increasing EMR_{PW}); (2) the side effect on demographic trends allowed by better economic conditions or, better said, by a widespread expectation for better economic conditions (experienced increase in HA_{PW}). As a consequence, the servicing of the debt, among other factors like exogenous shocks as the fall in oil prices, reduced the speed at which the country could capitalise its economic sectors. In this situation the rate of increase of dHA_{PW} (the rate of active population with a growth rate of THA of 2.6% a year) generated a "mission impossible" for the economy which was required to: (a) generate additional capital at a rate that could keep $dET_{PW} > dHA_{PW}$; and at the same time paying back the debt. As a result, improvements in EMR_{PS} were almost negligible. This different path taken by Ecuador is reflected in **Fig. 23** as a change in the scale of the economy (growth, determining more length of the segments relative to extensive variables on the axes) but not as a change implying development (a change in the values shown at the angles of the figure). For more details see Falconi-Benitez (2001).

9.2.2.3. Dendogram of ELP_i (relevant flow "Added Value" versus variable defining size "Human Activity")

Analogously to the previous section on Spain, we can represent the dendogram of ELP_i for Spain in the years 1976 and 1996. Again, we start our analysis by looking at the two extensive variables that are defining the size of the system, i.e. Total Human Activity (THA, extensive variable #1) and Gross Domestic Product (GDP, extensive variable #2). In our 4-angles representation this would be the upper right quadrant, and it represents **level n** of the analysis, the national economy. Here, the first disaggregation we made before does not apply since we are considering here the two sides of the economy, the production side (represented by all sectors included in PW) and the consumption side (represented by the households). Therefore, in this context level **n-1** implies analysing the performance of the household sector by different household types (such as *urban and rural*, or depending on income), and the paid-work sector between the different sectors of Productive Sector (PS, meaning industry and mining), Services and Government Sector (SG) and Agriculture (AG). As in the case of ExMR, in our 4-angles representation (**Fig. 24**), this would represent the left lower quadrant for the specific sector under analysis (PS in this particular analysis).

Figure 22: Dendogram of ELP in Spain in 1976



The ratio between extensive variable #1 and extensive variable #2 gives intensive variable #3, which is ELP_i. This variable reflects an economic accounting of the system. In fact, it just tells us the productivity in dollars per hour of work. This variable on its own is relevant for policy, especially if disaggregated for sectors, but it is even more relevant when linking it to the level of exosomatic metabolism of the sector considered as we shall see below.

As in the previous case for $ExMR_i$, the same logic - forced congruence of variables across levels - applies here for both historical (past - present) and future scenario (present - future) analysis.

The economic analysis based on the 4-angle framework is shown in **Fig. 23.** The approach used to draw **Fig. 23** is the same as explained before. That is "the set of activities producing the required input of useful energy for machines" (energy, mining and manufacturing)" within the autocatalytic loop of exosomatic energy has been translated into "the set of activities producing the required added value for stabilising the compartments of the sector".

Figure 23: Dendogram of ELP in Spain in 1996

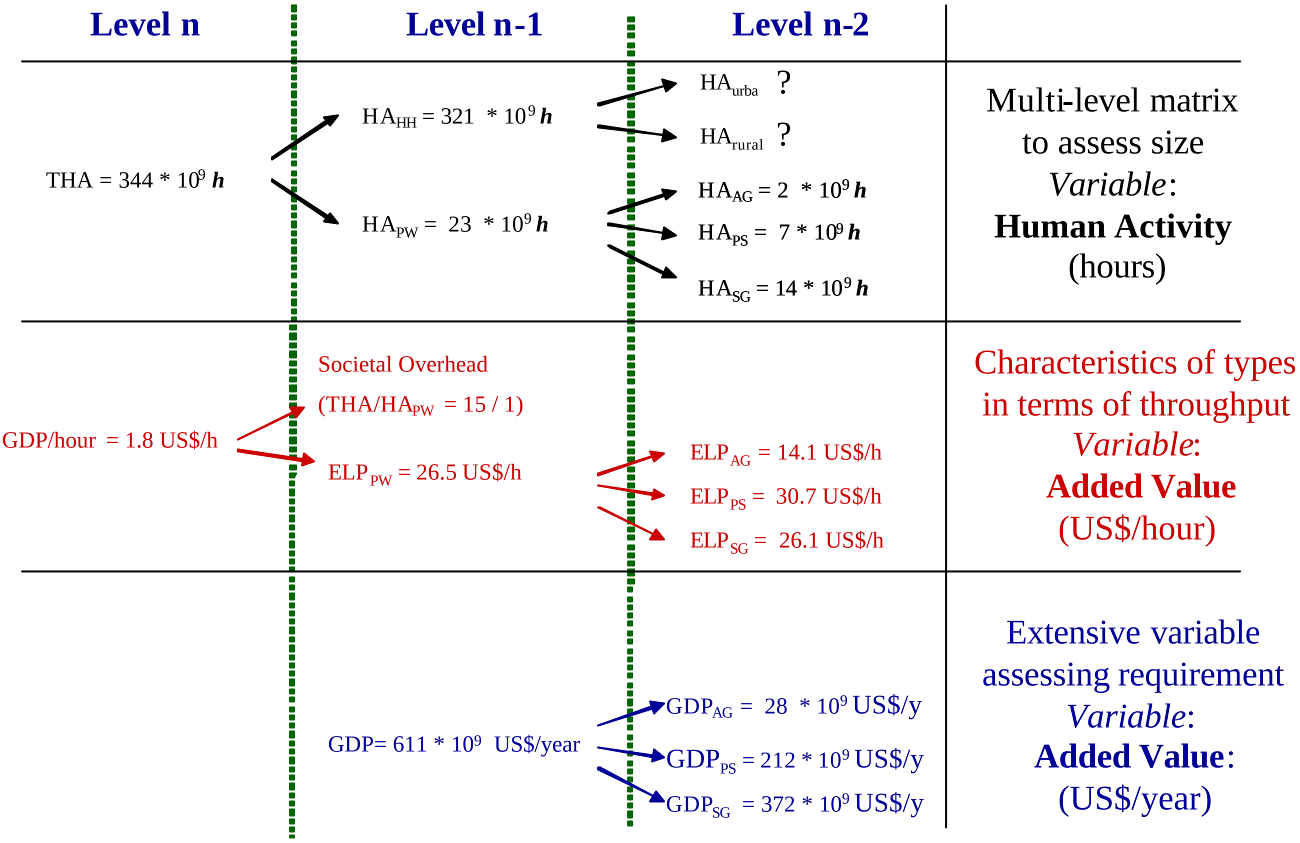
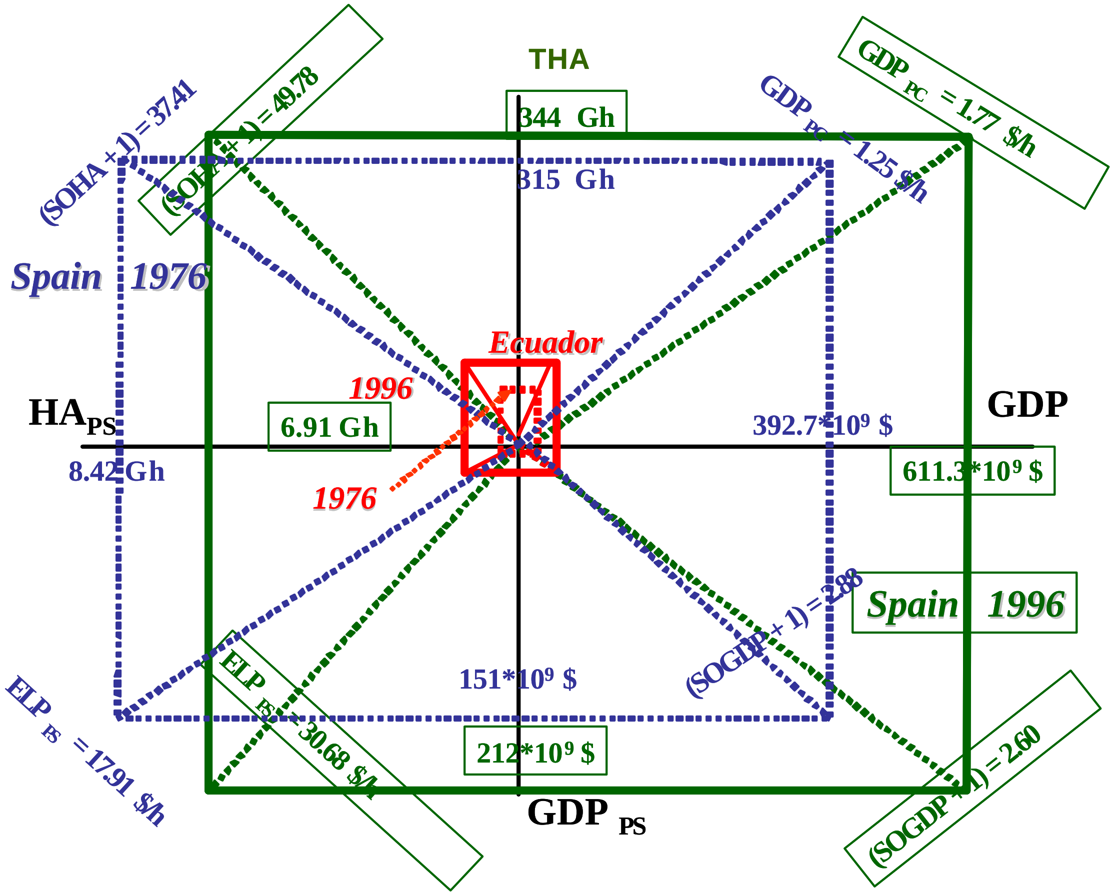


Figure 24: Economic impredicative loop for Spain and Ecuador



There are two sets of 4-angle figures which are shown in **Fig. 24**. The two smaller quadrants represent two formalisations of the impredicative loop generating the necessary added value for stabilising the components of Ecuador at two points in time (1976 and 1996). The two larger quadrants represent two formalisations of the impredicative loop generating the necessary added value for stabilising the compartments of Spain at the same two points in time: 1976 and 1996.

In the example given in **Fig. 24** we therefore represent the set of variables for both Ecuador and Spain. In particular, in the upper right quadrant we show a representation of extensive variable #1 (THA), extensive variable #2 (GDP) and the ratio between the two of them, intensive variable #3 (GDP_{PC}). In the upper left quadrant the societal overhead of available time that is left for the rest of activities apart from the productive sector is represented. In the lower left quadrant we address the representation of the behaviour of the Productive Sector in terms of three variables applied to that sector in particular (i.e. HA_{PS}, GDP_{PS}, and ELP_{PS}), where ELP is the economic labour productivity measured in dollars per hour and can be considered as a coefficient. Finally, in the lower right quadrant we show the societal overhead of available added value that is left for the rest of activities, which allow for an approximation for the ability of the economic system to adapt to future changes in boundary conditions, i.e. adaptability. We chose the PS sector for detailed analysis because this sector operates at the interface of **levels n, n-1, and n-2**, by guaranteeing the stability of the metabolism of the different components of the system at the short run. Therefore, it allows for explaining the basic differences between Spain and Ecuador in terms of the allocation of human activity and the generation of added value.

The logic of the analysis is as follows: **Fig. 24** shows the size of the system, and the performance, this time represented in economic terms, of the Productive Sector. This sector generates the necessary amount of added value to stabilise all other components of the economy (complemented by the added value generated by the services sector) in the short run. The level of ELP_{PS} affects the average value of ELP_{PW} (since ELP_{PS} is higher than ELP_{SG}) and therefore it guarantees that a larger amount of human activity can be invested in the Societal Overhead of Human Activity (for the activities guaranteeing the adaptability of the system in the long run). In fact, a higher economic productivity of labour ($ per hour), makes it possible – e.g. at the level of the household – to invest a larger fraction of total human activity in education and leisure.

As it can be seen in **Fig. 24**, Spain changed over the considered period of time the characteristics of its economic performance both in: (a) **qualitative terms** (***development*** – different profile of distribution of the throughput over the internal components – changes in the value taken by *intensive#3 variables*); and (b) **quantitative terms** (***growth*** – increase in total throughput – changes in the value taken by *extensive#2 variables*). This is reflected, for instance, by the increase in ELP_{PS} from 17.91 $/h to 30.68 in the period analysed, and by the related increase in GDP per capita. The increase in the productivity is both a consequence of: (a) the capital accumulated of the sector (as measured in biophysical terms by higher values of EMR_{PS}); and (b) a necessity for the system to be able to free an increasing fraction of human activity from those sectors guaranteeing short-term stability to be invested in sectors dealing with long-term adaptability (e.g. research and education).

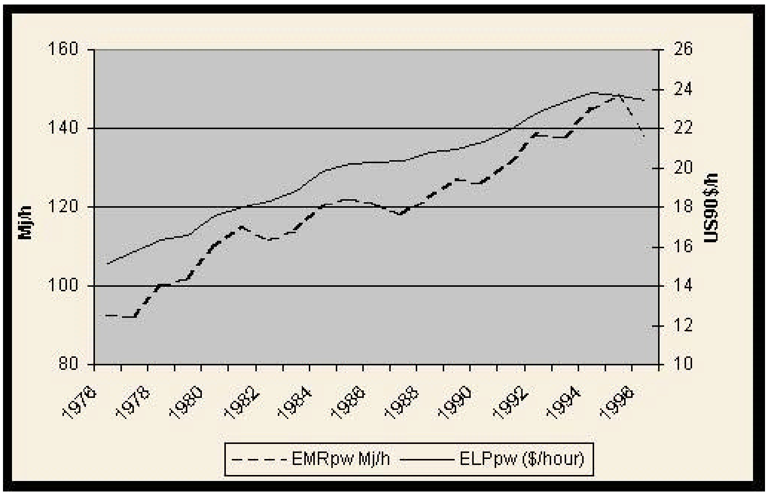
On the other hand, Ecuador, in the same period of time, basically expanded only the size of its economy (the throughput increased as a result of an increase in redundancy – more of the same – increase in *extensive variable#2*), but maintaining and even worsening the original relation among intensive variables (the same profile of distribution of values of *intensive variables#3*, reflecting the characteristics of lower level components, i.e. growth without development). For instance, Ecuador shows an increase in GDP and in Population, but rather shows a *decrease* in ELP_{PS} which explains why the system could not undergo a deep change in developmental terms, as reflected by the minor advancement in GDP per capita.

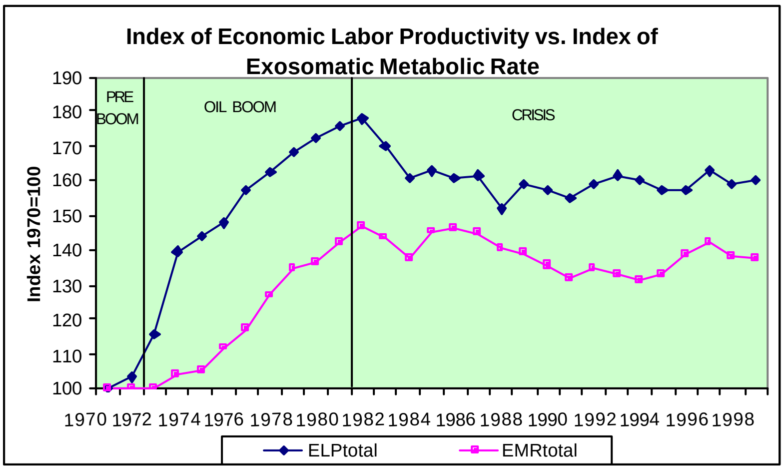
9.2.2.4. Establishing a bridge between $ExMR_i$ and ELP_i

The MSIASM approach makes it is possible to support an informed discussion about the required/expected levels of exosomatic energy metabolism in the various economic sectors including the household sector. The approach is based on the use of $ExMR_i$ as a proxy for the level of capital accumulation of economic sectors (explaining the availability of exosomatic devices to support human activity in an economic sector by increasing the exo/endo ratio), whose size is assessed in terms of investment of hours of Human Activity. Obviously, the performance of the different economic sectors can also be mapped in terms of the relative flow of added value they generate. This monetary flow can be mapped using: (i) extensive variables – the total amount of added value of the sector per year; and (ii) intensive variables – the amount of added value generated per hour of human activity. At this stage it becomes possible to use benchmark values to help building scenarios.

The assessment of "added value generated per hour of work" can be used to compare the situation of different economies, or the situation of different regions within the same country, as well as to compare the performance of different firms within the same sector of the same country. Moreover, it is well known that, at the national level, there is a consistent correlation between the intensity of biophysical empowerment of a productive sector ($ExMR_i$) and the relative ability to generate added value per hour of human activity (ELP_i) – (Cleveland et al., 1984; Hall et al., 1986). This link can provide a clue on what level of exosomatic energy metabolism can be expected in the future in the different economic sectors, by learning the benchmark values found in different trajectories of economic development of other similar countries.

Figure 25: Establishing a bridge between ExMR and ELP in paid work sectors (Spain and Ecuador)





Source: Ramos-Martin (2001), Falconi (2001) respectively.

We can use the MSIASM approach to check the validity of the possible correlation between the empowerment of productive sectors (assessed by their exosomatic energy consumption, fixed plus circulating) and their ability to produce

GDP. Accepting this hypothesis implies that $ExMR_{PS}$ and ELP_{PS} are correlated. The good correlation obtained by Cleveland et al. (1984) in their historic analysis of US economy, is confirmed by the curves shown in **Fig. 25** for Spain and Ecuador. Here, however, we represent instead changes of $ExMR_{PW}$ and ELP_{PW}, that is, all sectors generating added value in the economy (Productive Sector, plus Services and Government, plus Agriculture). In doing so, we find a similar shape or tendency for the considered period: exosomatic energy consumption per unit of working time in the paid work sectors follows the GDP trend. The relationship between these two curves does not imply that these countries have experienced the same course of development, a fact that is confirmed by the comparative analysis of their societal metabolism. In fact, each nation's development trajectory has been entirely different.

What are the implications, then, of the link between $ExMR_{PW}$ and ELP_{PW}, shown in **Figure 25**? In order to have economic growth the paid work sectors must increase their energy consumption faster than the rate at which human time is allocated to that sectors, otherwise, the energy surplus will be eaten up by the extra work force. This will be reflected in an increase in $ExMR_{PW}$, which will bring about a larger availability of investment for producing GDP. Such increased metabolism will lead, with a time-lag, to an increase in the productivity of labour that will help economies to reduce the amount of human time allocated in PS (short-term stability of components), and to allocate it to activities that increase the range of adaptation paths (i.e. services, medical assistance, research and education, leisure). Clearly, the priority among the possible end uses of available surplus ((1) increasing THA; (2) increasing $ExMR_{HH}$; or (3) increasing $ExMR_{PW}$) will depend on demographic variables, political choices, and historical circumstances.

In the case of Spain, as we developed in Chapter 7, the surplus generated by economic development was big enough to absorb both new population (due to internal demographic growth) and the exodus of workers from the agriculture sector. The demographic stability of the country made it possible to enter a positive spiral very quickly.

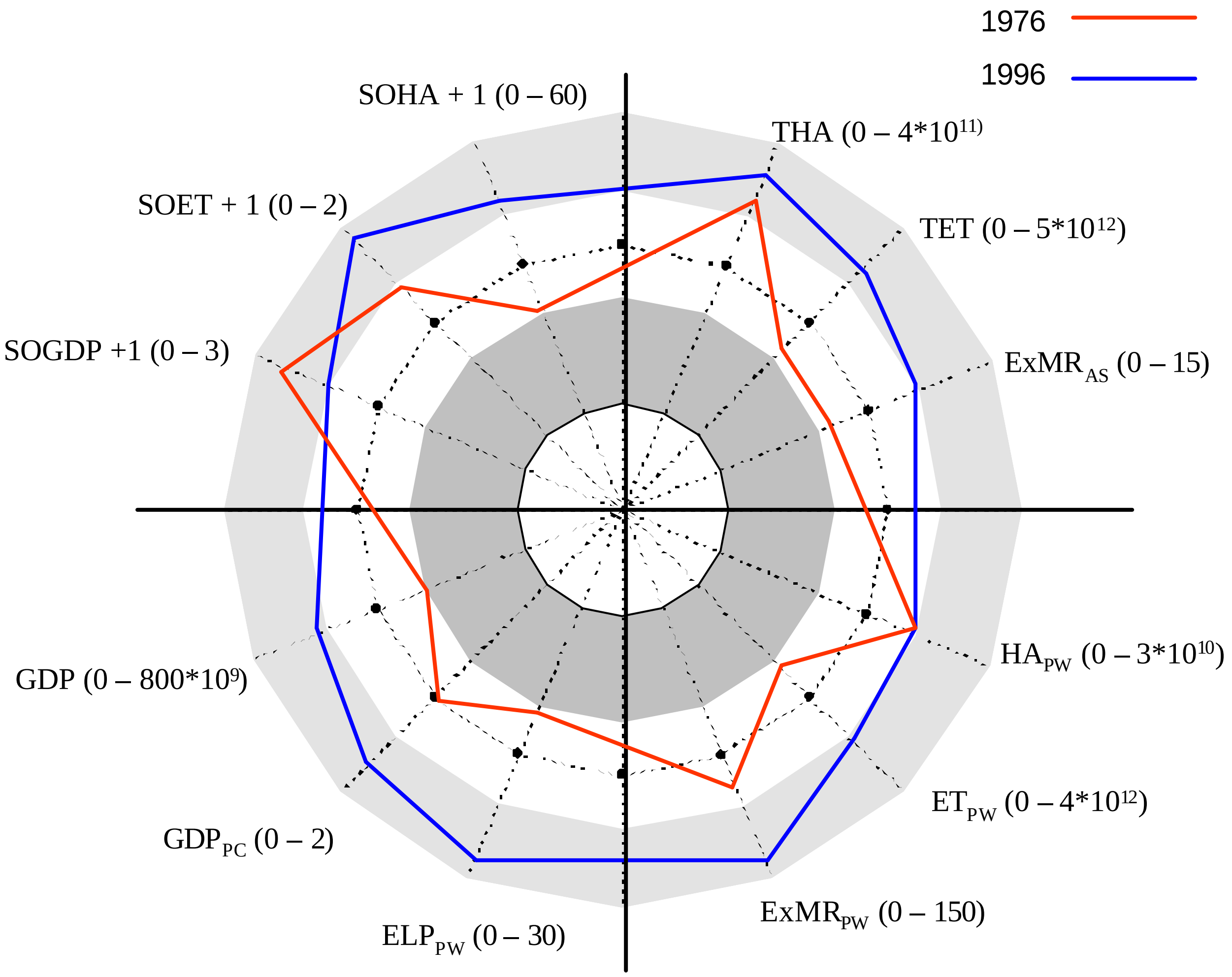
In the case of Ecuador, the crisis following the oil boom can be understood as generated by an insufficient exosomatic metabolic rate of the PW sectors (as shown before with $ExMR_i$) that drove the unsatisfying behaviour of ELP_i. This can be explained by the fact that economic surplus was almost entirely dedicated to pay the external debt, and to guarantee a minimum level of standard of living to the flow of new population implied by demographic growth. Therefore, the dramatic difference in demographic trends between Spain and Ecuador is crucial to explain the different side of the bifurcation taken by Spain in its trajectory of development.

What are the implications of this result from a methodological point of view? Representing the behaviour of the system across different hierarchical scales and using parallel non equivalent descriptive domains (e.g. economic, land use, energy use, and human time allocation) allows for seeing the inherent biophysical constraints on the socio-economic development of a system. Therefore, it acknowledges that a change of a variable (e.g. a GDP growth goal) implies always a certain requirement in terms of land use (depending on the structural distribution of GDP among sectors), a certain requirement in terms of investment of human activity (depending on how labour intensive the activities are) and in terms of energy consumption (depending on the exosomatic metabolic rates of the different system components).

9.2.3. Multi-Objective Integrated Representation of performance (MOIR)

The MSIASM approach maintains coherence in a heterogeneous information space referring to different dimensions and different hierarchical levels of analysis using the concepts of "mosaic effect" (dendograms of extensive and intensive analysis across multi-level matrices) and "impredicative loop analysis" (dynamic budget analysis). It is important, however, that this innovative tool can be interfaced with more conventional analysis – e.g. multi-criteria analysis – based on an integrated package of indicators reflecting different dimensions and attributes of performance. This is dealt with in more detail in Gomiero and Giampietro (in press). An example of a Multi-Objective Integrated Representation (MOIR) – a set of different indicators reflecting different criteria of performance selected in relation to different objectives associated with a given analysis – is given in **Fig. 26**. In this example, we have visualised in a graphical form the information given in Figures 17, 18, 20, and 21.

Figure 26: Multi-Objective Integrated Representation of performance in Spain



9.2.4. Lessons learned from this example

The four examples provided in **Fig. 24**, comparing the situation of Spain and Ecuador at two points in time – 1976 and 1996 – can be used to explain what has generated the differences in the value of extensive and intensive variables. The difference between growth and development can be studied by looking at the relative pace of growth of the value taken by the two types of extensive variables (e.g. the increase in GDP compared to the increase in population size). It is a commonplace that studying changes in the level of economic development of a country implies studying changes in GDP per capita (an intensive variable) rather than changes in GDP in absolute terms. By performing in parallel several impredicative loop analyses, based on different selections of extensive variable#1 and extensive variable#2, and by using different definitions of direct and indirect components, it is possible to study this very same mechanism at different hierarchical levels of the system and in relation to different dimensions of the dynamic budget. The approach also enables to compare in quantitative terms trajectories of development.

Just to give another example of the kind of results that we can get by adopting a MSIASM approach, we can anticipate how economic growth and energy consumption may drive changes in the values related to demographic variables. For instance, MSIASM supports a better understanding of the ongoing process of mass emigration occurring nowadays in Ecuador. Just looking at the previous graphs one can see that the major problem of Ecuador has been generated by a sudden increase in population that has induced a stagnation of the economic productivity of labour due to a low rate of exosomatic energy metabolism of economic sectors [$dHA_{PW} > dET_{PW}$]. This determined a poor performance in terms of increase of $ExMR_i$ over time. Therefore, one of the ways out of this impasse is that of allowing a fraction of the work force to emigrate (to reduce the internal increase in HA_{PW}). This is exactly what happened in Ecuador in the recent years. One should expect that people at the age of work tend to emigrate in order to achieve higher salaries, for instance in Spain. In this case, disposable human activity (HA_{PW}) no matter where generated, tends to follow gradients of empowerment (moving where $ExMR_{PW}$ is higher), no matter where located. This explains movements of work force from developing countries (where SOET and SOHA is lower) toward developed ones.

Spain has shifted its role from being a source of emigrants (in the previous century), to be a host for immigrants very recently. This is due to the fact that population has stabilised because of one of the lowest fertility rates in the world. In this context, further economic development of Spain requires not only adding new capital, but also new working population. This could be done by increasing the low activity rate (decreasing the Societal Overhead on Human Activity) of the whole economy (55% in 2003 - www.ine.es Spanish National Statistics Institute), or that of women in particular (only 44% of Spanish women in 2003 were in employment). The slow changes in the value of these variables due to cultural lock-in opened the door for new labour force coming from developing countries like Ecuador. Thus, in year 2002, the number of legal Ecuadorian immigrants in Spain has reached 125,000 (Colectivo Ioe, 2002), most of them arriving in Spain in the period 1996-2002 (122,000), due to the economic crisis of Ecuador.

A key characteristic of Ecuadorian emigration to Spain is that 90% of the people are aged between 21 and 50 (Anguiano-Tellez, 2002). Ecuadorians therefore go to Spain basically searching for work (a movement across countries of HA_{PW}).

The issue of migration is usually addressed by demography or economics, but without being able to establish a direct link between demographic or economic variables to environmental ones. With the MSIASM approach, on the contrary, it is possible to establish a clear link between these variables. The reciprocal effect of changes of demographic and economic variables can be explained in biophysical terms. For instance, when looking at the 4-angle figures presented above, it is easy to see that the Ecuadorian economy did not capitalise enough to raise the productivity of labour. This fact translated into an insufficient material standard of living. On the contrary, Spain, in the same period of time, experienced stagnation in population growth that, in the short-term allowed to rapidly increasing the level of exosomatic energy metabolism and therefore the material standard of living. This very same fact, however, implied, in the mid and long run, a shortage of human activity to be invested in the PS sector that may drive an economic crisis. This explains the need to receive immigrants to increase the working population. With the MSIASM approach we can see the inherent biophysical constraints (either in terms of available energy or of human time) of economic development. But there is more, by using a set of intensive variables #3 (those variables related to the intensity of interaction of different elements at different levels measured in terms of matter and energy flows) we can establish a bridge between this type of analysis (linking economic and biophysical variables describing the socio-economic system) to environmental analyses of the impact of societal metabolism. This would require complementing the analysis presented so far with a parallel analysis that uses as multi-level matrix – an extensive variable # 1 – a variable based on land use typologies.

In this Section we presented an example of application of a Multi-Scale Integrated Analysis of Societal Metabolism to the analysis of recent economic history of Ecuador and Spain, focusing on the relation between economic, demographic and energetic changes. This was done with the goal of providing a complementary tool of analysis to be used in addition to those already available (historical analysis, social analysis, institutional analysis, economic analysis, etc.).

The major advantage of this integrated method of analysis is not in the provision of totally “new” or “original” explanations for events. Rather it creates the possibility of integrating the various insights already provided by different disciplines. It can discover situations in which there are contradictions among them, or on the contrary, agreements. In the example discussed here we have just focused on human time as a variable to map the size and on added value and exosomatic energy consumption to map the interaction with the environment, but other key variables, such as land uses, may be used instead.

9.3. MSIASM for scenarios analysis: looking for biophysical constraints for economic development in Viet Nam 2000-2010

9.3.1 Goal of the example

In this section MSIASM is used for scenarios analysis. The goal of this example is to illustrate the mechanism through which MSIASM can perform a quality check on future scenarios of economic development. To do that MSIASM is applied to check the robustness of a set of hypotheses of economic development for Viet Nam in the year 2010. In the case of Viet Nam, we perform an impredicative loop analysis based on a 4-angle representation in relation to profiles of allocation of relevant flows (e.g. added value; exosomatic energy; endosomatic energy, i.e. food) over: (A) the economy as a whole; and (B) different economic sectors in charge for the production and consumption of these flows. This requires including the household sector in the analysis.

In this example we use two relevant extensive variables #1 (multi-level matrix):

(1) "**Human Activity**" to define the size of the whole (**THA**) and the size of the parts (**HA_i**); and

(2) "**Land Use**" to define the size of the whole (**TAL, Total Available Land**) and the size of the parts (**LU_i, Land Used in Activity i**).

9.3.2 Mapping flows against the multi-level matrix: Human Activity

In this example we do not carry out an exhaustive analysis as we did before for Spain and Ecuador; rather, we use data for Viet Nam in 1999 and a set of hypotheses of development for a few key variables in 2010. Data sources include: OECD Statistical Compendium (OECD, 2002) for data on population, GDP, and energy consumption in 1999. The working population and its distribution among sectors are taken from UN Statistics, whereas the GDP distribution among sectors is taken from Cuc and Chi (2003). Population in 2010 is derived from UN projections, whereas GDP, GDP distribution among sectors, working population and distribution among sectors are taken from Cuc and Chi (2003) reflecting Viet Nam government projections. Energy consumption for 2010 is assumed to remain at 3.41% of Asia's energy consumption, according to the projections from IEA (2003). We also assume that the work load is at 1,800 hours a year (a very generous underestimation), and that the fraction of working population increases to 50% of total population in 2010, due to a reduction in the fertility rate and the entrance in the working age of the previous generation.

9.3.2.1 Dendrogram of EMR_i (relevant extensive variable #2: "Exosomatic Energy" versus multi-level matrix – extensive variable #1: "Human Activity")

Figure 27: Dendogram of ExMR in Viet Nam in 1999

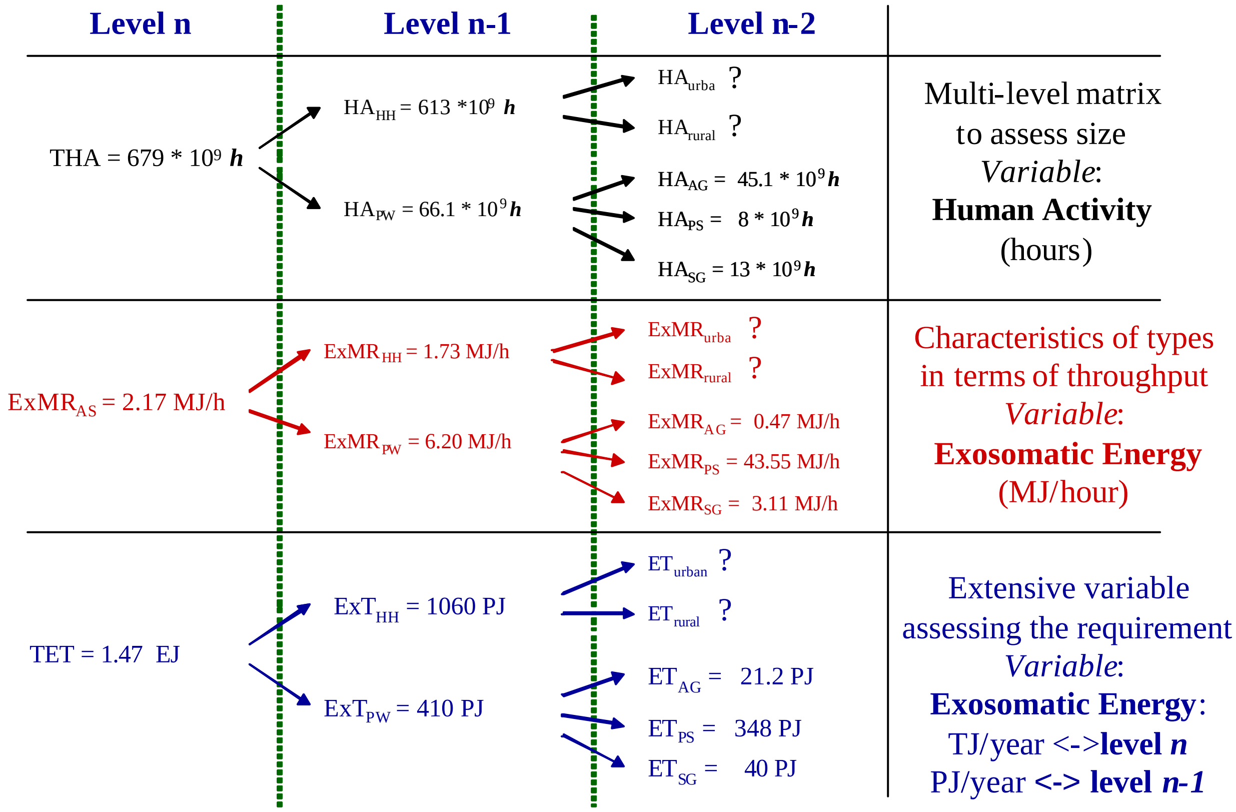


Figure 28: Dendogram of ExMR in Viet Nam in 2010

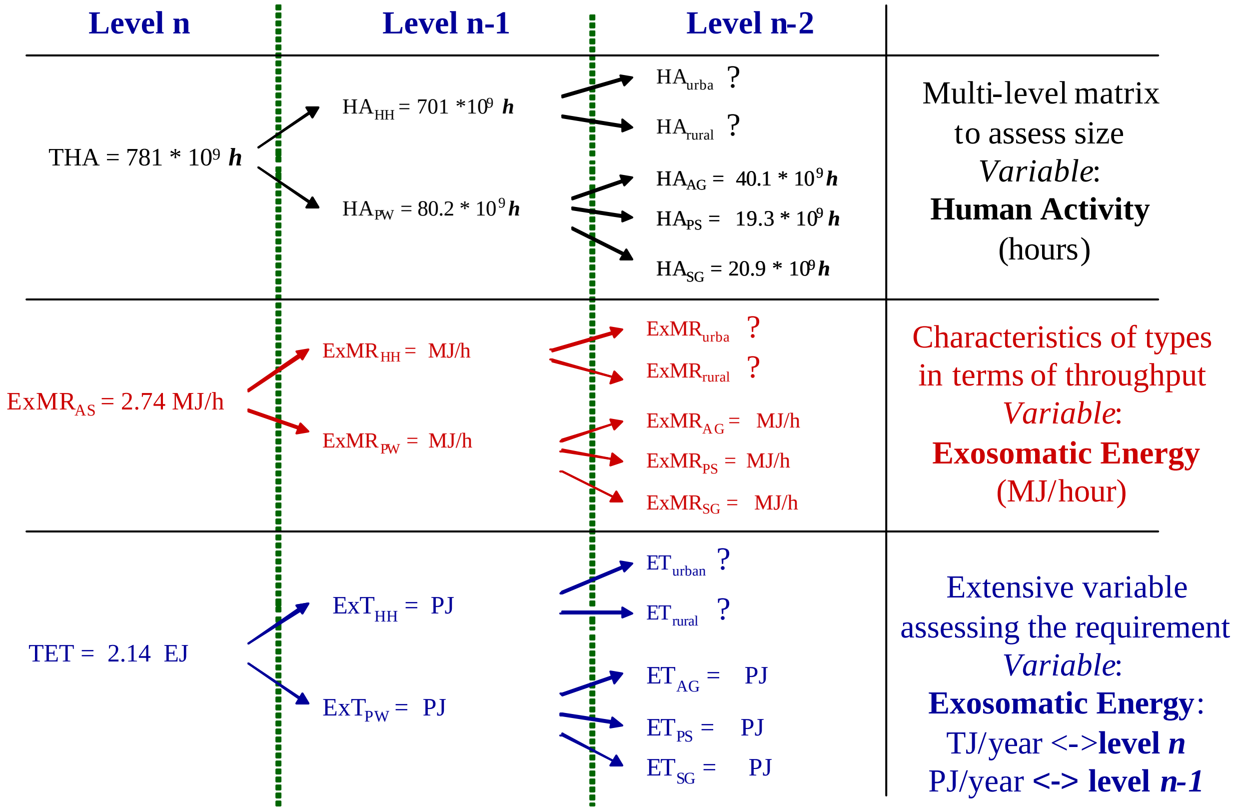
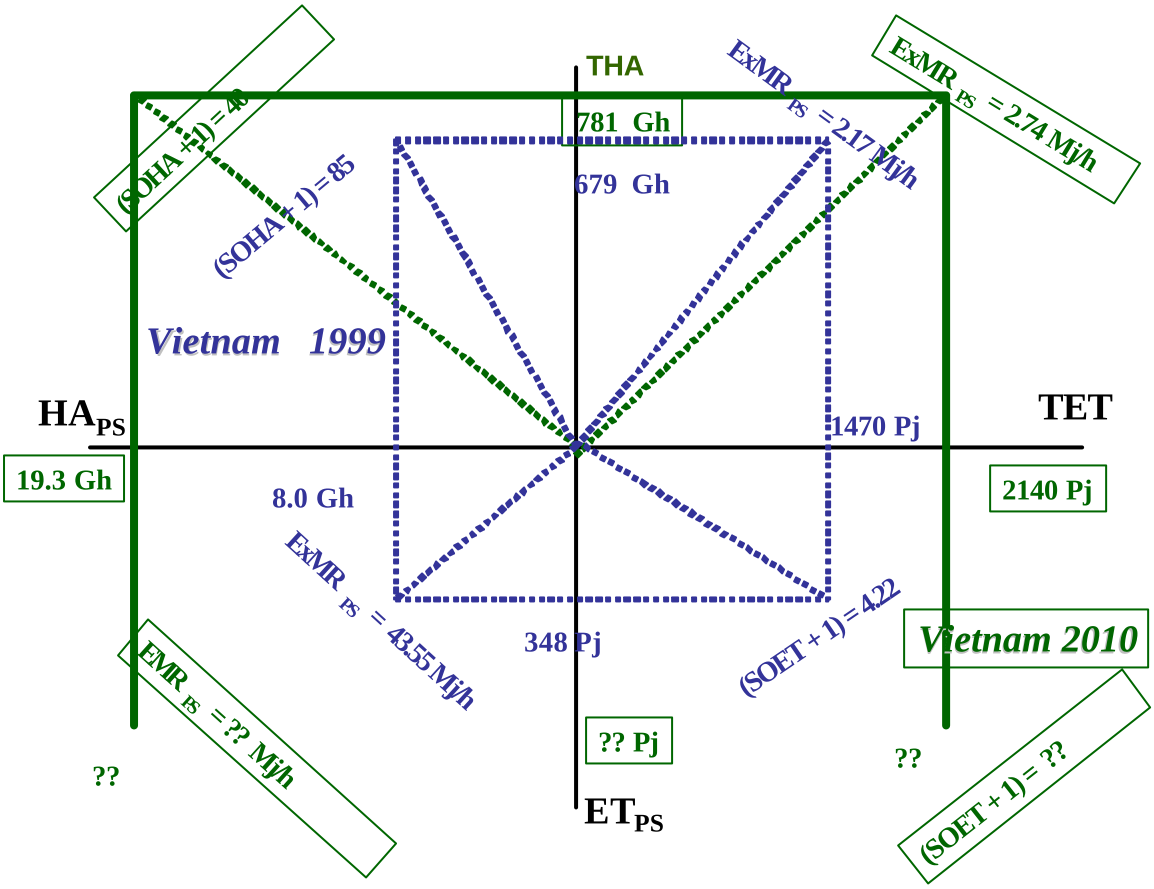


Fig. 27 and **Fig. 28** represent the dendograms of $ExMR_i$ for Viet Nam in the years 1999 and 2010. The rationale and interpretation of the figures are the same as in Section 9.2.2.2 for Spain. These variables, as explained before, reflect a biophysical accounting of the system.

Please note that because of the lack of projections for the distribution of energy consumption among the different components of the system for year 2010, in **Figure 28** we do not represent the disaggregation of the variable Total Energy Throughput. As we shall see in Section 9.3.2.3 this is where the 'mosaic effect' and the forced congruence among variables can help us in building future scenarios of development although some information is missing.

Figure 29: Biophysical impredicative loop for Viet Nam



Now that we presented the disaggregation of the different variables, dealing with the mosaic effect, we can proceed with an analysis based on the 4-angle figure as shown in **Fig. 29**, dealing with an impredicative loop analysis.

There are two 4-angle representations shown in **Fig. 29**. The smaller quadrant shows the performance of Viet Nam in the year 1999. The other, which is incomplete because of the lack of sectoral information for energy consumption, shows the expected performance in 2010.

From **Fig. 29** we see that there are changes in terms of growth embracing all key variables. We also assess a more-than-proportional increase in the human time allocated to the productive sectors (partly shifts from agriculture but also due to the absorption of new population in working age). This suggests the need of proportional adjustments on the economic side. In order to complete the figure – what is done in Section 3.2.3 – we proceed first, in the next section, to an economic representation of the same impredicative loop analysis for Viet Nam.

9.3.2.2 Dendrogram of ELP$_i$ (relevant flow “Added Value” versus variable defining size “Human Activity”)

Figure 30: Dendogram of ELP in Viet Nam in 1999

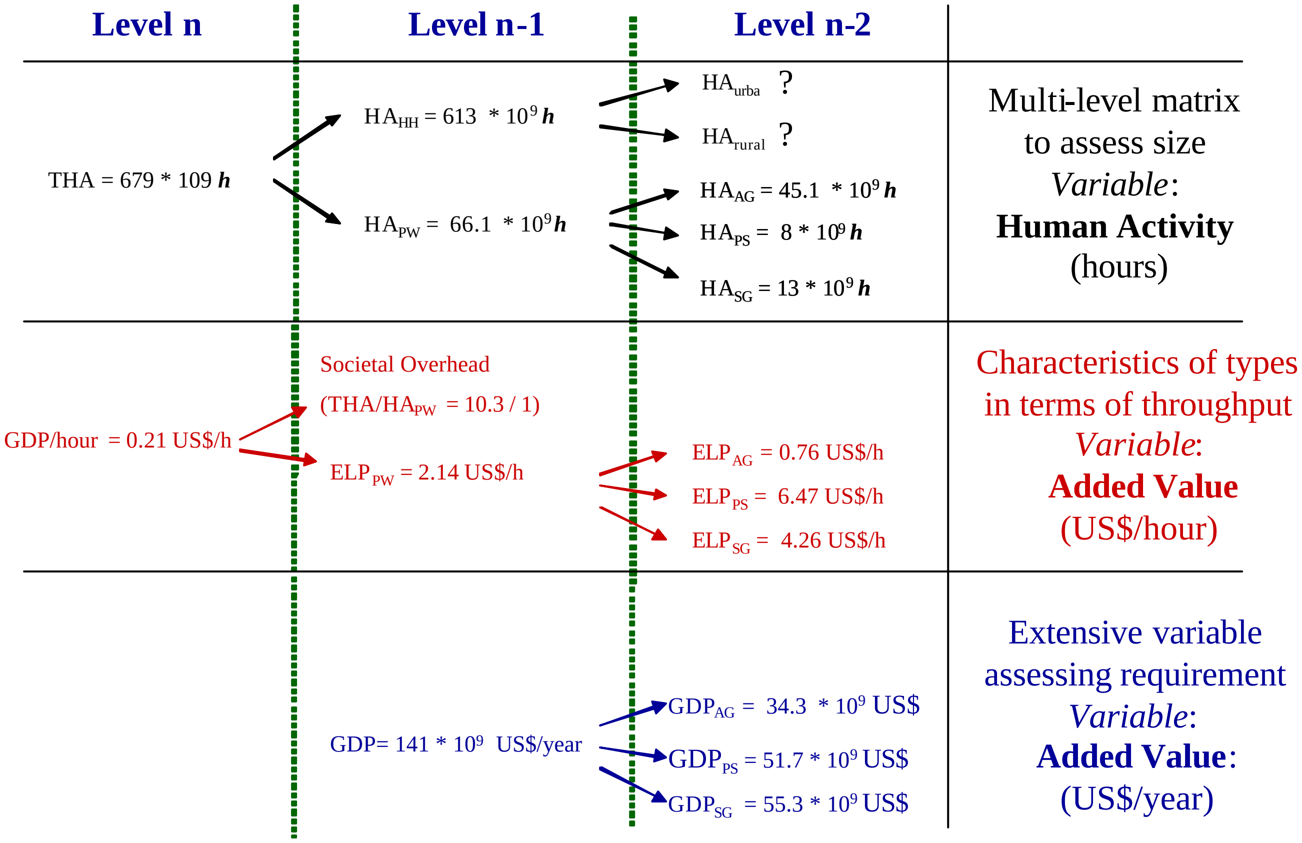


Figure 31: Dendogram of ELP in Viet Nam in 2010

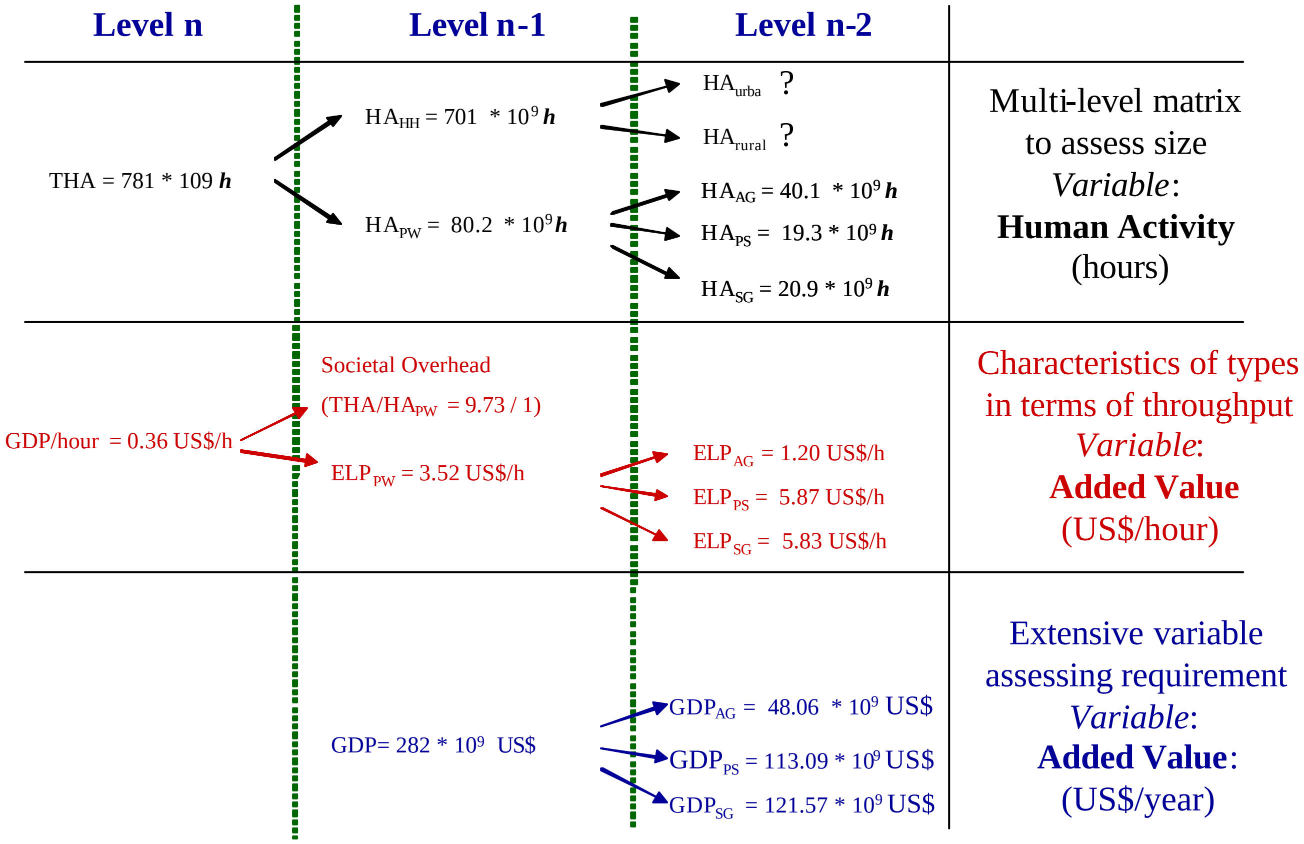
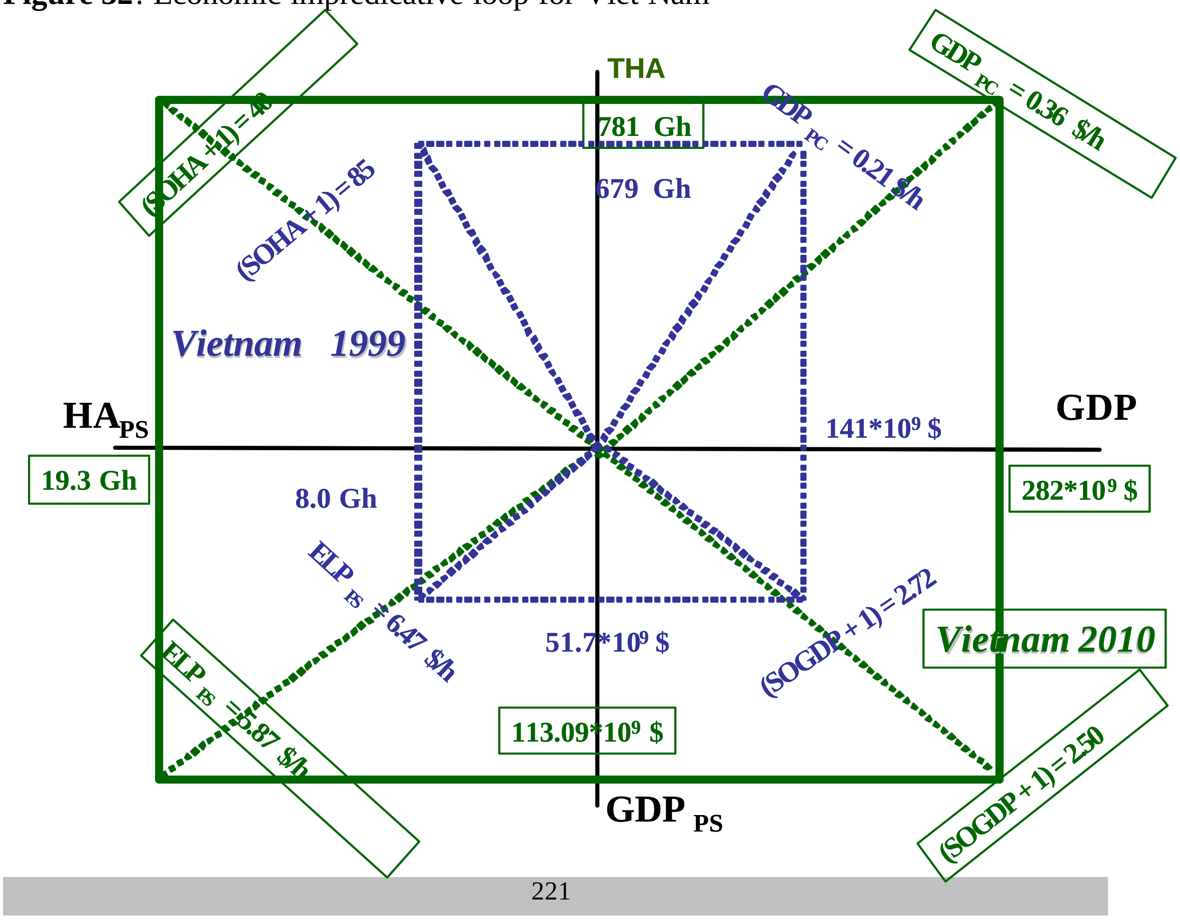


Figure 32: Economic impredicative loop for Viet Nam



As done in the previous section, we can represent the dendogram of ELP_i for Viet Nam for the years 1999 and 2010. All data are derived from assumptions and projections from governmental sources.

The logic of the representation is similar to the one for the Spanish case in Section 9.2.2.3.

An analysis based on the 4-angle framework is shown in **Fig. 32.** The approach used to draw **Fig. 32** is the same explained earlier.

As can be seen from **Fig. 32**, Viet Nam is expected to undergo important changes over the next decade. This implies new characteristics for Viet Nam's economic performance both in: (a) **qualitative terms** (***development*** – different profile of distribution of the throughput over the internal components – changes in the value taken by *intensive#3 variables*); and (b) **quantitative terms** (***growth*** – increase in the total throughput – changes in the value taken by *extensive#2 variables*). This is reflected, for instance, by an increase in per capita GDP. However, in contrast to what happened in Spain, and more similar to the development of Ecuador, the increase in GDP per capita is not expected to be associated with qualitative changes in the productive sectors. In other words, increases in the economic productivity of labour in such a sector, ELP_{PS}, are missing. Rather ELP_{PS} is expected to decrease. Therefore, the moderate increase of GDP per capita in Viet Nam will reflect two types of changes: (i) the movement of a certain fraction of HA_{PW}, from the AG (agricultural sector) to the SG (Service and Government) and PS (Productive Sector). That is, HA_{AG} will move from 68% of HA_{PW} to 50% of HA_{PW}; whereas HA_{SG} will move from 20% of HA_{PW} to 26% of HA_{PW}; and finally HA_{PS} will move from 12% of HA_{PW} to 24% of HA_{PW} (which results in a doubling of the human activity invested in PS!); and (ii) changes in demographic variables, that will imply a different profile of allocation of the budget of human activity. This can be associated with a decrease in the societal overhead (determining the difference between THA and HA_{PW}). SOHA = (THA - HA_{PW})/HA_{PW} will move from 10.3 to 9.7.

This result is most relevant, since it indicates that a good performance in the short run (i.e. a quick increase in GDP per capita) may be realised at the expense of long-term adaptability of the whole system. This is especially evident in the People's

Republic of China today, with almost 60% of the population in the work force (due to the drastic population control policy in the previous decades). However, when the relative age cohorts will reach the retirement age, it is not clear what type of consequences can be expected as we shall see in next chapter. Therefore, a warning sign must be put here to alert about the possible constraints, or lock-in that this scenario of development may impose on the Vietnamese economy in the future. The demographic dynamics remind of Ecuador that led to the present economic crisis in that country, as explained in Section 9.2.4.

If we accept the validity of the relationship between ExMR and ELP discussed before, that is, that we should expect a direct link between the level of exosomatic energy metabolism per hour of work in a given sector and the economic productivity of labour, we can use the values of ELP suggested by the hypothesis of development for 2010, to guess the values of ExMR for the same year. This permits closing the 4-angle representation of **Fig. 29**. This is done in the next section.

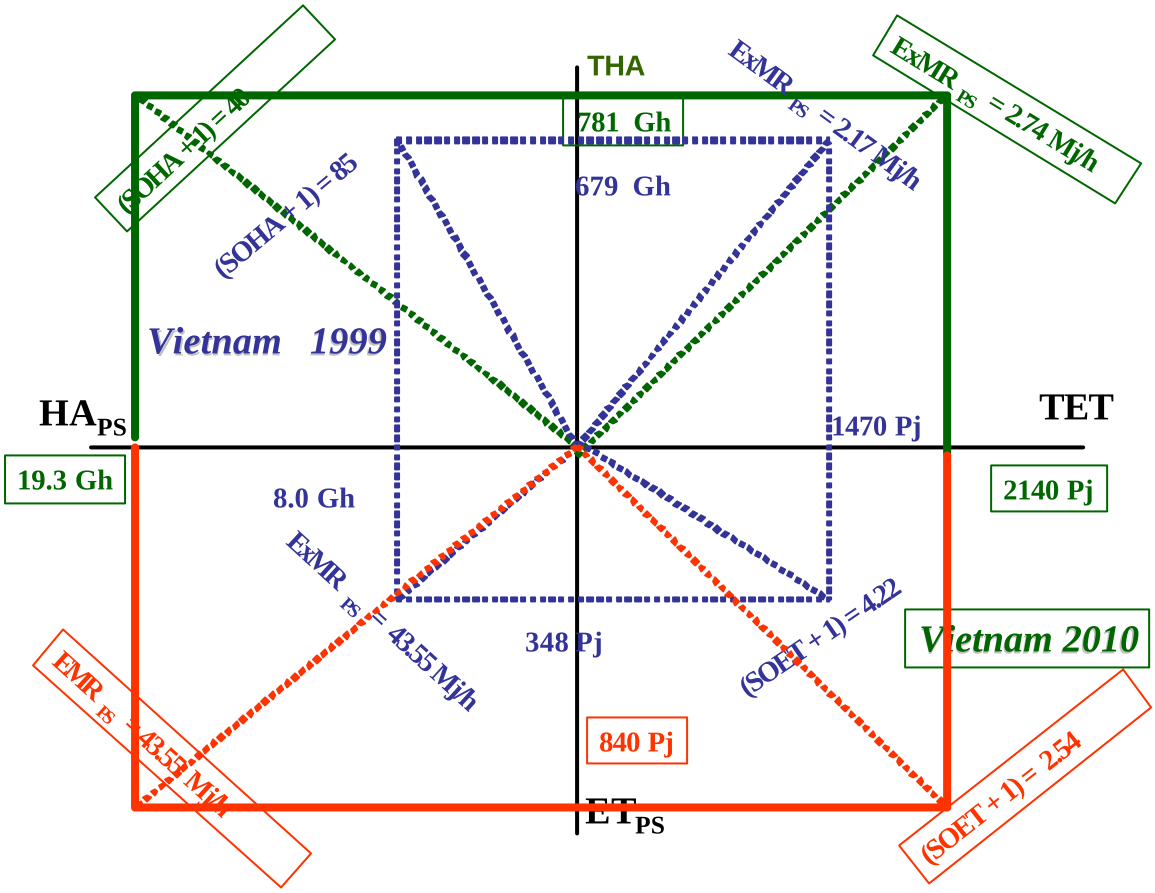
9.3.2.3 An application of the 'mosaic effect'

The representation of the characteristics of different elements defined at different hierarchical levels by using a dendogram makes evident the fact mentioned before that in this type of analysis, we *do not need to know* all data. Because of the forced congruence across scales, and because of the parallel non equivalent descriptive domains used to represent the behaviour of the Vietnamese economy, we can estimate the value taken by a variable using different ways, i.e. approaching it from information referring to the lower levels and scaling up, or approaching it from information referring to the higher levels of the system and scaling down. This is seen in **Fig. 33.**

The hypothesis of a link between ExMR and ELP is used to complete **Fig. 29**. By adopting this approach we can forecast a very limited increase in the material standard of living ($ExMR_{SA}$) for Viet Nam in spite of the expected increase in GDP per capita. Indeed, most of the increase in energy consumption will be invested for empowering the productive sectors of Viet Nam (ET will move from 348 PJ to 840

PJ). This may reduce the societal overhead over the Total Energy Throughput, that is the relative share of energy that can be invested in other activities (SG and HH), that may affect the long-term stability of the system. This is a result that we already found when doing the economic reading for the Vietnamese economy. As in the Ecuadorian case, this might have huge implications for future development, since it reduces the speed at which the country could capitalise its productive sector, at the very same moment in which the rate of active population will be peaking due to population rise. This may create a potential evolutionary lock-in for future development.

Figure 33: Biophysical impredicative loop for Viet Nam after using ELP



What is relevant in this example are not the predictions or the following interpretations given by us. Rather, what is relevant is the role that MSIASM can play in helping the social actors involved in a discussion of future scenarios to focus on the relevance and credibility of assumptions, hypotheses and scenarios, as well as providing criteria to verify the quality of the process (by using benchmark values to make comparison with other similar situations. Due to the internal congruence required in the information space, and due to the use of parallel non equivalent descriptive domains and different scales to represent the same facts, we can: (a) re-construct some data series in which some values are missing, a fact of particular relevance when working with scenarios of development; and (b) verify against known benchmark values the credibility of changes forecasted in different elements of the socio-economic system.

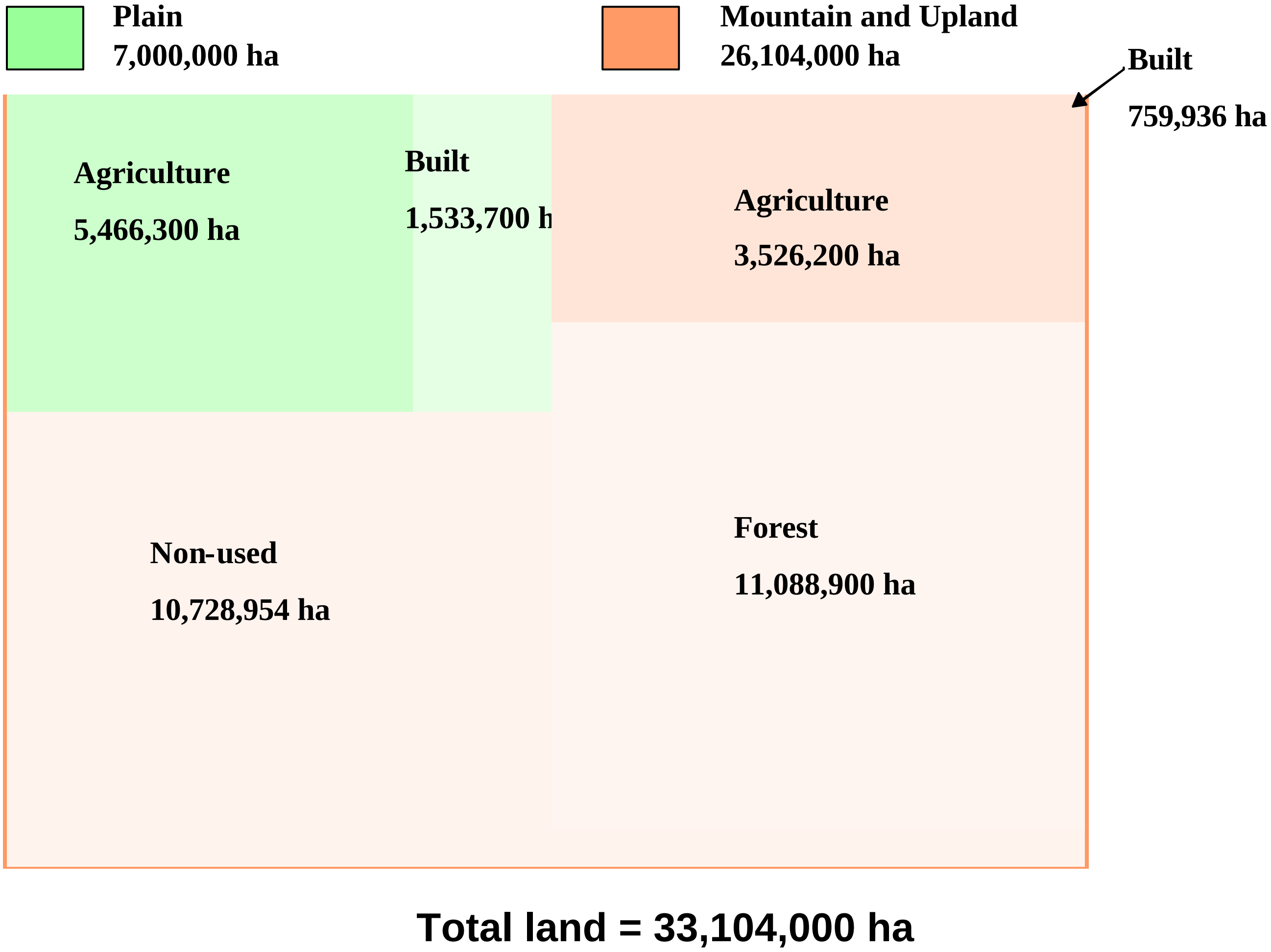
9.3.3 Mapping flows against the multi-level matrix: Land Use

In the previous section we have shown an example of application of MSIASM which was based on the same selection of variables used for describing the size of the system and its components as used in the case of Spain and Ecuador. The MSIASM approach, however, allows using other variables. We present here a simple exercise using as extensive variable #1 providing the multi-level common matrix, a variable for land use. In this simple example we focus on the existence of possible trade-offs between economic development and food security in relation to future choices of production/consumption of food in Viet Nam. Actual data, referring to the year 2000, are compared with two possible scenarios of grain production for 2010. The analysis looks for biophysical constraints that may help eliminating inconsistent scenarios. To make the example simpler, we focus just on rice production. A more sophisticated study, which is not done here, could provide, by using the same set of tools (dendograms and 4-angle figures) an analysis of the link between typologies of land use (associated to a definition of identities of whole and parts across levels) and: (a) generation of added value (economic reading); (b) consumption of exosomatic energy (biophysical reading).

9.3.3.1 Characterising the situation in year 2000

The distribution of a set of different land use categories for Viet Nam in year 2000 is given in **Fig. 34**. There is a first distinction between Plains (21% of the territory) and Mountains and Uplands (79% of the territory). In the lowlands we can define two land use categories: built-up area and agricultural land. For the sake of simplicity, we assume that all forest and non-used land is located in Mountains and Uplands. In fact, Viet Nam is a very densely populated country and there is a very high pressure on lowlands for agricultural, for infrastructures, and for residential uses. Moreover, most of the agricultural land producing rice is located in lowlands where soils are more fertile and do not suffer from high slopes. However, considerable parts of swidden agriculture are located in the uplands.

Figure 34: Viet Nam Land Use in 2000



With that distribution of land Viet Nam produced 34 million tonnes of grain in the year 2000, of which 3.6 million tonnes were exported (Cuc and Chi, 2003). This translates into a consumption of 389 kg/year per capita. Given the fact that only 85% of the agricultural land is in fact cultivated land (Tam and Hien, 1998), we can estimate the yields for lowland and upland rice production. Please take into account that these are rough estimates of the flow of produced rice per year (not accounting for the agronomic performance characterised when considering the Multi-Crop Index).

When doing this simplification by assuming that at the **level *n-1***:

* EV#1 - ha of land in rice production in lowland (T$\mathbf{ha}_{\mathbf{LL}}$ = 4.9 Mha)
* EV#1 - ha of land in rice production in upland (T$\mathbf{ha}_{\mathbf{UL}}$ = 2.7 Mha)
* IV#3 - yield of land in rice production in lowland (tonnes/$\mathbf{ha}_{\mathbf{LL}}$ = 5.3)
* IV#3 - yield of land in rice production in upland (tonnes/$\mathbf{ha}_{\mathbf{UL}}$ = 3.0)

we can write the assessment of total rice production as:

Level *n-1* = (4,900,000 $\mathbf{ha}_{\mathbf{LL}}$ * 5.3 t/ha) + (2,700,000 $\mathbf{ha}_{\mathbf{UL}}$ * 3 t/ha) = 34 Mt
Level *n* = 34 Mt (internal consumption + export)

9.3.3.2 Looking for biophysical constraints for future development: scenario A

We can assume that in the next decade, in Viet Nam the major part of the increase in built-up areas and infrastructures derived from economic development and population growth will take place in the lowland. Because of this, we should expect a reduction of agricultural land in production in these favourable parts of the country. We assume that in the year 2010 a share of 15% of the agricultural land actually in rice production in the lowland will be lost. If this is true, we should also expect that the increased demand for food and for agricultural commodities for both increased internal consumption (for a larger population) and increased export (for increased economic revenue from the agricultural sector) will generate an important pressure for increasing the land in rice production in the uplands. We can check the congruence between the amount of food required for internal consumption and for export, as predicted by the scenario and the biophysical constraints associated to the production of flows of food at the field level (at the **level *n-1***). The possible allocation of land in production both in lowland and highland has also to include the requirement of land for housing (for the growing population of the cities), industrial sites, infrastructures (as roads, railroads, ports, warehouses).

As mentioned before, it is very likely that the vast majority of these alternative land uses will occur in the low land (expanding the area around existing cities and transforming large villages into small cities).

On the other hand, agricultural land in the uplands has a lower productivity and this would require a huge increase in the quantity of fertilisers used for production to increase the yields, not mentioning the problem of soil erosion implied by high slopes. Moreover, accepting the natural low productivity per hectare will translate into an extensive deforestation of what is left of the original forest in the uplands. It should be noted that the hypothesis of economic growth considered here is also assuming that the forest coverage in 2010 will reach 45% of the total area as a part of a governmental reforestation plan (Cuc and Chi, 2003). In this case, we are experiencing parallel goals competing with the same limited endowment of land: (1) an increase in population requiring space for infrastructure and domestic production of food; (2) an increase in GDP from agriculture, requiring space for producing crops for export; and (3) an increase in the forest cover occurring mainly in the uplands, because of the governmental reforestation plan (where the additional crop production should take place) at the expenses of non-used land. The possibility of keeping a wide range of alternative land uses while reducing the pressure on the environment could only be matched by a dramatic intensification of agricultural production (in terms of a dramatic boosting of yields, both in high and low land).

Coming to an analysis of technical coefficients referring to lower level analysis (e.g. agronomic performance) we can say that in the lowland a dramatic increase of yields would result problematic. In fact, the major boost associated with the adoption of green-revolution technology has already been obtained and we are in the part of the curve yield/input that implies considerable diminishing returns. It is comparably easy to move from 2 tons/ha to 4 tons/ha, it is expensive to move from 4 tons/ha to 6 tons/ha, whereas it is extremely difficult to move from 6 tons/ha to 8 tons/ha. Moreover, an additional intensification of the use of technical inputs could worsen the already heavy environmental impact associated with agricultural production. On highlands, the problem of getting an intensification of yields will be even more noticeable when considering soil erosion for uplands cultivation of rice. But the main problem in this case would be related to the high labour demand of this system of production, that would imply locking a large fraction of the working population in agricultural production (and therefore on a very low level of ELP_i).

By using an analysis of flows of rice (used as extensive variable #2 in this example) against a multi-level matrix of land uses (used as extensive variable #1 in this example), we link agricultural production objectives (i.e. depending on the selected hypotheses of development scenarios) to land use and to possible environmental impact of agricultural production.

In the first scenario, we take population projections expecting a population in 2010 of 89 million people. We assume there is a minor increase in the per capita consumption from 389 to 420 kg, and that exports also increase to 6 million tones (according to the objective set out in government's development strategy). Despite being very expensive in terms of energy, and probably in terms of the resulting pollution, we also assume here that a rise in yields will be possible. Thus, yields in the lowlands increase up to 7 tonnes per hectare (i.e. due to a larger use of fertiliser), whereas yields in the uplands remain at 3 tonnes per hectare. This is so because an increase in fertilisers will have to make up for the lower fertility of marginal land added. These numbers, along with the lost of 15% of agricultural land in lowlands mentioned before provides the picture given in **Fig. 34.**

With these assumptions, we will have at **level *n-1***:

* EV#1 - ha of land in rice production in lowland ($T\mathbf{ha}_{\mathbf{LL}}$ = 3.9 Mha)
* EV#1 - ha of land in rice production in upland ($T\mathbf{ha}_{\mathbf{UL}}$ = 2.7 Mha)
* IV#3 - yield of land in rice production in lowland (tonnes/$\mathbf{ha}_{\mathbf{LL}}$ = 7.0)
* IV#3 - yield of land in rice production in upland (tonnes/$\mathbf{ha}_{\mathbf{UL}}$ = 3.0)

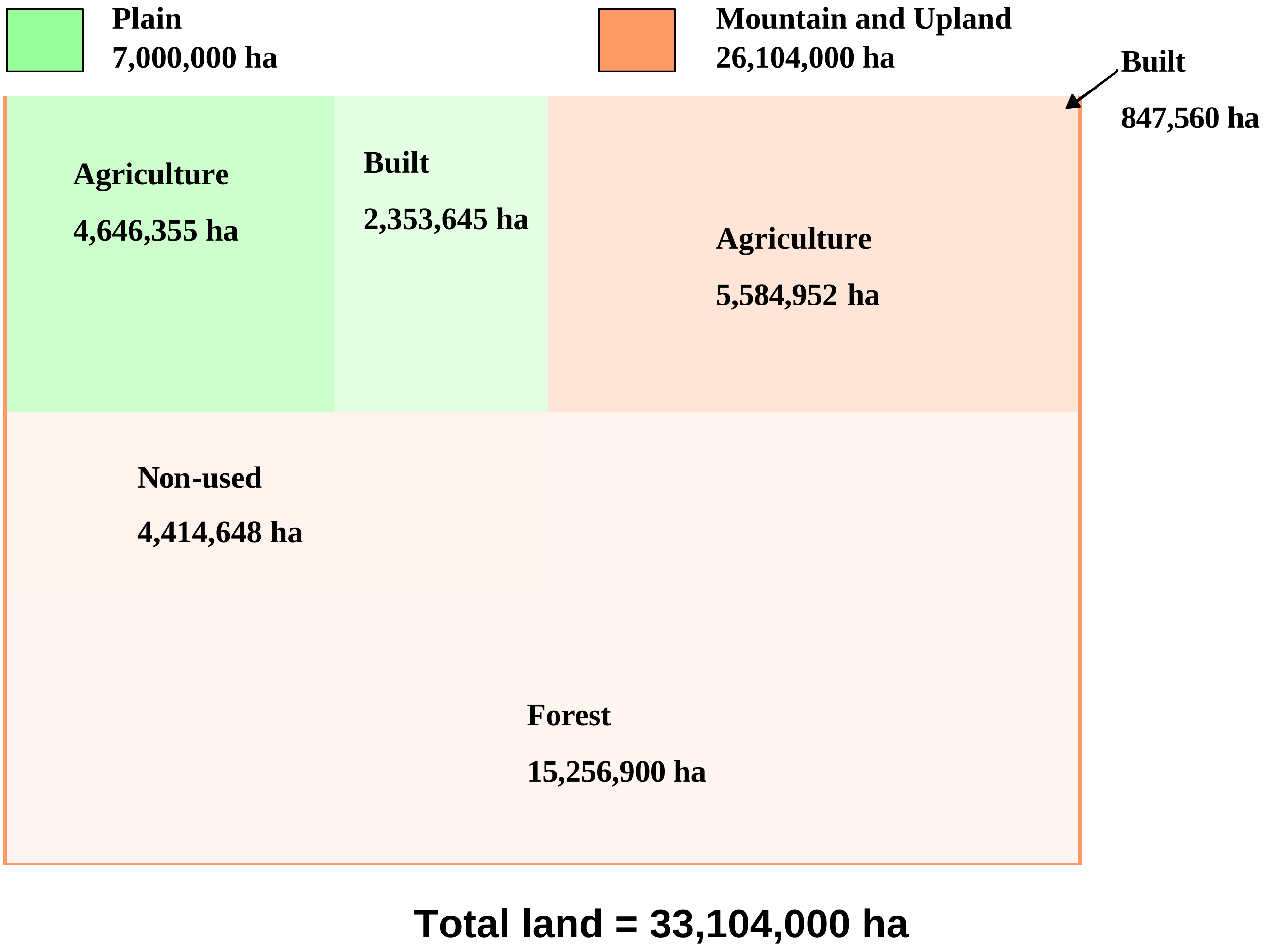
we can write the assessment of total rice production as:

Level $n\text{-}1$ **=** $(3{,}900{,}000\ \mathrm{ha}_{LL} * 7\ \mathrm{t/ha}) + (5{,}600{,}000\ \mathrm{ha}_{UL} * 3\ \mathrm{t/ha}) = 44\ \mathrm{Mt}$

Level n **= 44 Mt** (internal consumption + export)

In order to produce the rice necessary for internal consumption and exports, Viet Nam would have to increase agriculture land in rice production in the uplands up to more than 5.5 million hectares. This would imply adding 2 million hectares to the area already in production in the year 2000!

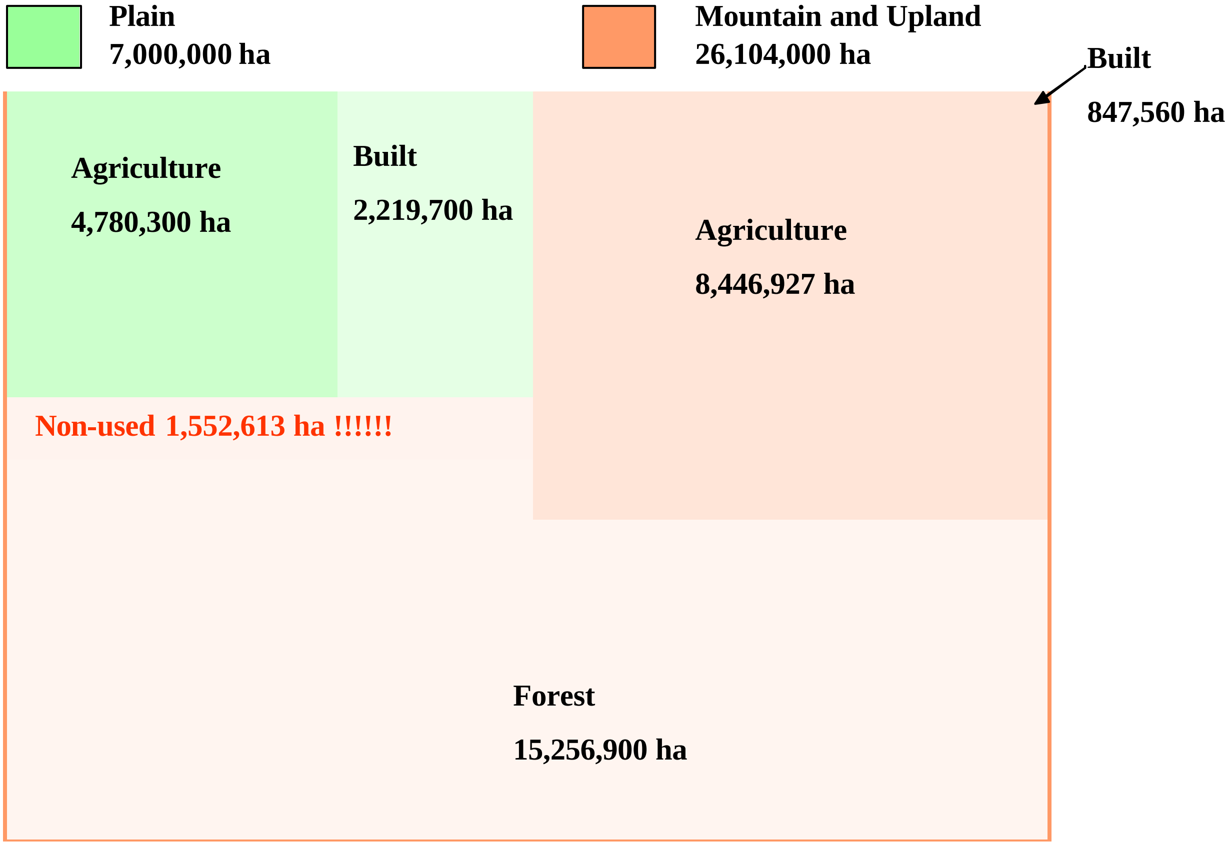
Figure 35: Viet Nam Land Use in 2010 scenario A



It is interesting to notice that just producing more food for feeding the new population would imply major problems from an environmental point of view. For instance, the increase in both agricultural production and forests in the uplands implies a dramatic reduction of the category “land not in use” to less than half of the value in year 2000. This change is in conflict with the goal of increasing the forest cover. We are talking of an incongruence that has to be analysed in detail, since strong incongruence in conflicting demands for different land uses may have permanent impacts in ecological terms. Moreover, it is clear that a strong tension between the objective of reforestation and increasing agricultural production should be expected. Moreover, a certain part of the land not in use is not suitable for any activity. This could concentrate the conflicts in particular locations.

9.3.3.3 Looking for biophysical constraints for economic development: scenario B

Figure 36: Viet Nam Land Use in 2010: Scenario B



Total land = 33,104,000 ha

This is a less optimistic scenario based on the same set of hypotheses of socio-economic development used in **Scenario A** but adopting the same level of agricultural yields achieved in the year 2000. The rationale for this choice is that increasing yields at any cost, not necessarily should result in the most convenient choice (diminishing returns imply a more than proportional use of inputs, which can have negative effects both in economic and environmental terms). Moreover, the analysis done in section 9.3.2 seems to indicate that we should not expect an increase in the level of exosomatic energy metabolism of the economy as a whole. This should therefore translate into a shortage of energy and resources to be invested in agriculture. In fact, it is well known that investments in the agricultural sector do have lower returns than that in other sectors of the economy. To make things worse, we should recall here that the Societal Overhead of Energy Throughput was even expected to decrease. Put in another way, it is very unlikely that we will see a major change in the technical coefficients for rice production especially in the uplands. So, if we keep the given yields at 5.3 tons per hectare for lowland and 3 tons per hectare in uplands, in order to produce the required 44 million tonnes of rice, Viet Nam should increase the agricultural use of land in the uplands up to 7.7 M ha in rice production, without including other agricultural land uses (to arrive to 8.4 M ha). This would represent an almost threefold increase as compared to the amount of agricultural land in the year 2000. Again, if this is to be achieved along with the reforestation plan, this will imply that only 1.5 million hectares will be left as non used land (see **Fig. 33**). This seems to be an unachievable scenario to be checked using a more detailed analysis of possible land uses and land cover changes.

9.4. Conclusion

The analysis of economic development and its relationship with the relative environmental impact implies dealing with the interaction of ecosystems and economic systems considered both as complex, nested, hierarchical systems. When doing so, individual reductionist analyses are not useful for describing the results of such an interaction. An integrated approach such as the one presented here offers some advantages since it links, by means of relations of congruence, the economic reading to the biophysical reading, as well as it offers the possibility to gather data on different hierarchical levels. This helps to better understand the inherent constraints associated with the process of change. That is, economic growth *shall always* imply a growth in the metabolism of the socio-economic system; therefore, we should always expect an associated impact on the environment.

The MSIASM approach can be used for both carrying out historical analysis – as done in Section 2 – and for prospective analysis – as carried out in Section 3. In the first case, the use of MSIASM can help us to characterise the development path followed by the system, by means of different 'useful types' such as economic sectors, different groups of agents, along with their associated impact.

We have acknowledged here the fact that economic systems are complex systems. When using MSIASM for conducting prospective analysis, like in the case of Viet Nam, we do not see the possibility of making predictions. From an epistemological point of view, this was already said by Rosen, who stated that if a basic characteristic of complex systems is that "they can only be approximated, locally and temporarily, by dynamical systems", but we still try to control them by using predictive dynamic models, we may face a *"global failure"* (Rosen, 1987: p.134, emphasis in the original) in the form of a growing discrepancy between what the system is doing and what the model can predict.

We believe that the selection and discussion of scenarios has more to do with the selection of useful narratives (i.e. soft modelling) rather than with forecasting (i.e. hard modelling). This is so because of the nature of complex adaptive systems, characterised by irreversibility and stochasticity in their evolution. The existence of numerous possible future trajectories associated with high levels of uncertainty (the sure emergence of novelties) implies that their future is largely unpredictable. We have to admit that there are no deterministic explanations (universal and a-historical) for the present states of complex adaptive systems. Rather we can describe and understand these systems by finding historical and spatial regularities, and by looking at the emergence of specific systems' properties. This requires still finding useful types for conducting research at the different levels. However, the selection of types must be later on tailored for coping with the particularities of specific situations. In this way, we can inform the decision process about the possible constraints implied by different courses of action. In our view, this translates into improving the quality of the narratives used to characterise, analyse, and describe the behaviour of complex system such as ecosystems, economies, and their interaction.

Coming to technical aspects of the MSIASM methodology we would make the following 4 points:

(i) When building scenarios, we need to use in parallel *non equivalent descriptive domains*, that is, parallel readings of the system referring to different dimensions of analysis and perceptions of events referring to different levels and scales. An integrated use of information coming from different disciplines applied at different scales provides more insight than the use of disciplinary findings (e.g. economic variables) used one at the time in relation to a single scale at the time.

(ii) The use of different dimensions of analysis applied at different hierarchical levels of the system requires a certain degree of congruence across levels. This entails the use of an accounting system especially tailored on this task. The proposed approach – MSIASM – can fulfil this requirement.

(iii) The congruence in the definition of the whole, the parts, and the relations that link them (over the same level and across levels) is what generates the 'mosaic effect'. Mosaic effects are desirable because they generate redundancy in the information space. Within a proper accounting system able to define certain 'types' of activities and expected relations among components of the system one does not always need to know all data for generating and analysing future scenarios. The example of crossword puzzles should be recalled here. If the value of a variable is missing at a lower level (e.g. a particular ExMR) that information can be obtained by our knowledge of the situation on the higher level by crossing information related to a different reading.

(iv) The impredicative loop analysis of dynamic budgets (against a multi-level matrix used for defining compartments across levels) allows a better understanding of the internal constraints affecting the stability of the budget. In this way, it becomes possible to identify possible bottle-necks, and lock-in situations. This makes it also possible to define which part of the metabolic flow is directed to short-term stability – usually linked to efficiency – and which part may be allocated to long-term stability – linked to adaptability. It should be noticed that in general reductionist analysis of scenarios does not deal with this second part. Efficiency is considered as a key optimising factor and adaptability is not considered as relevant for driving future unknown trajectories of development. The MSIASM approach explicitly acknowledges the need of operating a continuous mediation between the two contrasting goals of increasing efficiency and adaptability.

Chapter 10[88]: Multi-Scale Integrated Analysis of Societal Metabolism applied to the study of the evolution of economies: the case of China[89]

10.1 Introduction

In recent years China is becoming a key actor in world economy. This is due first of all to the remarkable size of its population and then to its formidable potentiality of expansion of the rate of production of goods and services both for internal and external consumption. The impact that the fast economic development of such a giant is having and may have in the future on the rest of world economy is becoming more and more evident[90]. China integration in the WTO and the consequent liberalisation of textile trade within that agreement are making this process more visible. However, the present status is not the result of a sudden change in Chinese economy. Rather what is happening in these years is the logic consequence of China enormous size (in terms of population) and the aggressive policies of economic development that Chinese government has been implementing in the last decade to improve as quick as possible the quality of life to its citizens.

The case of development of China represents a very interesting case study in which the standard ingredients of analysis of sustainability scenarios are all present (population size and peculiar demographic trends, limited access to resources, severe economic constraints, concern for pollution and environmental impact associated with economic growth, danger of destabilization due to social conflicts, the welfare of the population representing a goal requiring top priority). But there is more, China is a socio-economic system where not only all these factors are in play, but also a

---

[88] This chapter builds on a paper of the same title written with Mario Giampietro and Kozo Mayumi, and to be presented at the 6th International Conference of the European Society for Ecological Economics, to be held in Lisbon in June 14 – 17 2005.

[89] I would like to acknowledge Ming LU, from the Dep. of Economics, and Employment & Social Security Research Center, Research fellow at China Center for Economic Studies, Fudan University, for the kind help in finding some data for employment and its distribution among sectors for China.

[90] See for instance the coverage that The Economist or The New York Times are doing on China, i.e. "Gas-fired Dragon", *The Economist* February 17th 2005; "2 Big appetites take seats at the Oil table", *The New York Times*, February 18th 2005, and so on.

system in which all these factors are "on the edge" of critical thresholds. This is why, studying the process of development of China cries for the adoption of an integrated analytical framework. An approach which should be able to handle the different pieces of the puzzle whenever they happen to be (inside or outside the country, at the level of the households, at the level of individual economic sectors or at the level of the national economy). Put in another way, we firmly believe that an analysis of the sustainability challenges of China based only on conventional economic variables tends to miss crucial aspects, especially in relation to future scenarios. Therefore, we decided to apply to such a case study an analytical approach called Multi-Scale Integrated Analysis of Societal Metabolism (MSIASM), that, in our view, makes it possible to handle in an integrated way the analysis of these relevant factors, which are usually explored more in detail, but one at the time, within conventional disciplinary analyses.

This chapter has two goals: (1) to verify whether or not the MSIASM approach is effective in handling in an integrated way variables belonging to the different academic disciplines referring to different dimensions (economic, social, demographic, technical, ecological, biophysical) of sustainability. If this is true, then MSIASM can represent a useful analytical tool able to complement (by providing the big picture and an integrated analytical framework) more conventional disciplinary analyses; (2) to provide a Multi-Scale Integrated Analysis of the trajectory of development of China in relation to a characterisation of the existing situation in relation to different dimensions and scales of analysis; individuation of possible constraints affecting the feasibility of considered scenarios; characterisation of the situation associated with the selected future scenarios in relation to different dimensions and scales of analysis.

In relation to the second goal the analysis presented in this chapter is structured over four tasks:

(1) individuating a set of benchmarks that makes it possible to compare different characteristics and features of China in relation to other countries and the averages values found at the world level;

(2) explaining the differences in value found over the selected set of benchmarks used to characterise China against other countries, by looking inside the compartments of Chinese economy;

(3) understanding existing trends and future viable paths of future development of China by studying the existence of reciprocal constraints of the set of key parameters used to characterise its metabolism of added value, matter and energy flows. This analysis is based on the acknowledgment of the obvious fact that the characteristics of each individual sectors are affecting the characteristics of the whole economy and vice versa.

(4) examining possible future scenarios of development in China and the effects that the changes associated with these scenarios can imply at the world level. In particular we look at the possible impact on world energy market.

The rest of the chapter is structured as follows: Section 2 presents the theoretical background and basic concepts associated with Multi Scale Integrated Analysis of Societal Metabolism (MSIASM); Section 3 deals with the interface world level/China level. The MSIASM approach is used to identify relevant cluster of countries expressing typical patterns of metabolism. Then such an overview is used to put the characterisation of the metabolism of China in perspective; Section 4 deals with the interface national level/sectoral level of the Chinese economy. This section looks first at the existing relation between the metabolism of the whole and the metabolism of parts found in China when using the MSIASM approach at a given point in time (year 1999). Then it looks at the trend of this relation over the last 20 years. The relation between changes occurring within the various sectors and at the average values found at the national level is discussed in terms of the effect of reciprocal biophysical constraints and potential lock-in operating within the multi-level dynamics of societal metabolism. Section 5 deals again with the interface world level/national level, by considering possible future scenarios of development for China and the relative effect that the resulting characteristics of metabolism of China could have on world trade. In particular we focus on the possible impact on world energy market.

10.2. The theoretical background of this analysis

10.2.1. Key points associated with Societal Metabolism within the MSIASM approach:

The main points of this section are taken from an overview of this topic given in Giampietro et al. (in press), to which we refer for a more detailed discussion.

(i) Metabolic Systems are dissipative systems, this implies that they must be open systems, becoming in time and operating on multiple scales

All living systems when analysed at levels of organisation and scales above the molecular one are "dissipative systems", which are self-organising, open systems, away from thermodynamic equilibrium (Glansdorf and Prigogine, 1971, Nicolis and Prigogine, 1977, Prigogine and Stengers, 1981). Because of this they are necessarily "becoming systems" (Prigogine, 1978). In turn, this implies that they are: (i) operating in parallel on several hierarchical levels (where patterns of self-organisation can be detected only by adopting different space-time windows of observation); and (ii) changing their identity in time. This means also that the essence of living and evolving systems entails: (1) **parallel levels of organisation** on different space-time scales, which can be associated to the need of using multiple identities for their perception; and (2) **evolution**, which does imply that the identity of the observation space, which is required to describe their behaviour in a useful way, is changing in time. Even though they change their identity in time, metabolic systems must be able to maintain their own identity at any point in time. This requires the ability to: (a) stabilise a coordinated inflow of matter and energy resources – e.g. food, fossil energy and useful materials for human societies; solar radiation, nutrients and water for terrestrial ecosystems; (b) make use of these inputs to express their characteristic pattern of organisation (= transformations, activities); and (c) dispose of degraded matter and energy flows to their context.

(ii) Metabolic systems do have a natural identity

An important aspect of the concept of societal metabolism is that it introduces a dynamic relation between the definition of the characteristics of the input and the characteristics of the metabolic system that will use it (Cottrell, 1955, Giampietro and Mayumi, 2004). The provocative question of Schrödinger (1945) "what is life?" wanted to point at a major epistemological challenge introduced by living systems. That is, for living systems there is no substantive definition of resource or cost or benefit. Hay is exergy for a mule but not for a car, electricity is exergy for a refrigerator but not for a human being. [In this example exergy is the modern term that can be used to operationalise the concept of negative entropy used by Schrödinger in relation to the characterisation of an energy input for a given converter in a given context]. Oil was an entertaining burning water at the time of Marco Polo, but is a key resource today justifying wars. To deal with this issue Rosen introduced the class of M-R systems [Metabolism-Repair System - Rosen, 1958a; 1958b; 1972]. This expected identity for the metabolism of parts and the metabolism of the whole makes it possible to establish a bridge between the characteristics of individual elements and the characteristics of the whole network to which the elements belong.

(iii) When dealing with metabolic systems the perception/representation of what is a resource, a level of consumption, a cost and a benefit is "converter" and "scale" dependent

This point derives directly from the previous one. Any assessment of flows of either money, matter or energy input and throughput associated with an element of a nested hierarchical system cannot be assumed to be substantive. In fact: (1) added value, matter and energy flows do not exist without a system which is actually metabolising them; and (2) any one of these assessments requires always a preliminary definition of a sound narrative. That is an arbitrary definition of "inputs", "converters" and "the whole system" to which the converter belongs. The characteristics of the converter define what has to be considered as an input, from the point of view of the user. At the same time, when dealing with nested elements any assessment of a flow at a given level for a given element on a given scale can always be different when considering the same process on a different scale. Well known examples of this fact are the discount of capital, in economics, and assessment of embodied energy referring to transformations occurring at different levels, in energy analysis.

The key implications for the MSIASM approach are:

(i) it is impossible to characterise (= perceive/represent) in a substantive way what a socio-economic systems is and does.

The expression "to characterise in a substantive" wants to mean "to assign a formal identity that will be agreed-upon and accepted as valid by all the social actors operating within it" (Giampietro et al. in press). With formal identity we mean a finite set of attributes to which it is possible to associate a set of proxy variables which is used to identify what the socio-economic system under analysis is and does (Giampietro, 2003; Mayumi and Giampietro, in press).

(ii) it is impossible to simulate and predict the future of socio-economic systems and living systems in a deterministic way

Economies and socio-economic systems are complex, adaptive, self-reflexive, and self-aware system (Kay and Regier, 2000). They together with living systems belong to the class of self-modifying system (Kampis, 1991). This implies that their evolution cannot be simulated by formal systems of inference in terms of deterministic analyses (Rosen, 2000; Mayumi and Giampietro, in press). Deterministic analysis (e.g. based on differential equations) must adopt a single scale and a single narrative at the time. In technical jargon this means that they must rely on a given finite selection of variables and a preliminary focus on a given direction of causality (Kampis, 1991; Rosen, 2000; Giampietro, 2003; Mayumi and Giampietro, in press).

(iii) it is possible to take advantage of the peculiar characteristics of metabolic systems to develop alternative approaches for studying the evolution of socio-economic systems

By moving outside the standard set of rules and assumptions associated with reductionism it is possible to handle different characterisations of the performance of a socio-economic system in relation to different dimensions of analysis. Such an integrated representation must be based on a finite set of attributes referring to a set of different dimensions considered as relevant. This introduces a clear degree of arbitrariness, since the list of relevant criteria of performance and the choice of attributes associated with each criterion for different social actors is very large. To make things more difficult an integrated analysis requires the simultaneous use of 'non equivalent descriptive domains' [= economic reading, demographic reading, technical reading, biophysical reading]. In face of these challenges, the approach called MSIASM has the goal of guaranteeing the coherence and congruence among the selected set of different characterisations which are criterion and scale dependent. This means that by applying the MSIASM approach it is not possible to have "the right" characterisation of a socio-economic system. It is not possible to forecast the future behaviour of the socio-economic system. That is, it is not possible to determine the value that will be taken by the selected set of variables. Rather the goal of MSIASM is to improve the quality of the narratives adopted when characterising a system and building scenarios. MSIASM helps a discussion on the choice of a set of variables, indicators and attributes which should be used to better match the demand from the users for a relevant characterisation. After having reached an agreement on how to characterise the system under analysis MSIASM can: (1) individuate scenarios that are not feasible, because of inconsistency with internal constraints; (2) individuate cases in which the chosen narrative (= selection of the set of relevant attributes and relative proxy variables, plus the hypothesised set of causal relations) is neither relevant nor credible; (3) provide hints on future trends expected for key variables. This can be obtained by looking for the existence of lock-in of biophysical, or economical constraints within future development scenarios; (4) individuate those attributes of performance that are likely to become critical – in terms of uncertainty and/or need of dramatic changes - when selecting and evaluating scenarios.

10.2.2. Two key concepts associated with the MSIASM approach

Again we refer to Giampietro et al. (in press) and Giampietro and Mayumi, (2003), for a more detailed discussion of the two concepts briefly introduced in this section.

10.2.2.1. 'Mosaic effects across levels'

To illustrate this concept let us use an example of two alternative methods to assess endosomatic metabolism. The conventional method the assessment of food consumption for a given population is based on the assessment of a flow of food energy per person over a given period – e.g. 2,200 kcal/day per capita. This would be a typical value for developing countries. An alternative way for characterising the food consumption of a given population is illustrated in **Fig. 37a**. Rather than assessing the amount of kcal of food energy per person per day, such an analysis may be based on a flow of food energy per kg of human body mass – e.g. kJ of food energy per kg of body mass per hour. By adopting this characterisation we can assess this value simultaneously at two different hierarchical levels: (1) as an average value for the whole population; and/or (2) as a value resulting from the distribution of body mass over different age classes. When adopting the second choice, the total energy consumption of the whole population can be expressed as a combination of different typologies of energy consumption per kg of body mass which are associated to different age classes.

The expression "endosomatic metabolism" was introduced by Georgescu-Roegen (1971) elaborating on the insight of Lotka (1956) to indicate the conversion of energy and nutrients in a given society, which is occurring inside the human body. When dealing with endosomatic metabolism in the way illustrated in **Fig. 37a** it becomes possible to use simultaneously two external referents (independent sources of data) for the assessment of total food consumption: (1) the assessment of consumption of food at the level of the whole population may be based on the measurement of the flow of the food intake from national statistics; (2) the assessment of the metabolic flow of nutrient - which is associated with the metabolism of human body mass belonging to different age classes found in the population - can be based on inference based on physiological and nutritional studies (e.g. James and Schofield, 1990).

Figure 37a: Endosomatic metabolism of a society having the size of 100 people

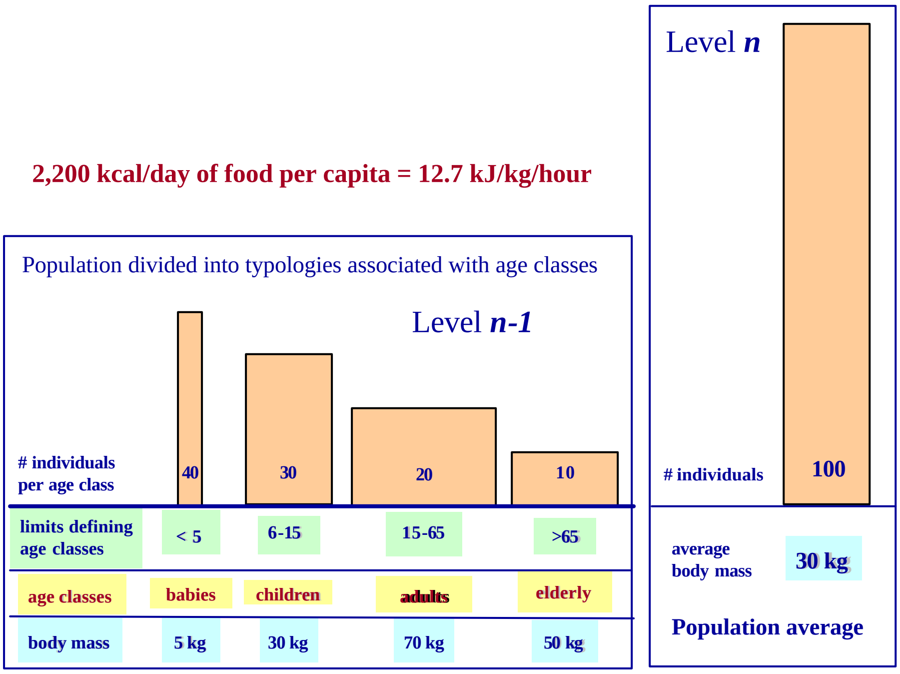
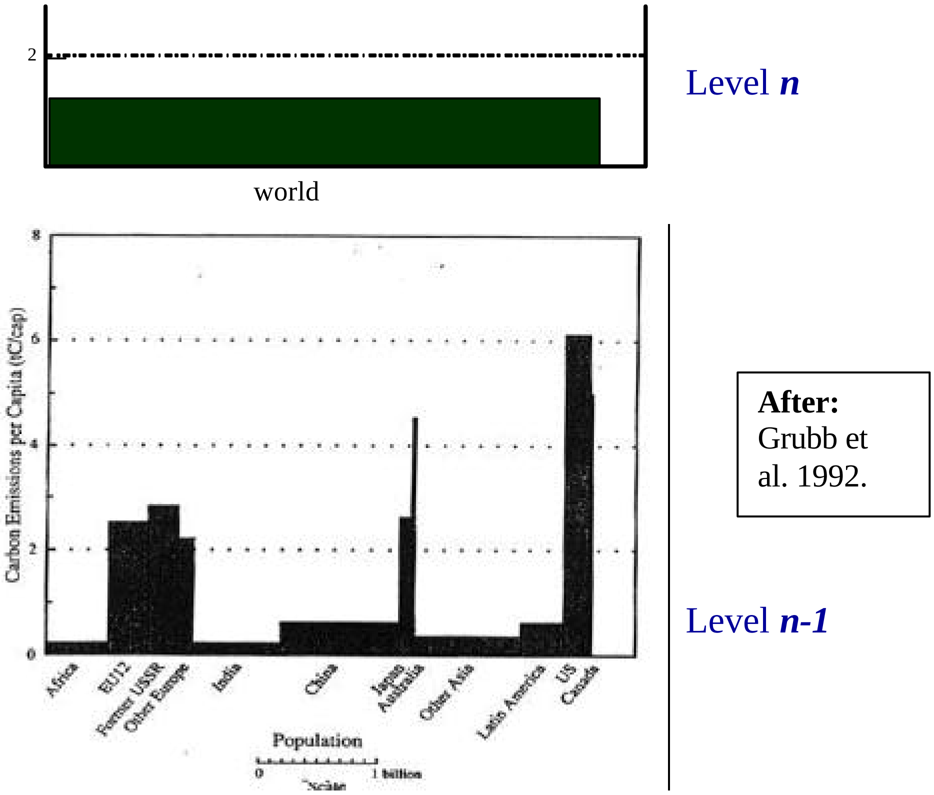


Figure 37b: The effect of the exosomatic metabolism of humankind in terms of Carbon emission



After: Grubb et al. 1992.

The fact that metabolic systems express a predictable behaviour (by defining for themselves what is which is metabolised and at what pace) in parallel on different levels (the metabolism of a human being is the result of the metabolism of its components, the metabolism of a population is the result of the metabolism of lower level elements) makes it possible to obtain a Mosaic Effect when assessing the characteristics of the same metabolism while looking in parallel across levels.

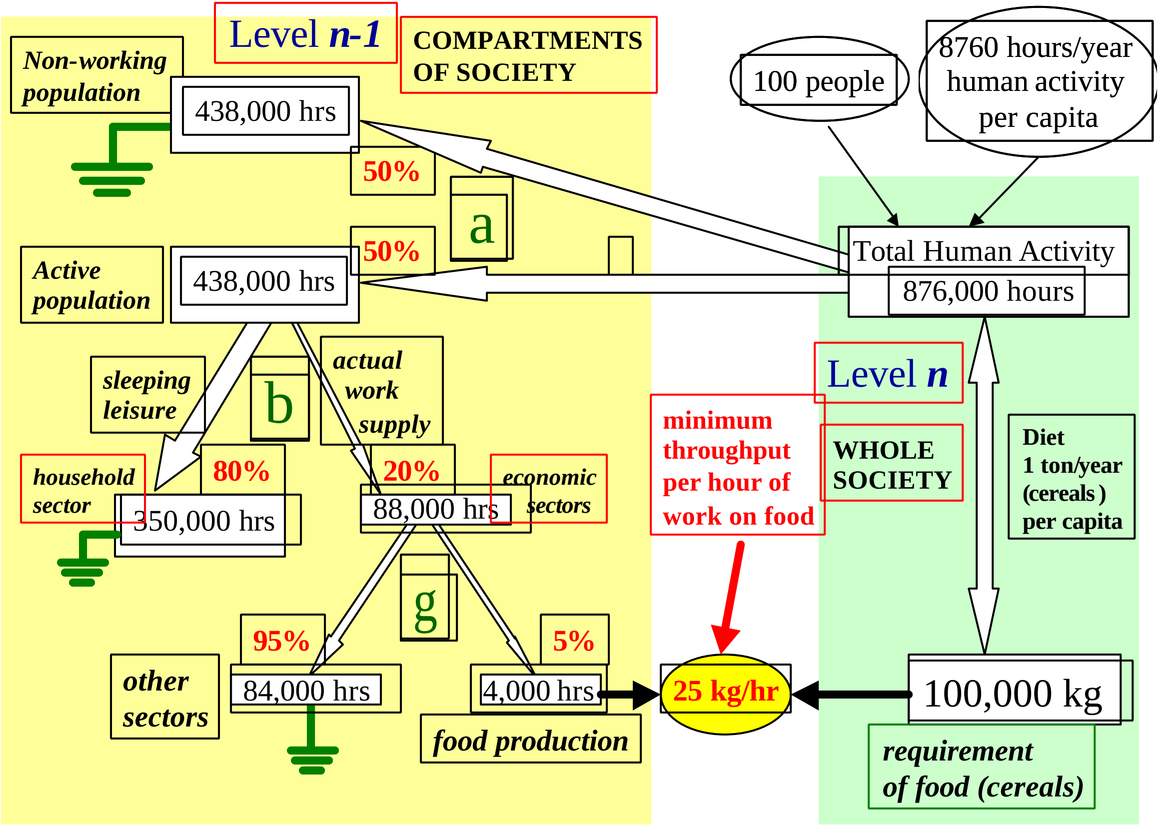
In the example given in **Fig. 37b** we have an analysis similar to that reported in **Fig. 37a**, but this time related to the exosomatic metabolism of societies. The expression "exosomatic metabolism" has been introduced by Georgescu-Roegen (1971) elaborating on the insight of Lotka (1956) to indicate the conversion of energy and other useful material input occurring outside the human body. That is, the total carbon emissions associated with the exosomatic metabolism of humankind (the whole) can be expressed as a combination of characteristics of the exosomatic metabolism of a set of typologies of countries (parts) over which human population is distributed. If only we were able to define a set of lower level typologies with predictable levels of consumptions per person, then we could infer changes in the whole, by studying possible changes in extensive (relative population size) and intensive variables (consumption per capita). This is the function of Impredicative Loop Analysis, which is discussed in the next section.

10.2.2.2. 'Impredicative Loop Analysis'

The term Impredicative Loop Analysis (Giampietro, 2003) wants to indicate that this analysis, contrary to what done by reductionism, does not claim to be either substantive or deterministic. Moreover, such an analysis has the explicit goal of addressing, rather than denying, the existence of chicken-egg paradoxes in the perception and characterisation of self-organising adaptive systems organised on multiple scales. The expression ILA wants to indicate that whenever we are dealing with a metabolic system the identity of the whole defines the identity of the parts and vice versa. The mechanism that generates convergence helps to identify robust typologies that can be used later on to scale-up characteristics of lower level elements (parts) into characteristics of the whole.

To make a long story short (a detailed discussion of this concept is available on Giampietro, 2003 – chapter 7): we can use in parallel: (1) the scheme provided in **Fig. 37a** to establish a mosaic effect across levels; and (2) the scheme provided in **Fig. 38a** to visualise forced relations between the characteristics of the metabolism of a given element (a part) of a socio-economic systems and the characteristics of the metabolism of the whole.

Figure 38a: Representation of the disaggregation of Endosomatic metabolism



Also in this case, we start with the metabolism of food for the introductory example. Very briefly, let us imagine to have a hypothetical society of 100 people that over a year will generate 876,000 hours of human activity. This human activity entails the consumption of a certain flow of food energy. Assuming the same demographic structure and the same set of social rules operating in a developed society, we can make the following assessments:

(A) at the *level* ***n*** - that is the box on the right in **Fig. 38a** - we have an analysis of average values of metabolism for the whole. This is obtained by dividing the total amount of food consumed by such a population by the amount of Total Human

Activity available at the level of the whole. This ratio represents an average level of consumption per hour for the whole;

(B) at the *level **n-1*** - that is within the box on the left in **Fig. 38a** - the whole of Total Human Activity is divided in societal compartments (parts). In this example, differently from what done in **Fig. 37a** we are defining and measuring the compartment rather than in age classes in terms of hours of human activity invested in different sectors. In particular, there is a series of splitting determining different ratios:

* **a.** - the "Total Available Human Activity" (876,000 hours) which represents the potential for action, in a modern society is reduced by 50% due to the dependency ratio (demographic structure).

* **b.** - the potential human activity expressed by the active population (438,000 hours), is reduced by 80% by investments in sleeping, leisure and personal care. The two reductions **a.** and **b.** together translate into a meagre 10% of the total initially available human activity (88,000 hours) which is invested, at the societal level, in work supply. This means that in a modern society, looking at the profile of investments of human activity, there is only 1 hour of work invested in the economic sectors producing goods and services in front of 9 hours spent in activities associated with consumption.

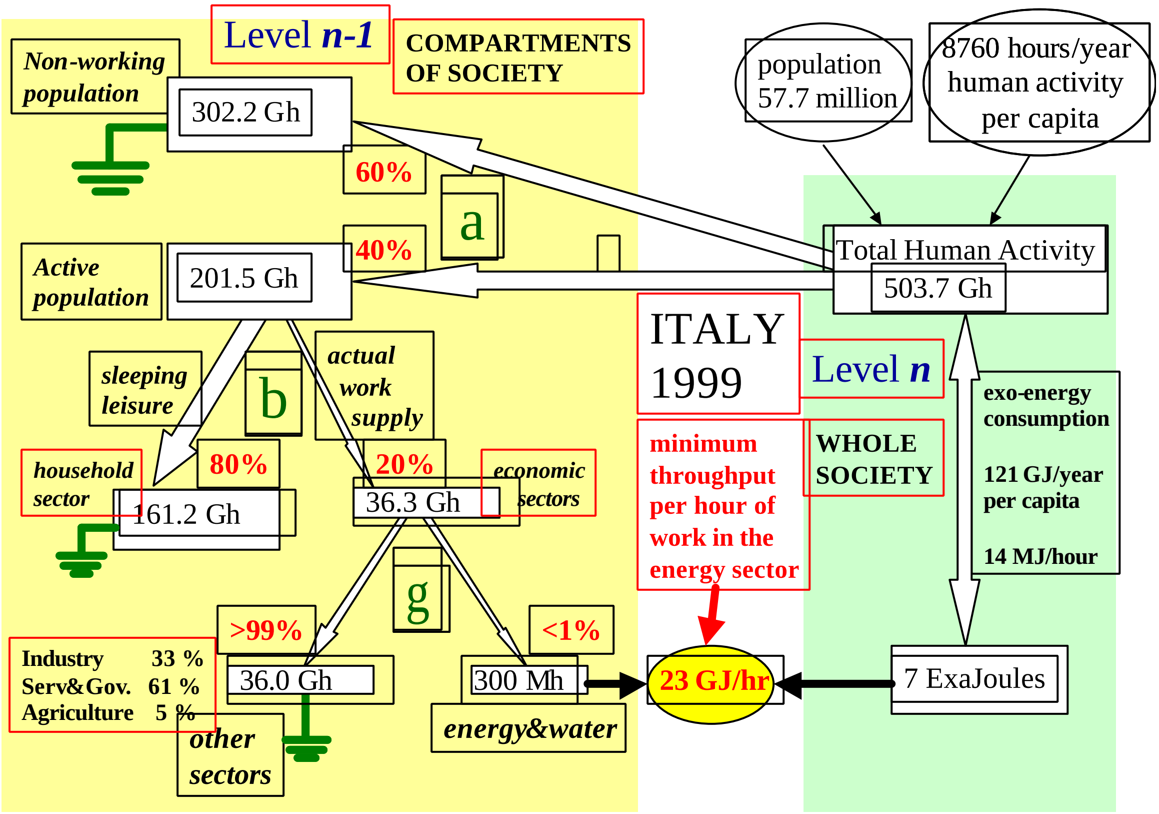
* **c. –** the activity available for work has to be split among competing tasks. There is an additional characteristics of modern societies that has to be considered when coming to the last reduction indicated in **Fig. 38a** Modern societies are very complex and this translates into a huge variety of goods and services produced and consumed. This in turn, requires a huge variety of sectors of activity, jobs descriptions and different typologies of expertise (Tainter, 1988). This implies that the actual hours of work supply available tend to be spread as evenly as possible over different sectors and tasks (with service and government getting more and more a bigger share). This is why, in a developed country it is unthinkable to have 60% of the work force in agriculture. Actually, the share of work force allocated in agriculture, is below 5% in all developed countries. It is well known that the process of industrialisation and post-industrialisation of modern economies is based on the dramatic reduction of the fraction of the work force allocated in agriculture. If we

account for all the previous reductions (**a.** and **b.**) and this additional splitting over a lot of requirements of working time for competing activities (**c.**), we are left with a negligible fraction of the total human activity which can be dedicated to food production (in our example not even the 0.5% of total human activity) – 4,000 hours for our 100 people.

In conclusion, in our hypothetical society, which reflects the standard characteristics of a modern society, all the food consumed in a year by a single person has to be produced with less than 40 hours of work. That is, given an average level of food consumption per hour of human activity for the whole society (**level *n***), there is a biophysical constraint on the flow of food in the sector (the part analysed at the **level *n-1***) where the food is produced for (made available to) the rest of society. In the example illustrated in **Fig. 38a** this implies a minimum threshold for the productivity of labour in the sector guaranteeing food production which is indicated in 25 kg/hour of work. This means that if the society would adopt a technique of food production with a labour productivity of 2 kg/hour of labour (a value typical of pre-industrial subsistence societies in rain-fed agriculture) it would be impossible to sustain the level of consumption indicated in this example (i.e. 1 ton of cereal per year, which is the actual level of consumption of US citizens when including the cereals used for animal and beer production) while maintaining the socio-economic characteristics associated with the values of **a.**, **b.**, and **c.**.

An analysis related to the metabolism of exosomatic energy of modern societies is exactly the same as the one illustrated in **Fig. 38a**. An overview of the set of values for **a.**, **b.**, and **c.** which are characteristic of a developed society, is given in **Fig. 38b** (Italy in the year 1999). It should be noted that Italy has a level of consumption per capita (14 MJ/hour or 120 GJ/year per capita) which is lower than the range of values found in other developed countries (30 ÷ 40 MJ/hour or 250 ÷ 350 GJ/year per capita). On the other hand, its population structure implies a dependency ratio of 60%, which is higher than that found in other developed society such as USA or Australia (about 50%). This is due to the large fraction of elderly in Italian population.

Figure 38b: Representation of the disaggregation of Exosomatic metabolism of Italy



In the examples given in **Fig. 38a** and **Fig. 38b** it is clear that the same approach can be applied over and over to different types of flows, considering each time, different selection of compartments (for additional examples see Giampietro et al. in press). At each application, a given metabolic flow of a society is assessed simultaneously in relation to the whole system and to the lower level elements. This parallel check makes it possible to look for:

(1) reciprocal relations of congruence among characteristics of the whole and its parts. Looking for a relation of congruence does not imply a deterministic analysis. In fact, it is not possible to say that: (a) it is the rate of food metabolism of the whole country which is determining the level of productivity of its food system; or (b) the throughput per hour of the energy sector is determining the average consumption of a society. In such an analysis there are a lot of factors that affect each other. For example, the effect of trade associated with economic activity; technological change; adaptation based on slower moving variables such as social rules, cultural habits, demographic structure, average body size, can all be perceived as factors determining different directions of causality. However, the direction of causality will change when considering this very same set of relations on different time horizons

(Giampietro, 2003). This is why this approach is called Impredicative Loop Analysis. The point is, that after having reached an agreement on the narrative (= what are the variables, and what are the parameters determining a given direction of causality which are of interest for the analysis) the relative values taken by extensive and intensive variables must result congruent for both what has been defined as the whole and what has been defined as the parts.

(2) benchmark values. These can obtained by looking at: (a) the vector of values associated with the chain of the splitting of the multilevel matrix of human activity into different sectors (this is called the dendogram of THA across levels). This dendogram in fact defines the distribution of extensive variables (amounts of hours of human activity) over the various parts; (b) the different rates of exosomatic metabolism of these different sectors (the intensive variables characterising the rate of metabolism of the various part).

Let us imagine now that we want to apply this method of representation to the exosomatic metabolism of humankind mapped against a multi-level matrix of human activity (the various sectors representing where humankind does invest its total human activity). The resulting representation is provided in **Fig. 39a**. The figure shows a combination of extensive and intensive variables which have to generate a congruent figures over 4 angles. Here we provide just a general overview of the approach. More details will be given in the next sections, when this analysis will be applied to China.

* angle d - (on the upper-right quadrant) we can say that this is the angle characterising the rate of metabolism of the whole. In this example, we have: (i) Total Human Activity (THA) per year on the vertical axis expressed in hours. This is considered as an extensive variable for metabolic systems (even if it is expressed in hours per year). THA is equal to Population x 8760 hours/year per capita; (ii) Total Exosomatic Throughput (TET) per year on the horizontal axis expressed in Joules. This is considered as an extensive variable for metabolic systems (even if it is expressed in J per year); (iii) Exosomatic Metabolic Rate (EMR), which is the level of metabolism of the whole – assessed at the level n – which is the ratio between TET and THA. This is considered as an intensive variable for metabolic systems (it is expressed in J **per hour**). The special characterisation for dissipative systems for

extensive variables (average values per year affected by the size of the system) versus intensive variables (averages values per hour and referring to a unit of system) is discussed in Giampietro, (2000). The intensive variable – exosomatic metabolic rate per hour – in fact, can be used as a benchmark to comparing this value over socioeconomic systems having different size. For example it is possible to check whether or not China has – as a country – an EMR higher or lower of that found as world average. It is possible to see whether or not the Agricultural Sector of China has an EMR which is higher or lower than the Chinese national average, if the average of a given Province in China is above or below national average, or in alternative if the EMR of the Agricultural sector of China is higher or lower of that of Belize.

* angle a - (on the upper-left quadrant) this is the fraction of THA which is actually invested in Paid Work activities. That is the angle a reflects the effect of the two reductions (**a.**, **b.**) considered in **Fig. 38**. The combined effect of demographic structure, social rules and habits, level of education, work load for paid workers all determine this overall cut on THA. The value of this angle implies (or reflects) the ratio between THA and HA_{PW}. HA_{PW} is the amount of hours allocated in the Paid Work sector per year in the socio-economic system. Being on the horizontal axis, this is another extensive variable (defining the size of the compartment PW).

* angle b - (on the lower-left quadrant) this angle is the ratio between the amount of J of Exosomatic Throughput invested in the PW sector per year (an extensive variable whose value is indicated on the lower part of the vertical axis) and the amount of hours of paid work spent in the PW compartment. HA_{PW} is the extensive variable (in hours) whose value is reported on the right side of the horizontal axis. The resulting Exosomatic Metabolic Rate, expressed in J per hour, is an intensive variable, characterising the metabolism of this sector (at the **level *n-1***). It can be interpreted as a biophysical assessment of the level of capital accumulation of the economic process. That is it is an indicator of how much the ratio exo/endo is boosted, in the PW sector by the use of exosomatic devices and by injection of fossil energy. That is a higher level of investment of fossil energy per hour of labour in a given sector, reflects a larger investment of technology and fossil energy. Also in this

case, this is a benchmark value that makes it possible to make comparison with the average value found for the whole. In this way, one can: (1) check the existence of biophysical constraints on the compatibility between this value - found at the level of the compartment (**level *n-1***) – e.g. technical coefficients - and the value found at the level of the whole society (**level *n***); and (2) compare the value found for this compartment in this socio-economic systems – China - with the analogous compartment of a different socio-economic system - USA.

* angle g - (on the lower-right quadrant) this angle is the ratio between the amount of energy spent in the activities performed in the Paid Work sector (= exosomatic energy used by the economic process to produce goods and services) – ET_{PW} – measured on the lower vertical axis - and the Total Exosomatic Throughput of the whole society – measured on the right of the horizontal axis. This angle represents the fraction of saturation of the total consumption of exosomatic energy of society, which is required for running the economic process. The level of saturation of 72% indicated in **Fig. 39a** implies that only 28% of the TET is invested in final consumptions in the household sector. Also in this case, this information can be used to calculate another important benchmark value. The level of Exosomatic Metabolic Rate achieved in consumption within the household sector - EMR_{HH}. This value can be obtained by dividing the extensive variable ET_{HH} [= TET - ET_{PW}] by the amount of human activity invested in HA_{HH} [= THA - HA_{PW}]. Such a benchmark is very important to characterise the material standard of living of households, which can be associated with the characteristics of housing and life styles (household metabolism).

When looking at the forced congruence over the four angles figure between extensive and intensive variables we can appreciate the power of integration of this method of analysis, which establishes a bridge between: (i) demographic variables (population size and distribution over age classes); (ii) technological variables related to both compartments referring to the production (exosomatic energy metabolism rates of economic sectors producing goods and services) and compartments referring to the consumption of goods and services. This is an important feature, since this biophysical analysis shows that for consuming more, it is necessary to invest more: (i) human activity; (ii) exosomatic energy; and (iii) capital (meaning reaching higher levels of EMR_{HH}) in the household sector.

Figure 39a: ILA at the level of the World in 1999

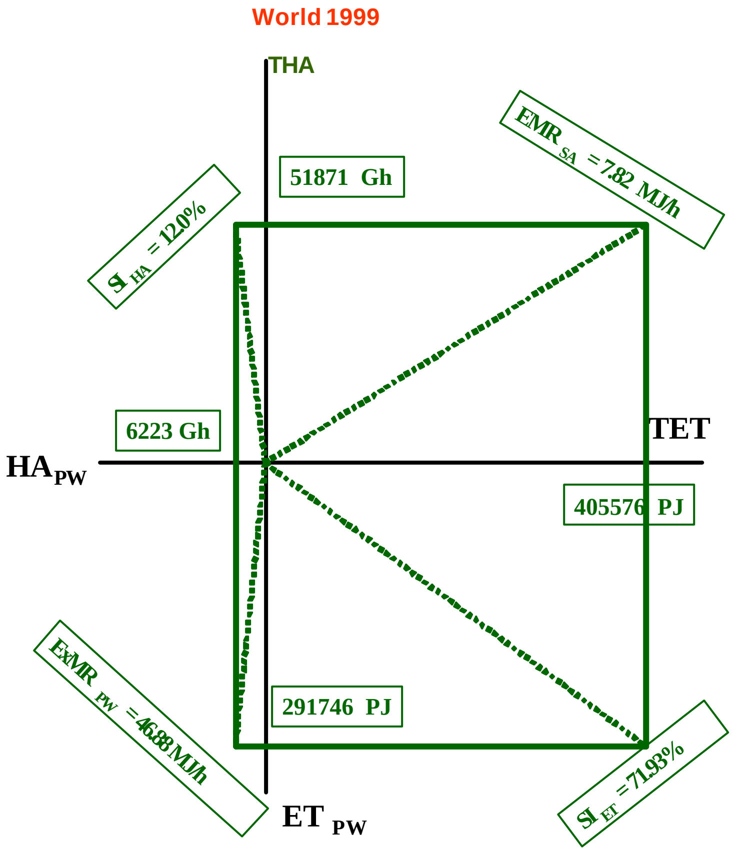
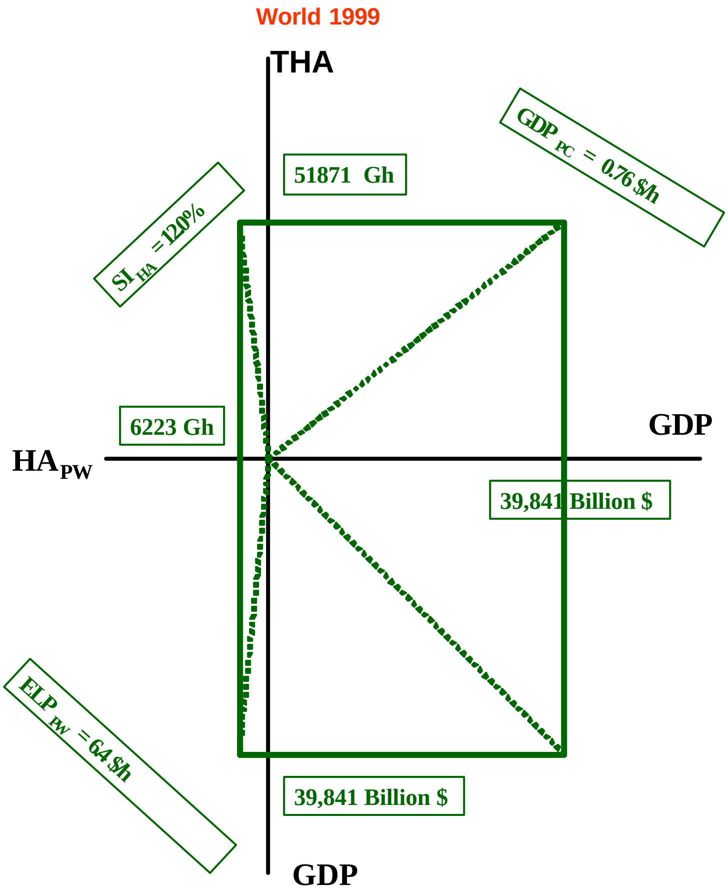


Figure 39b: Economic ILA at the level of the World in 1999



By adopting this method it is possible: (i) to represent the reciprocal entailment of values referring to intensive and extensive variables over the impredicative loop at each level of analysis (in this example the world level); and (ii) establishing bridges across representations referring to different levels.

Before closing this section we would like to point out that this meta-approach is very generic and can be applied to different definitions of metabolised flows. For example, the same ILA performed at the world level using added value instead of Exosomatic energy is given in **Fig. 39.b**. The same approach can be applied to land uses (using land area as the multi-level matrix in place of Total Human Activity). For a more detailed explanation of the formalisation used in the 4-angle figures see Giampietro (1997, 2003), Giampietro et al. (2001), and the two special issues of *Population and Environment* [2000, Vol. 22(2): 97-254; and 2001, Vol. 22(3): 257-352].

10. 3. The interface world level/national level: Looking for benchmarks useful to characterise and contextualise China metabolism

10.3.1 The approach used in this analysis

Calculating the two 4 angles figures depicted in **Fig.39a** and **Fig. 39b** starting from a data set referring to the world is impossible. In fact, this would require calculating for each country existing on this planet the values taken by the set of variables determining the 4 angles of those figures and then re-aggregate them, by averaging the various values over the relative size of countries, at the world level. We can expect that at the world level there are different demographic situations both in the size of the population and in the distribution of individuals over age classes. At the same time, we can expect that different social rules and laws about compulsory education and retirement, work-load for paid work, acceptable levels of leisure time. The combined effect of all these differences will determine a different value for the angle a found in each country. We can add to this list different levels of capital accumulation of the economic sectors, different level of economic competitiveness, which will affect the value taken by the other angles. In order to be able to take advantage of the mosaic effect [expressing the characteristics of the whole (the world) as determined by the set of lower level types] we have to look for a set of typologies of countries, that combined: (i) cover the whole population of the world. This implies that one of the selected categories has to include “rest of the world”; and (ii) represents a set of clusters of countries sharing similar characteristics.

The set of variables considered in the analysis is the same used when describing **Fig. 39**.

We refer the reader, for a description of the variables, to Section 7.4.1. Moreover, we added two more variables:

SI_{HA} = Saturation Index of Human Activity. This is the fraction of Human Activity that is allocated in the sectors generating added value, HA_{PW} /THA (where PW indicates the hours of work in all the sectors generating added value; that is, Productive Sectors [PS] + Services and Government [SG] + Agriculture [AG])
SI_{ET} = Saturation Index of Exosomatic Energy Throughput. That is, the fraction of Total Energy Throughput that is allocated in activities generating added value, TET/ET_{PW}

Sources of data and assumptions for calculations are given in **Table 1**.

Table 1: ILA World and Country types 1999

	THA[a] Gh	HA_{PW}[b] Gh	TET[c] Pj	ET_{PW}[d] Pj	EMR_{PW}[e] Mj/h	EMR_{SA}[f] Mj/h	SI_{HA}[g]	SI_{ET}[h]
World	51,871	6,223	405,576	291,746	46.88	7.82	12.00%	71.93%
AUSCAN[i]	2,825	295[j]	109,503	83,005	281.25	38.77	10.45%	75.80%
Rest OECD	6,955	546[k]	109,088	82,038	150.15	15.68	7.86%	75.20%
India	8,738	945[l]	20,081	10,759	11.38	2.30	10.82%	53.58%
China	10,982	2,020[m]	45,493	31,947	15.81	4.14	18.40%	70.22%
ex-USSR	2,545	216[n]	38,272	28,093	130.00	15.04	8.49%	73.40%
RoW[o]	19,827	2,200[p]	83,139	55,903	25.41	4.19	11.10%	67.24%

Sources: OECD (2002, 2004), ILO website (www.ilo.org), Ramos-Martin (2001), Giampietro and Mayumi (2000).

Giampietro, M. and Mayumi, K., (2000): Multiple-scale integrated assessment of societal metabolism: Integrating biophysical and economic representations across scales, *Population and Environment*, 22 (2): 155-210.
ILO Statistics. Laborsta data base. www.ilo.org
OECD (2002). *OECD Statistical Compendium on CD-ROM*, Paris.
OECD (2004). *OECD Employment Outlook 2004.* Paris.
Ramos-Martin, J. (2001): "Historical analysis of energy intensity of Spain: From a "conventional view" to an "integrated assessment", *Population and Environment* 22 (3): 281-313.

---

[a] Total Human Activity, in Giga hours. 1 Gh = 10^9 or 1 billion hours. Population x 8760 hours. Data on population from OECD (2002).

[b] Human Activity in the Paid Work sectors in Giga hours. PW sectors are those generating economic added value. PW = PS + SG + AG, where PS stands for Industry, Mining and Energy; SG for Services and Government; and AG for agriculture, as in Giampietro and Mayumi (2000b). HA_{PW} is generated from combining employment data with working hours. Data from Laborsta data base, ILO website (www.ilo.org). Otherwise, see specific notes for calculations.

[c] Total exosomatic Energy Throughput, in Peta Joules. 1 PJ = 10^15 Joules. We use Total Primary Energy Supply (TPES) for our calculations. Data on energy from OECD (2002).

[d] exosomatic Energy Throughput in the Paid Work sectors, in Peta Joules. That is, TET minus the energy consumed at the Household Sector (HH). For HH energy we use Residential Energy plus 50% of energy use at Transportation sector (our assumption, see Chapter 7 for the rationale). Disaggregated data on energy use by sectors from OECD (2002).

[e] Exosomatic Metabolic Rate of the Paid Work sectors, in Mega Joules per hour of activity. $EMR_{PW} = ET_{PW} / HA_{PW}$. 1 MJ = 10^6 or 1 million Joules.

[f] Exosomatic Metabolic Rate, societal average, in Mega Joules per hour. $EMR_{SA} = TET / THA$.

[g] Saturation Index for Human Activity in the Paid Work sectors. Fraction of Total Human Activity dedicated to generating added value. $SI_{HA} = HA_{PW} / THA$.

[h] Saturation Index for Exosomatic Energy Throughput in the Paid Work sectors. Fraction of Total exosomatic Energy Throughput dedicated to generating added value. $SI_{ET} = ET_{PW} / TET$.

[i] Australia, USA, and Canada.

[j] Employment data from OECD Employment Outlook 2004. working hours based on ILO statistics: 1600 h for Australia, 1927 for USA, 1645 for Canada.

[k] Employment data from OECD Employment Outlook 2004. 1700 hours for Total OECD, then deduction of AUSCAN.

[l] Employment data interpolated from ILO data for 1998, and 2000. 1800 hours per year.

[m] Employment from ILO. 8 hours a day x 7 days x 50 weeks.

[n] 1800 hours per year.

[o] Rest of the World.

[p] Our assumption, based on ILO statistics. 45% of Economically Active Population, and 10% unemployment. 2400 hours per year.

10.3.2. Getting into the analysis

What we get from **Fig.39** is a representation of two kinds of budgets for the world economy: (i) that of Human Activity versus Energy Throughput; and (ii) that of Human Activity versus Added Value (expressed in terms of GDP per year).
The values of all variables characterising the metabolism of humankind at the global level can be disaggregated at a lower level, using an appropriate set of typologies of metabolism associated with a set of typologies of countries. Obviously, this approach requires a mechanism guiding the choice of typologies for the disaggregation in groups. According to the experience already done in previous studies we selected 6 groups/typologies of countries listed in **Table 1.** India and China (cluster #1 and cluster #2) due to their size have been considered in the category "clusters" in spite of being an individual country. Actually, as it will be discussed later on, the big size of China and the existence of internal geographical gradients of socio-economic characteristics suggests that the average benchmark values found for China may be better explained by using a combination of at least two lower level sub-typologies. To check the validity of the choice of these 6 clusters of countries, however, it is necessary to check at the national level, whether or not for each one of these 6 clusters of countries, the elements belonging to that set express similar benchmark values.

Figure 40a: EMR$_{AS}$ and EMR$_{HH}$ for a selected group of countries, 1990 and 1999

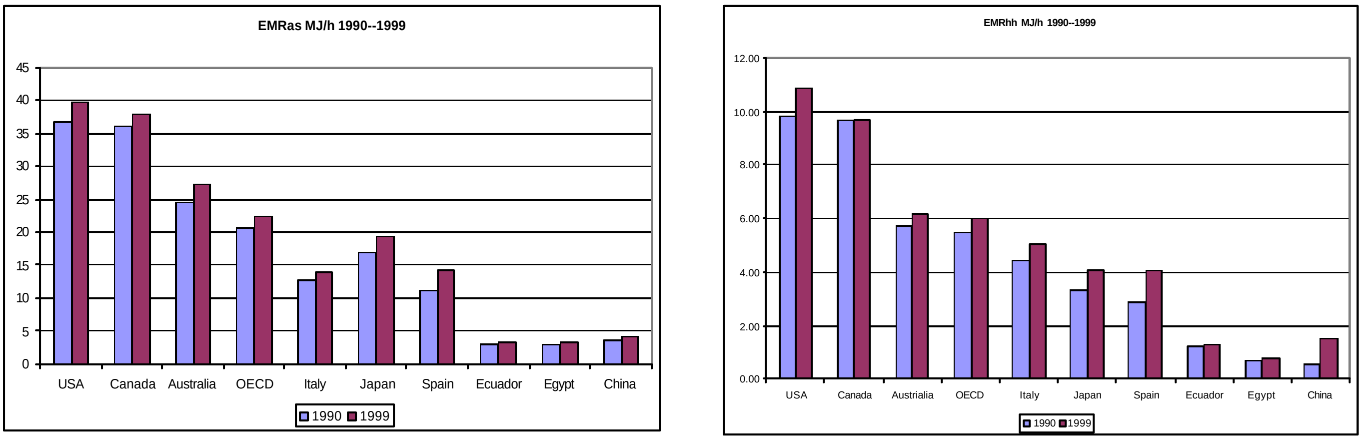
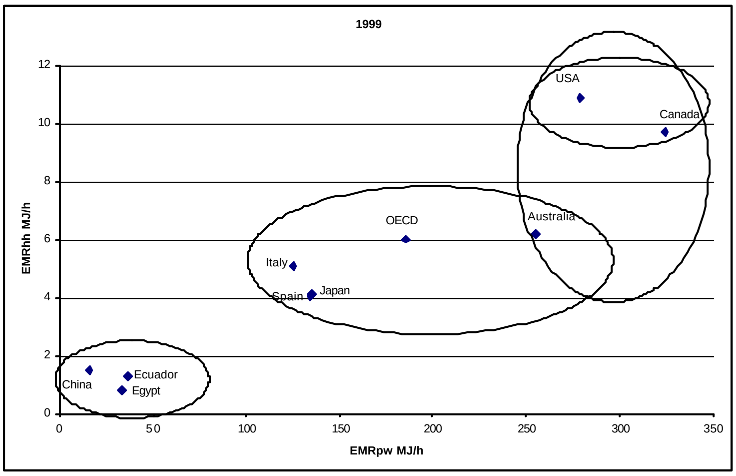


Figure 40b: EMR_{HH} and EMR_{PW} for a selected group of countries, 1999

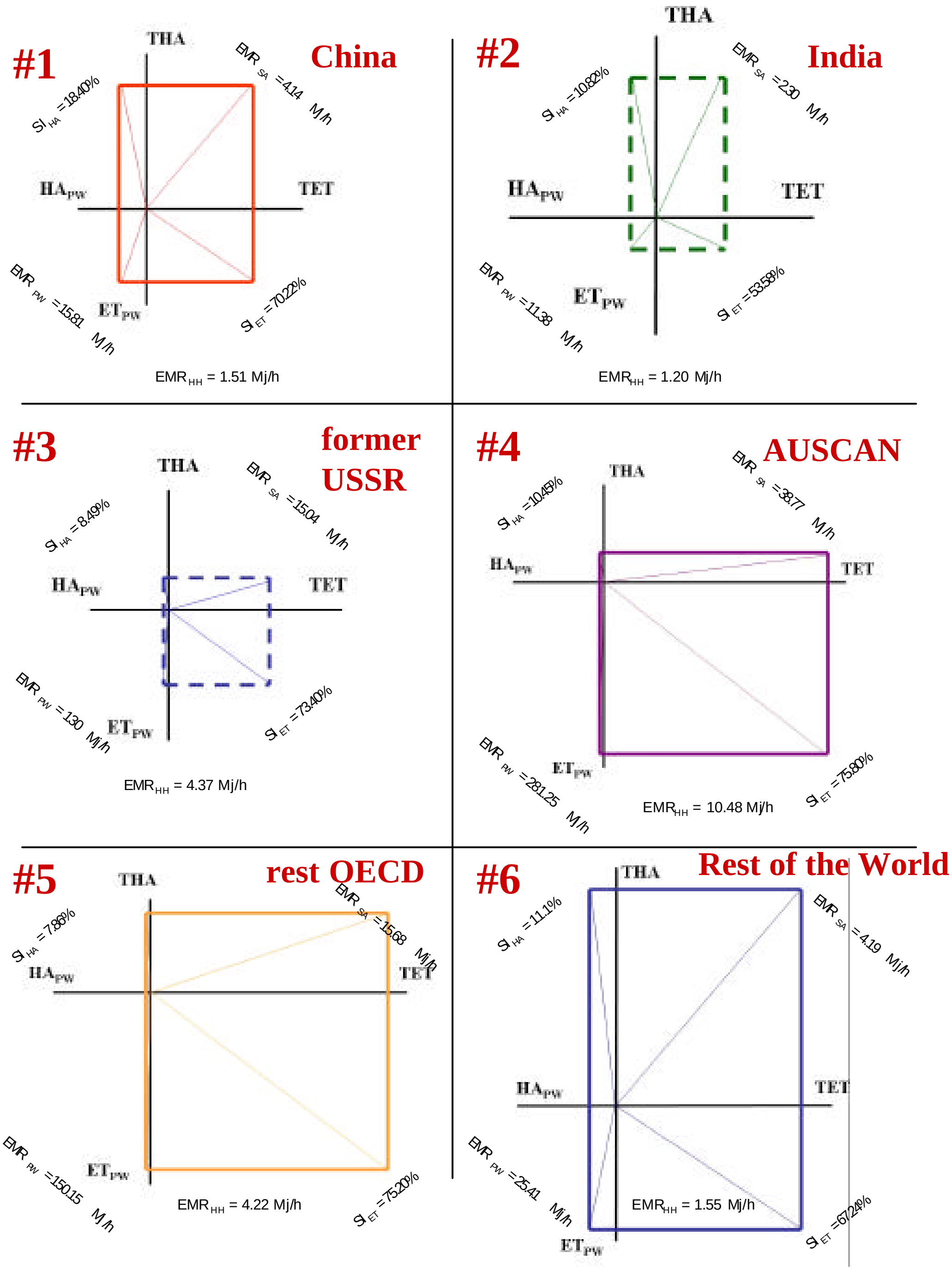


An example, of this analysis is given in **Fig. 40a**. When looking at the characteristics of individual countries over the given sample, we can individuate three main groups. (1) USA, Australia, and Canada - characterised by a population slightly growing, and a huge amounts of both fixed capital and natural resources; (2) another group (Italy, Japan and Spain) characterised by a stable size of population, high level of fixed capital but no resources endowment; and (3) the countries of the sample (Ecuador, Egypt) that may be considered representative of developing countries – characterised by fast growing increasing population and low levels of fixed capital. In this way, even when using this limited sample of countries, it is possible to have a first idea of how China compares with other countries. We used this limited sample of countries to decide whether or not considering all developed countries within a single cluster (OECD) or rather to split such a cluster into two. According to what shown in **Fig. 40a** and **Fig. 40b** we decided to split the OECD big cluster into two: (i) Australia, USA and Canada, on one side and (ii) the rest of OECD countries on the other. However, it is worth noting that when such an analysis is performed by looking simultaneously at different benchmarks we can detect differences within the same cluster. For example, in **Fig 40.b**, when looking in parallel at: (i) the exosomatic metabolism of the household sector - EMR_{HH}; and (ii) the exosomatic metaboloism of the paid work sector – EMR_{PW} - we can detect differences among countries that are not visible when considering the aggregate consumption at the national level – EMR_{SA}. For example, the case of Australia is very interesting. In fact, in terms of level of exosomatic metabolic rate of the economic process producing goods and services – EMR_{PW} – Australia is in the same cluster as USA and Canada, which is above the average benchmark for OECD countries. Whereas in terms of level of exosomatic metabolic rate of the household sector, Australia has a much lower level than the US and Canada, with values typical of the rest of OECD countries.

This is an interesting feature of MSIASM approach. In a case like this one, it is possible to search an explanation for these differences by looking at the characteristics of the lower-lower level. That is by looking at what is defining the profile of investments of both human activity of exosomatic energy on the various activities making up the PW sector and the HH sector. In this particular case, for example, we can attempt to explain the similarity found for this cluster of three countries when considering EMR_{PW}. In fact the three countries share a large exosomatic metabolism of the productive sectors. A fact, which was triggered by the original abundance of natural resources and by the high running costs of the whole economy due to sparse population. At the same time the difference between Australia - on one side - and USA + Canada on the other can be explored by considering what determines the characteristics of EMR_{HH}. (factors affecting household metabolism, income, climatic conditions, housing typologies, life styles). Adverse climatic conditions require a much higher investment in the household sector in USA and Canada, than in Australia. Another explanation could be a legacy of the colonial status in Australia, that left an economic structure based on export of natural resources, with a lower fraction of revenue for final consumption. This is just an hypothesis that we do not want to test now. This chapter is about China. The point we want to make is that in this type of analysis is possible to further disaggregate the system, using historical series, or lower level information (house typology, geographic differences) to check the various hypotheses formulated to explain differences in benchmark values found across different socio-economic systems. Time to get back to our analysis of world metabolism, we selected 6 typologies of ILA. of societal metabolism which are associated to clusters of countries with similar characteristics: (#1) India; (#2) China; (#3) former-USSR; (#4) AUSCAN (→Australia, USA, Canada); (#5) Rest OECD; and (#6) Rest of the World.

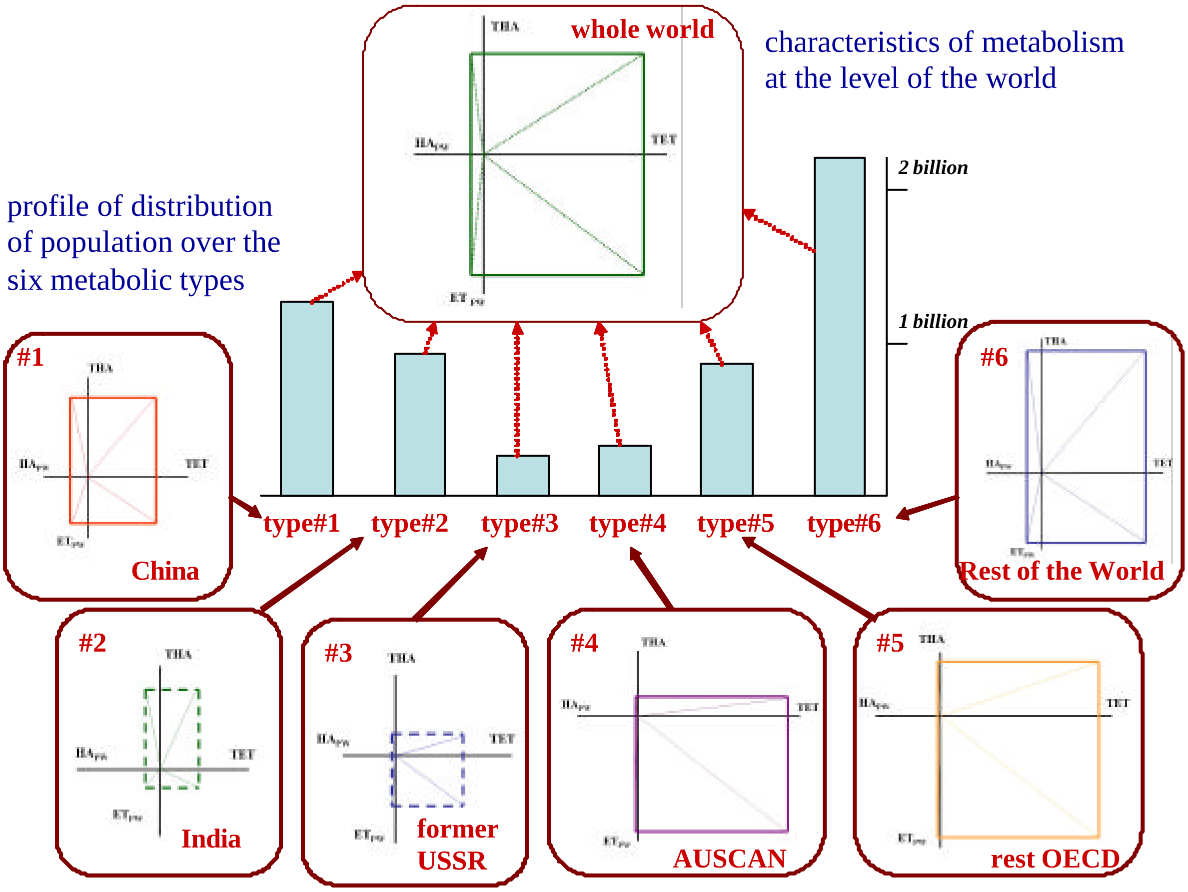
The relative representations with the benchmarks determining the ILA for these 6 typologies of countries are given in **Fig. 41**. It should be noted that the definition of the 4 benchmarks associated with the 4 angles implies also the definition of the benchmark EMR_{HH}. In fact, the value of $EMR_{HH} = \delta \times (1-\alpha) / (1-\gamma)$. That is: $EMR_{HH} = EMR_{SA} \times (1 - SI_{ET})/(1 - SI_{HA})$.

Figure 41: ILAs for the categories of countries



At this point we can visualise the mechanism that led to the generation of **Fig. 39**. By utilising the typologies of ILA characterising societal metabolism of the 6 clusters (shown in **Fig. 41**, based on benchmark values allowing comparisons among systems of different population size) it is possible to define the characteristics of the whole by using the profile of distribution of the world population over the 6 types. This is illustrated in **Fig. 42**. This in turn makes it possible to finally represent the exosomatic metabolism of the world economy using two external referents in parallel as shown in **Fig. 43** (following the original idea discussed in **Fig. 37.b**):

Figure 42: Representation of exosomatic metabolism of the World as composed by different country types

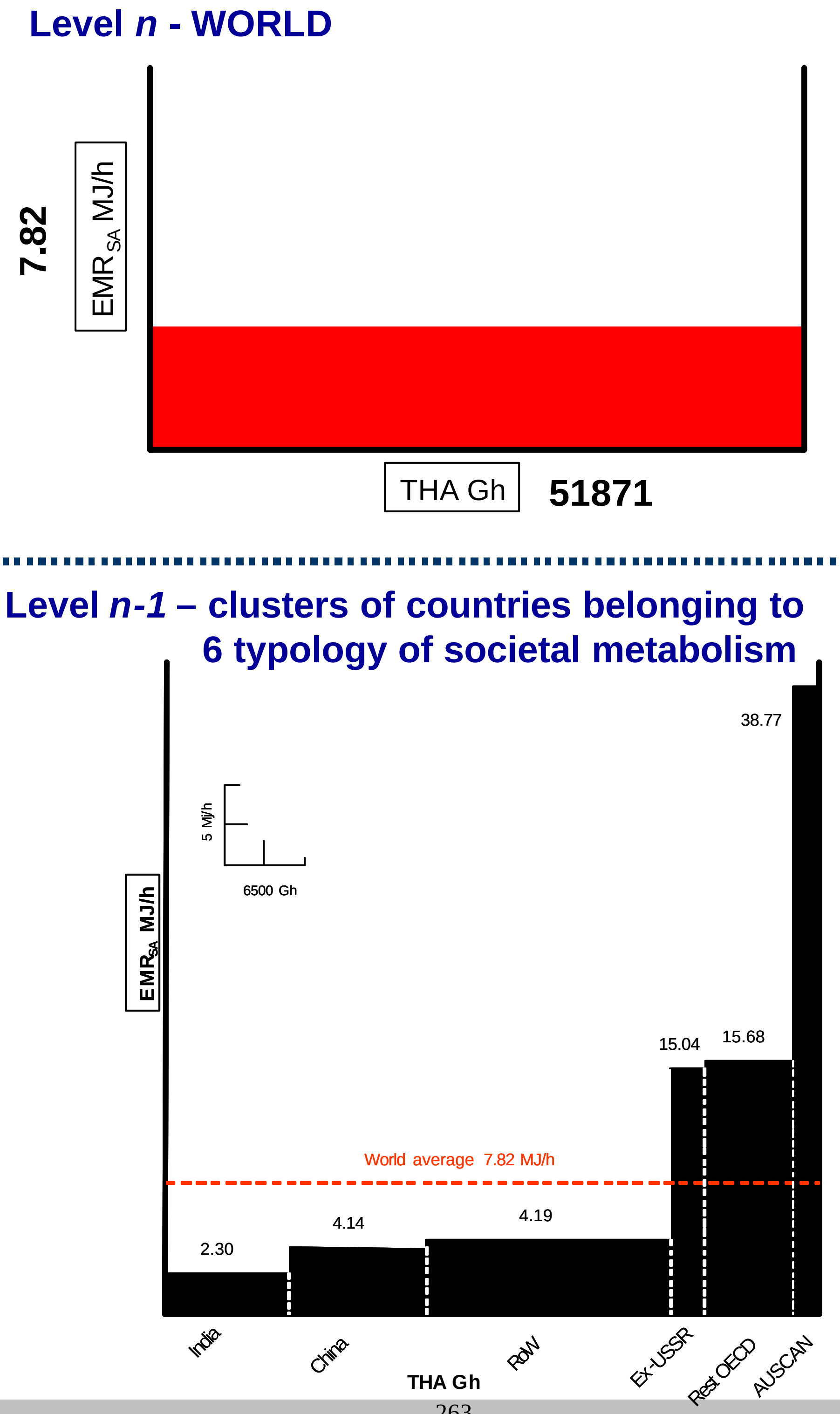


(1) in the upper level of **Fig. 43** we have the assessment of THA, TET and EMR_{SA} useful for characterising the exosomatic metabolism of humankind at the global level. This can be obtained by using statistics aggregated at the global level.

However, such a characterisation does not provide any relation with lower level external referents;

(2) in the lower level of **Fig. 43** we have an example of characterisation of the exosomatic metabolism of lower level types, which can use not only to characterise the metabolism of each of one of these clusters, but also to calculate THA, TET and EMR_{SA} for the global level. The scaling procedure is shown in **Fig. 42**.

Figure 43: EMR_{SA} for the World and country types



After having done this, MSIASM makes it possible to benchmark the characteristics of the exosomatic metabolism of China against: (i) average values found for the world (at the **level *n***); (ii) other typologies of countries (at the **level *n-1***); (iii) lower level component of China such a province, a town or even a household (at the **level *n-3*** and below).

10.4. Interface national level/sectoral level: Characterising the metabolism of China in 1999 and in the historical series 1980-1999

Looking at the evolution of economies in both economical and biophysical terms by using MSIASM makes it easier to detect the existence of biophysical constraints that are affecting the final trajectory (Ramos-Martin, 2000; Falconi-Benitez, 2001). In the case of China the MSIASM system of accounting pinpoints at the key role that the variable “disposable working activity” [= what fraction of THA is actual available for work in the economy] is playing in the recent performance of Chinese economy. When dealing with this variable, we are dealing with demographic dynamics which is affected by a clear lag-time effect. Such a lock-in mechanism of demographic variables is not only important to explain the current characterisation of societal metabolism of China (in terms of the actual profile of benchmarks) but also in terms of future feasible paths for China.

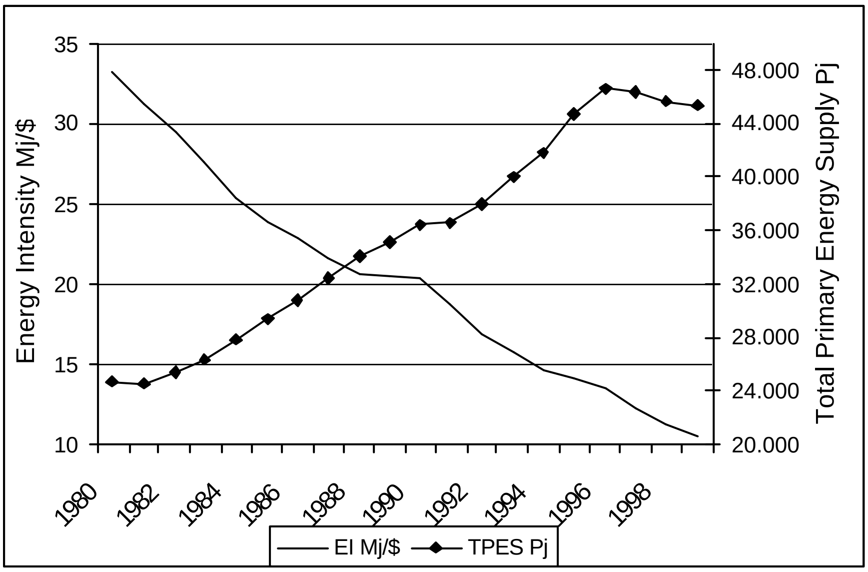
But let us first start with the basic analysis of benchmarks for the various sector of Chinese economy over the period between 1980 and 1999.

10.4.1 The evolution of energy consumption and energy intensity at the national level

In the period of 20 years analysed in this study, the Chinese economy has shown a clear path towards an increase in energy consumption and efficiency in the use of energy. For instance, the Total Primary Energy Supply has risen from 24,767

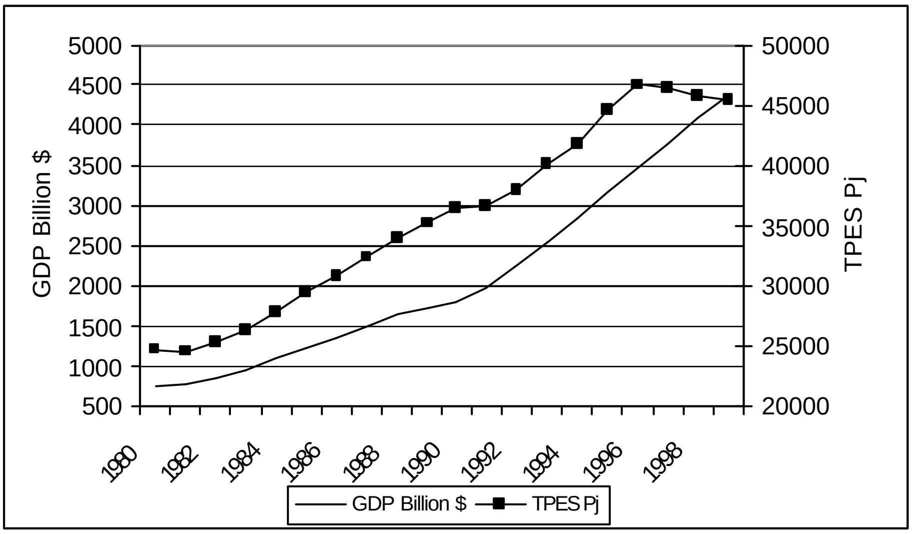
PJ in 1980 to 45,493 PJ in 1999. In absolute terms, China is increasing its exosomatic energy metabolism without any doubt. However, in relative terms, the energy intensity, that is, the amount of energy per dollar of GDP generated, has been decreasing over time, from 33.3 MJ/$ in 1980, to 10.4 MJ/$ in 1999. Defenders of the so-called "dematerialisation hypothesis", based only on the latter data would argument that China is a clear example of a country that is dematerialising in energy terms. Unfortunately, such a statement has no grounds at all. Looking at **Figure 44** it is clear that while the ratio MJ/$ can be decreasing, the total consumption of energy of the country is increasing. . This implies a first peculiarity in the behaviour of the economy. Even though China is still a developing country when considering the very low level of GDP per capita and other economic indicators of development, it is not increasing the energy intensity of its economy, as the hypothesis of the so called environmental Kuznet's curve would suggest. We can investigate the reason of this behaviour by applying the MSIASM method.

Figure 44: Evolution of Energy Intensity and Total Primary Energy Supply in China, 1980 – 1999



10.4.2. The relationship between energy consumption and the evolution of GDP

Figure 45: Evolution of GDP and TPES, 1980 – 1999



For long time energy analysts have been stressing the close relationship that exists between economic development and final energy consumption (Cleveland et al., 1984; Hall et al., 1986; Ayres and Warr, 2005). This relationship would imply for a single economy a tendency towards increasing energy consumption over time, associated with the ability of using such an energy input in a more efficient way. This hypothesis assumes a kind of analogy with other dissipative systems such as living systems. We have seen that China shows these two tendencies (when considering the biophysical aspect of its metabolism). Let us see if this holds also in the case of the relationship of energy with GDP. GDP has increased from 744 billion dollars in 1980 to 4,358 billion dollars in 1999[91]. Is the evolution of Chinese GDP driven by the associated increase in energy consumption, as shown in **Figure 45**?

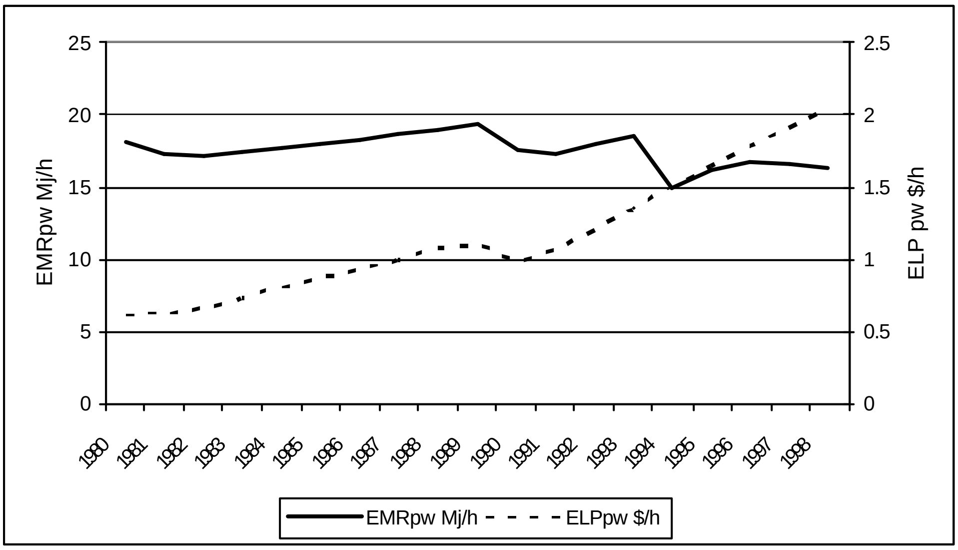
If so, this would be another evidence of a clear link between the level of exosomatic energy metabolism of the economy and the economic productivity of labour associated. A link that it is already been shown for several other economies (Cleveland et al., 1984; Hall et al., 1986; Ramos-Martin 2001, Falconi 2001). In order to verify this assertion, we can use the benchmark "economic productivity of labour" ELP (the equivalent of EMR for exosomatic metabolism) assessed at the level of the Paid Work sector. That is, ELP_{PW} is the ratio between GDP produced by the economic sectors (AG, PS and SG) and the amount of working hours in the Paid

---

[91] As throughout the text, we use constant 1995 dollars at PPP.

Work. Paid Work sector includes all the economic sectors that are generating economic added value. Therefore, PW consists of an aggregation of PS (energy, mining and industry), SG (services and the government), and AG (agriculture). At this point we can look at the changes in time of the two benchmarks ELP_{PW} and EMR_{PW}.

Figure 46: ELP_{PW} and EMR_{PW} over time



The evolution of the value taken by these two variables is represented in **Fig. 46**. Such a figure does not indicate a clear link between changes occurring in the two variables. This can be explained by several factors.

#1 The first one is associated to the fact that the values taken by this benchmark in China is very low when compared with other values found in more developed countries. That is, the hypothesis of the link between the level of economic productivity and the level of exosomatic energy metabolism holds better within developed economies in which there is a clear situation of market economy (extended monetarisation of transactions). In China the combination of the legacy of the Communist regime, especially in the poor rural areas of the country implies that a large fraction of what is considered to be Human Activity invested in the Paid Work sector (we are talking mainly of the Human Activity invested in agriculture) can also be considered as Human Activity invested in subsistence activities and not in economic activities.

In fact, when coming to the analysis of Benchmark values across country we have to note that the EMR_{AG} in China is lower than the EMR_{HH} found in the household sector (in final consumption) in developing countries. Let alone, considering the EMR_{HH} of China. This seems to indicate that actually, the large fraction of farmers accounted now within the work force and as contributing to the HA_{PW} in reality belongs to a different category and should be counted as separated. This may also indicate a systemic problem in the mechanism of accounting of GDP. In fact, a lot of food, goods and services produced and consumed in rural areas in which a subsistence economy is operating may not show up in the official statistics of GDP. That is when the workers are working as farmers, there is a systemic underestimation of the GDP, since a certain fraction of goods and services are produced and consumed without being monetarised. These goods and services can suddenly shows up in terms of the relative added value, when they are produced and consumed inside a real market. This progressive move toward a full monetarisation of the economic process would result as an increase of added value per unit of work (ELP) which is not associated with any change in the biophysical activities of production and consumption (same EMR). The growing of ELP in this case, can be due just to a change in the system of accounting. Looking at the very low value of these two benchmarks (EMR and ELP) and to the huge challenge facing Chinese economy (the fraction of work force in agriculture was at the 70% level in 1980 and the legacy of the communist economic regulation is still strong in rural areas) we may infer that this could represent a reasonable explanation. Actually, the real challenge for Chinese economy is to absorb the huge mass of workers at the moment labelled as working in the AG sector, that in reality are operating close to conditions of subsistence.

#2 The second issue which can determine a lack of relation between these two variables is more related to the technical relation among these two benchmark. That is, another explanation can be that we are not accounting in our analysis for the quality factor of exosomatic energy inputs. Since centuries China has been relying on coal for its exosomatic consumption. Lately, an increasing fraction of exosomatic consumption of energy within Chinese economy is in the form of oil and gas. It is well known that oil conversion into final exergy has a higher quality than coal conversion for the metabolism of modern society (Adams and Miovic, 1968; Kaufmann, 1992; Kaufmann, 1994; Stern, 1993;). Quality here is defined as the ability to achieve the same amount of end uses (or delivery of energy services) in the economic process with less amount of primary energy equivalent entering into the economy. This explains why modern economies are largely based on oil and whenever possible on natural gas. Whereas the Chinese economy is still largely based on coal. For instance, in year 1999, oil accounted for only 17.4% of TPES while coal accounted for 57.3%. If the process of economic development implies a gradual substitution of oil and/or gas for coal, that implies a constant increase in efficient in the use of energy. This would result in the ability of raising the economic productivity of labour (ELP) while keeping more or less constant the energy used per hour of work (EMR).

#3 The third issue is related with the size of China. The very large size of this country implies that we are dealing with a system which expresses different characteristics in its different parts. It is well known that in China there is a huge gradient between the very rich and market oriented provinces of South-East and the provinces of North and West of the country. This gradient may justify the use of two sets of benchmarks for two patterns of metabolism found in different parts of China. The expected relations between EMR and ELP is based on the idea that both demographic changes (affecting the amount of work force available and the amount of human activity to be invested in consumption) and structural changes of the economy (i.e. changes in the structure of GDP between sectors over time) are happening in a homogeneous system whose exosomatic metabolism can be characterised using a given ILA. Probably the ILA of China - indicated in **Fig. 41** - is the result of a mix of two different typologies of societal metabolism. One – relative to the poor areas - more similar to that found for societies operating close to the subsistence level – and the other – relative to the most developed and rich areas of the South-East – more similar to what found in societies in fast economic growth. If this is true, then it would be better expressing the national averages found for China, as the result of the combination of these two typologies (as done in **Figure 42**

for the world). Again this is a hypothesis, not tested in this study, that can be tested, if considered worth of additional investigation.

10.4.3. Breakdown of the evolution of Chinese economy to the sector level

Since we are interested in the effects of demographic variables, we first check the evolution of population in the period analysed. Chinese population increased from 841 million people in 1980 to 1,253 million in 1999 – an increase of almost 410 million. This is more than the combined actual population of USA, Australia and Canada that for sustaining their metabolism uses more than twice the exosomatic energy of China. This fact represented a major challenge for the economy of China. In fact, it implied the need of increasing energy supply just in order to provide in 1999 to the new population the same level of basic services and goods, as well as exosomatic devices per worker, that were present in 1980. This may explain why the Exosomatic Energy Metabolism of the society, EMR_{SA} changed only from 2.8 MJ/h in 1980 to 4.1 in 1999. These are values that are still much lower that those found for world average - 7.8 MJ/h. Let alone the benchmark value found when considering the OECD countries - with an average of 22.3 MJ/h. As in the case of Ecuador (Falconi, 2001) demographic variables may play a relevant role in explaining the (lack of) economic development of a country.

The analysis of relevant changes in extensive and intensive variables referring to the various benchmarks of the exosomatic metabolism of Chinese economy is given in **Fig. 47** in the form of dendograms of exosomatic metabolic rates. Again, we start our analysis by identifying two extensive variables that are defining the size of the system at the **level *n***, in this case Total Human Activity (THA, extensive variable #1) and Total Energy Throughput (TET, extensive variable #2). In our 4-angles representation for China (**Fig. 52**, this would be the upper right quadrant, which represents the **level *n*** of the analysis, that of the national economy.

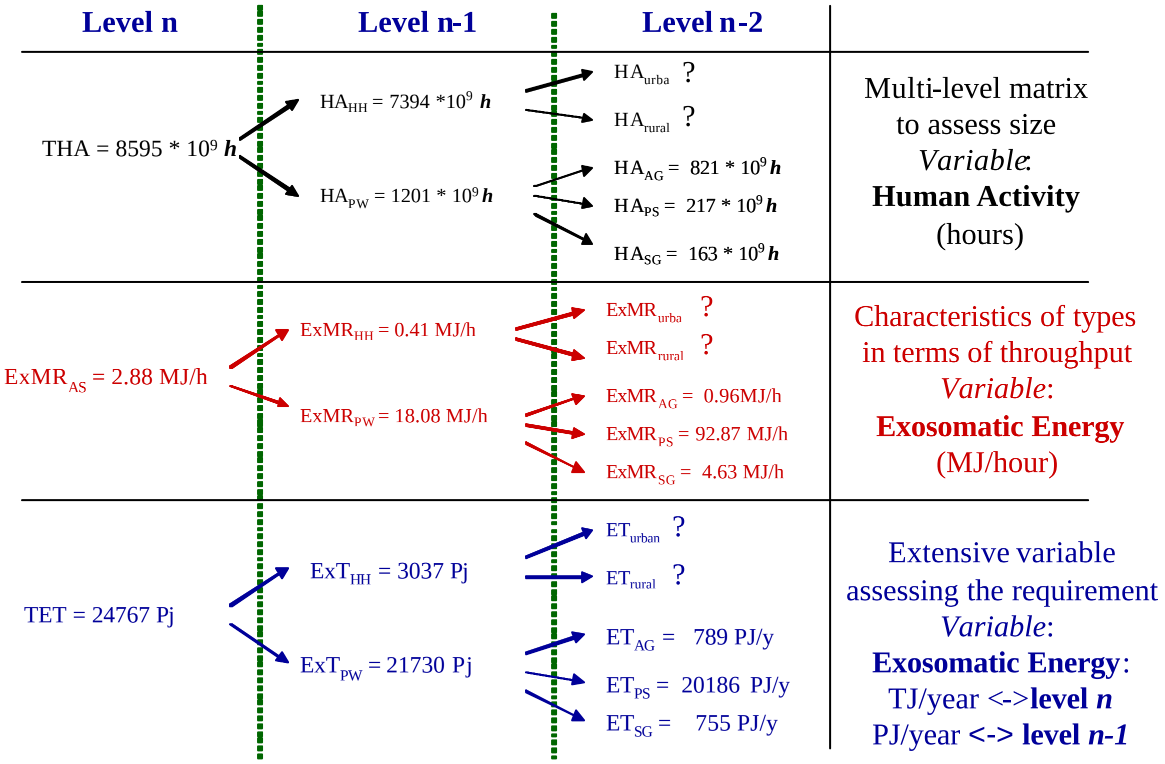
Then, remaining within **Fig. 47** the first disagregation distinguishes between investments of both “Human Activity” and “Energy Throughput” either in the

"Household sector (HH)" [on consuming] or in the "Paid-Work sector (PW)" [on producing]. In other words this represents the split between the consumption side and the production side. The concept of societal metabolism, in fact, implies that investments of human activities, capital and exosomatic energy, are not only requested for producing goods and services, but also for consuming them! This first split represent a disaggregation at **level *n-1***. A second disaggregation may imply splitting again the performance of the household sector into different household types at the **level *n-2*** (such as *urban and rural*, or different household types depending on income level). Since, in this study we do not have data for the household sector at this level of disaggregation (**level *n-2***), we do not consider this level for the consumption sector, as done for the paid-work sector. The MSIASM mechanism of accounting, however, is so robust that this decision does not affect the possibility of obtaining relevant information about different characteristics of the socio-economic systems on the side of productive activities. In fact, we can stop the splitting on the consuming side to the **level *n-1*** whereas we can keep splitting the paid-work sector, at the **level *n-2***, between the different sectors: Productive Sector (PS, including industry and mining), Services and Government Sector (SG) and Agriculture (AG). Going back to the 4-angles representation, adopted so far in this chapter, this means that we can check the characteristics of the angle β – the intensive variable defining the angle in the left lower quadrant – for the PW sector using information referring to lower hierarchical levels. In this case, such an intensive variable refers to a benchmark defined at the **level *n-1.*** At this point, by looking at the values taken by lower level elements at the **level *n-2*** we can study how the characteristics of the PW sector in reality depends on: (a) the set of characteristics of lower level sectors (i.e. PS, SG, AG sectors), which are expressed at the **level *n-2***; and (b) the profile of distribution of investments of Human Activity over these sub-sectors – that is, how the extensive variable HA_{PW} – assessed at the **level *n-1*** – is distributed over these sub-sectors at the **level *n-2***. We are back at the trick of bridging hierarchical levels using mosaic effect.

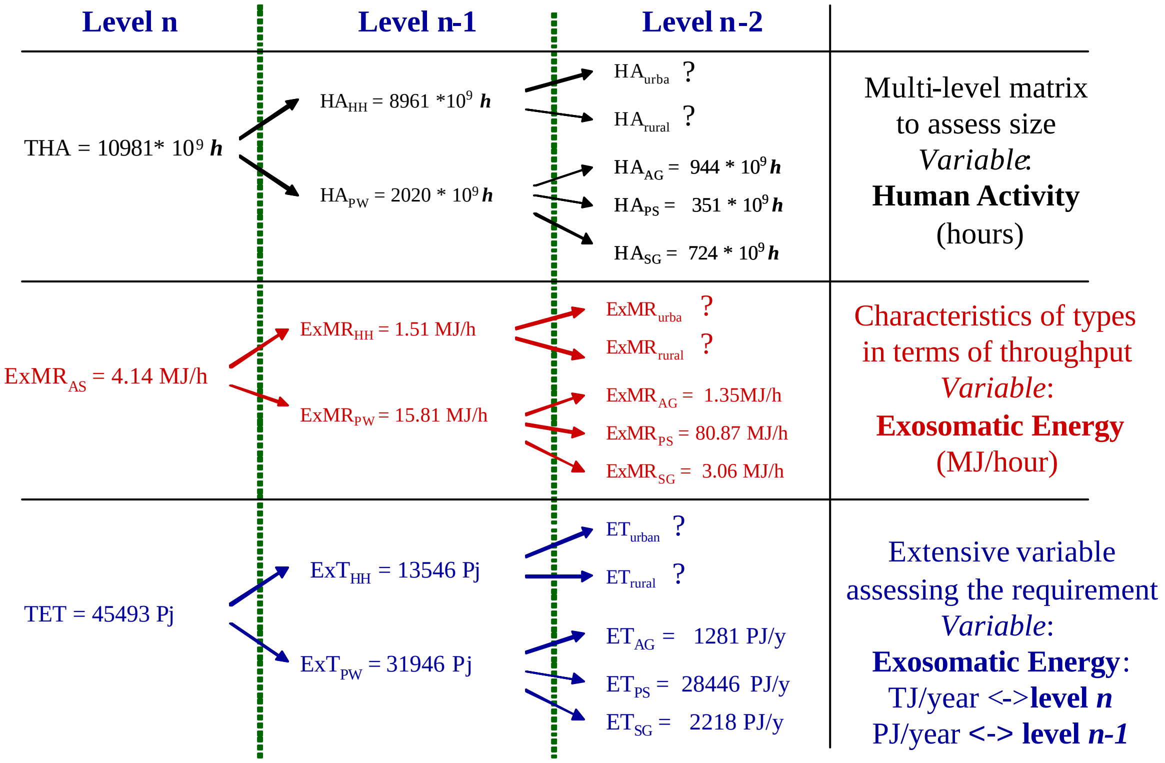
The representation of the characteristics of elements belonging to different hierarchical levels by using a dendogram makes evident an important characteristic of MSIASM: the ability of simultaneously handling a set of values taken by key variables on different hierarchical levels. That is, a given value of an intensive variable can be seen as being determined by: (a) relations of values taken by variables belonging to a higher level, or (b) the aggregation of values associated with typologies defined on lower levels. For instance the value taken by the variable EMR_{HH} can be used as a proxy for the level of material standard of living of the household sector (average for the whole country). This value can be found using a bottom-up approach if we know: 1) the set of households types existing in the country - i.e. urban/rural, income levels, household size; 2) the profile of distribution of these households types over all households; and 3) the different EMR_i of these household types (observed using a 'consumption survey', for instance). On the other hand, if we approach the assessment of the value of EMR_{HH} with a top-down procedure, we will just need to look at the values of ET and HA for this sector found at **level n** of analysis. The value of EMR_{HH} is the ratio between ET_{HH} and HA_{HH}. In alternative, we can calculate the very same value as a difference at the level n. That is $ET_{HH} = TET – ET_{PW}$ and $HA_{HH} = THA – HA_{PW}$.

Figure 47: Dendograms for China 1980 and 1999.

Dendogram of EMRs in China in 1980

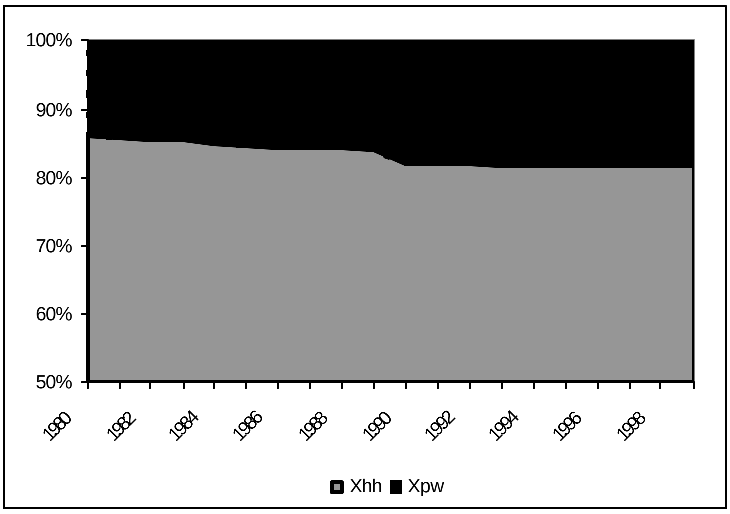


Dendogram of EMRs in China in 1999



Let's start then checking the evolution in time of how total human activity was distributed between working activities (a variable we call X_{PW}) and non working activities (X_{HH}). The former would be related to guaranteeing the functioning and growth of the system at the short run (i.e. the hypercycle generating profit in the socio-economic process, see Giampietro, 1997; 2003; Ramos-Martin and Giampietro, in press). The latter would represent the net dissipative side of the economy, that we call here the Household Sector (HH) and that includes non working people (young and elderly) and non-working time of active population (sleeping, leisure, personal care, education, etc). This later fraction of human activity is linked with the long term stabilisation of the system. Such an analysis is provided in **Figure 48**.

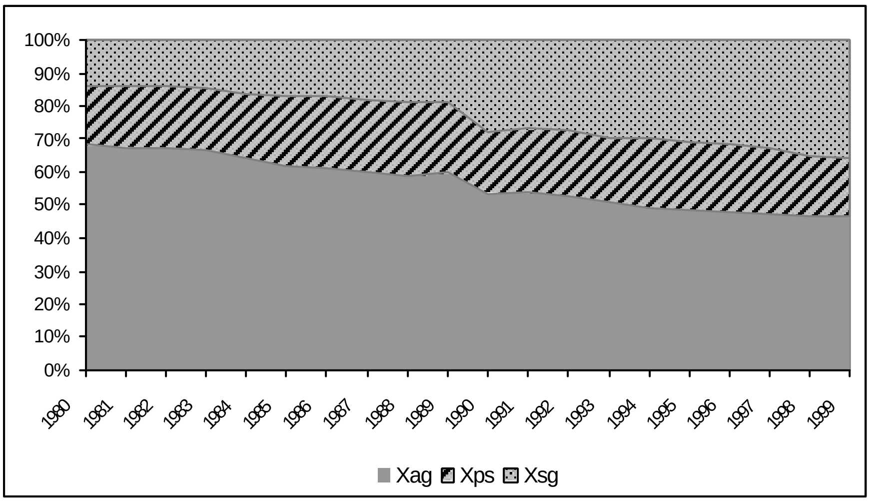
Figure 48: Evolution of working and non-working time over time



In that figure we can see how the fraction of working time in China has risen from 14% of total available time in 1980 to 18.4% in 1999. Therefore, not only China saw a huge increase in population in absolute terms, but also a growing fraction of its THA was directed to work. This implied an additional challenge, in terms of capital accumulation of the economy. In fact, not only the level of capital accumulation of the Chinese economy had to keep a pace coping with the absolute increase of population size, but also the peculiar demographic trend resulting from the policy of birth control implied a wave of adults entering in the work force in this period. That is, the degree of increase of the extensive variable HA_{PW} was driven by the combined effect of the increase in the extensive variable THA and by the increase in the Intensive Variable SI_{HA} – which is associated with changes in the dependency ratio. That is more capital was required by China not only to deliver more goods, services and infrastructures to the growing population, but also to maintain the original level of EMR_{PW} (exosomatic devices and fossil energy input per worker) for an increasing working population.

Another important aspect of our analysis is to see where (in which compartment of human activity), this huge increase of Working Time in the Paid Work sector will end up. This requires checking the trends of changes occurring at the **level *n-2***. The effect of changes in demographic variables (determining a change in HA_{PW} at the level n-1) can be only studied by looking at the structural change of the economy itself. In order to do that we will add two piece of information here: (1) the distribution of the increased amount of working time - HA_{PW} - over the three sub-sector sectors at the **level *n-2*** (X_{PS}, X_{SG}, X_{AG}); and (2) the different values of Exosomatic Metabolic Rates for each of the three sectors: PS, SG, and AG. It is only when we look at this information, at a lower scale of the system, that we can understand the overall trend of exosomatic metabolism of the Chinese economy (EMR_{PW} at the **level *n-1***) over time.

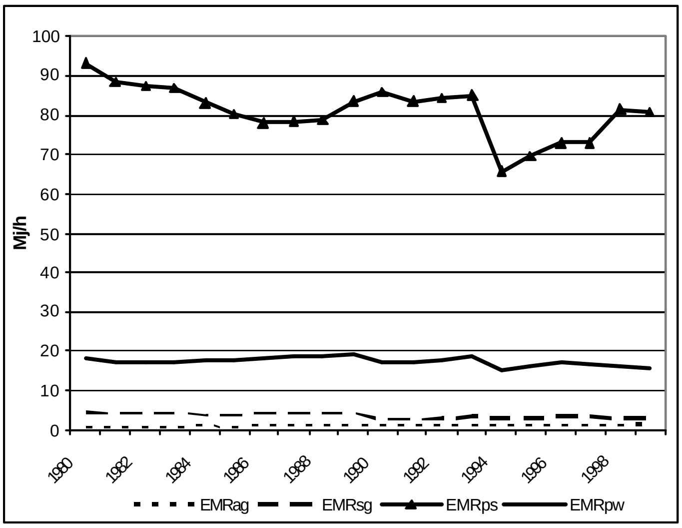
Figure 49: distribution of working time between economic sectors



From **Figure 49** we can see that the fraction of working population in industry (PS sector) has remained more or less constant. That is, 18% of HA_{PW} in 1980 with **a slight decrease** to a 17% of HA_{PW} in 1999. Whereas there is a dramatic reduction of Human Activity in agriculture. This is significant not only by the figure itself, a deep decrease from 68% in 1980 to 47% in 1999, but because of what it implies in terms of side effects for the economy of China. Abandoning agriculture goes hand in hand with emigration to cities. In turn this requires more infrastructures to cope with the needs of an increasing urban population. At this point it is obvious that the services sector is the sector that has to absorb this massive shift away from agriculture. During this time window HA_{SG} went from 14% of HA_{PW} in 1980 to 36% of HA_{PW} in 1999.

Can we explain this unexpected behaviour? Why the PS sector is not absorbing the massive flow of working time escaping the agricultural sector? This would be the typical path – wild industrialisation – found in the history of developed economies. In order to answer this question we have to check both the relative levels of exosomatic energy metabolism of these three different sectors and their evolution over time. Such an analysis is provided in **Figure 50**.

Figure 50: EMR for the three sectors under analysis



Looking at **Figure 50** one can realise two things. The three different sectors considered at the **level *n-2*** do have very different metabolic rates. Therefore the general benchmark value for EMR_{PW} defined at the **level *n-1*** does not carry much information about typologies of metabolism of lower level sectors. Rather such a value is determined by the characteristics of the sub-sectors defined at **level *n-2***. Since the value of EMR_{SG} is higher than the value of EMR_{AG} one should expect that the shift of a larger fraction of working population and HA_{PW} would imply an increase in EMR_{PW}.

According to what said at the beginning an increase in EMR_{PW} would imply the country is accumulating capital [= increasing the amount of exosomatic devices and consumption of fossil energy invested per hour of working time in the productive sectors] over time. Actually, this is not happening in China. In fact, EMR_{PW} has dropped from 18 MJ/h in 1980 to 15.81 MJ/h in 1999. This same tendency is observed in the productive sector where EMR_{PS} moved from 92.9 MJ/h in 1980 to 80.9 MJ/h and in the SG sector, where EMR_{SG} moved from 4.6 MJ/h in 1980 to 3 MJ/h in 1999. The only sector that shows an increase – even if very slight – in its exosomatic metabolic rate is the agricultural sector that moved from an EMR_{AG} of 0.96 MJ/h in 1980 to an EMR_{AG} 1.35 MJ/h in 1999. However, this benchmark value remain absolutely low when compared with international standards (e.g. much lower that the metabolism of the household sector in developed countries) and can be easily explained by the massive reduction of the working population within the AG sector. This indicates a clear paradox. How it is possible that China, one of the fastest growing economies of the world, despite the huge increase in energy consumption in the period considered (as shown in **Figure 44**), is reducing EMR of its more strategically important sectors (PS and SG) over time? We already gave a partial answer to this question before when mentioning the effect of demographic changes. But there is another important aspect to be considered before getting in a more complete explanation.

Looking at the relative value of EMR of these three sectors (PS, SG, and AG) – **Fig. 50** – one can immediately see that moving an hour of human activity from the AG sector to the PS sector requires a dramatic increase of the rate of exosomatic metabolism. This explains why the massive move away from agriculture, for the moment is absorbed by the SG sector. In fact, such a move implies "only" – so to speak – an increase of EMR of 2.4 times (from 1.3 MJ/hour in the AG sector to 3.1 MJ/hour in the SG sector, data in **Fig. 47**). Whereas a move from the AG sector to the PS sector implies an increase in EMR of 62.2 times (from 1.3 MJ/hour in the AG sector to 80.9 MJ/hour in the PS sector). No wonder that so far we did not experience important increases in the relative value taken by HA_{PS}. Actually, the slightest decrease of this sector over time, seems to indicate that for the moment it is a continuous increase in efficiency that makes it possible to hold such a value constant.

At this point we can clearly see a combined effect of three factors: (1) population growth – an absolute increase in THA; (2) the extraordinary growing fraction of working population within the given THA - that in China is now almost 60% (versus the 50% of AUSCAN and 40% of many European countries) – as illustrated in **Fig. 48**; (3) the massive switch of working activity away from the agricultural sector which has the lowest exosomatic metabolic rate. toward the more energy intensive SG sector – illustrated in **Fig. 49**. The combination of these three factors generated a “mission impossible syndrome” for empowering the two sectors SG and PS. In spite of the formidable increase in energy consumption and the wave of investment in the different sectors which is occurring in China in the last decade, the increase in the supply of exosomatic devices and input of fossil energy is not matching the pace of increase in HA_{PS} and HA_{SG}. This is why, the characteristic benchmark of the exosomatic metabolic rate of these two sectors - PS and SG - have been falling as illustrated by **Fig. 50**. The trend over the values taken by these variables over the period in analysis shown in **Fig. 50** is self-explanatory.

In conclusion China was trapped by its large size of population (determining very low return for agricultural activities based on farms having less than 1 ha of size – Giampietro et al, 1999), and by demographic trends induced by the policy aimed at reducing the negative effect by population growth. As shown in a similar analysis performed to study the process of economic development of Spain (Ramos-Martin, 2001) demographic variables (and in particular certain stability in size and relative fraction of the various compartments) is a necessary requisite for countries that want to empower the PW sector. This makes it possible for these economies to direct energy surplus to both accumulating capital in the economic sectors (the EMR_{PW} in the productive sectors), and raising the material standard of living of the citizens (the EMR_{HH} in the sector in charge of consumption).

This may be an explanation for the fact that China has not yet been able to make the leap other Asian countries did manage to do. This requires escaping from the spiral of relying more and more on high labour intensive/low labour cost commodities. However, such a choice may result an obliged one, when the level of EMR_{PW} remains low. We believe that Chinese authorities are well aware of the risk of remaining in such a lock-in and this may explain why China entered the energy market so aggressively in the last years. In fact, China is not only becoming one of the larger importers of oil in the world, but also it is buying prospecting rights for oil and natural gas that can fuel economic growth in the near future[92]. The same occurs for other raw materials that are necessary at this stage of development, in particular cement and other construction materials[93].

From what discussed so far it is clear that China is facing a daunting dilemma. It has to invest huge amounts of money and energy: (i) in building infrastructure for the new urban population; (ii) in developing new industries to increase the level of capital accumulated of the PW sector so that in the next future the increase in economic productivity of labour can be based not only in low cost labour; and at the same time (iii) in increasing the ability of Chinese citizens to spend in order to improve the tough material standard of living experienced by a large fraction of its population. From an economic point of view, the latter is also necessary for helping building up an internal market large enough to rend Chinese economy more robust, stable and resilient towards the dollar fluctuation. From a political point of view, the necessary short-term compression of consumption (in order to be able to invest the surplus into the needed capital accumulation of the economy) has at least two major likely risks. The first one is social unrest that already happened in northern parts of the country that used to be more industrialised, and in rural areas since peasants already have a very low level of material standard of living. The second, more relevant from economic point of view, is that present development occurs mainly in the South East part of the country. This unbalanced development may lead to local and regional governments (who see themselves closer to Taiwan or Hong-Kong in many senses) to ask for some kind of autonomy that may eventually imply the risk of a breaking up in pieces of motherland China.

---

[92] See, for instance, *The Economist*, April 29th 2004 "in the pipeline", which reports the deals with Russia; or November 25th 2004 "A new scramble" which evidences deals with Sudan, Angola, Gabon and Nigeria.

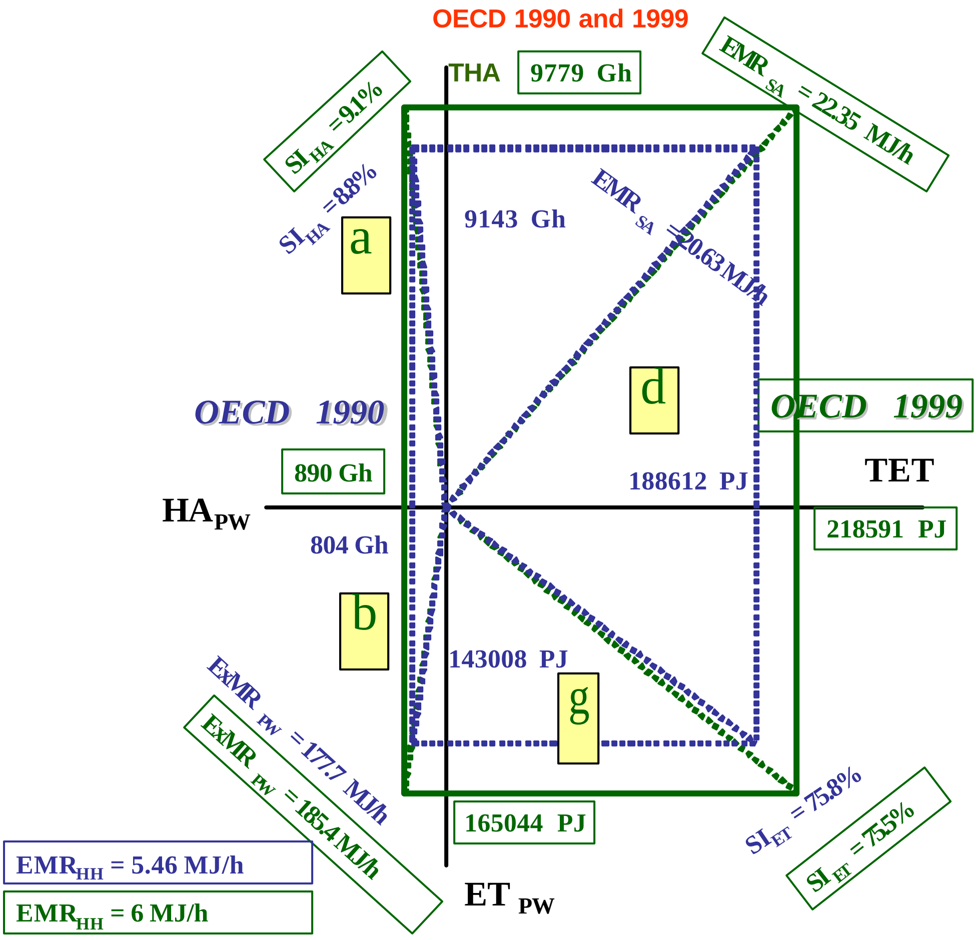
[93] Again, *The Economist*, February 19th 2004 "The hungry dragon" reported China consuming in 2003 half of the cement of the world. In September 30th 2004 "A hungry dragon" reports in year 2003 China consumed 40% of all the coal, 30% of al the steel in the world.

10.5. Back to the interface world level/national level: Future scenarios of development for China and possible effects on world trade

10.5.1. The comparison between China and OECD

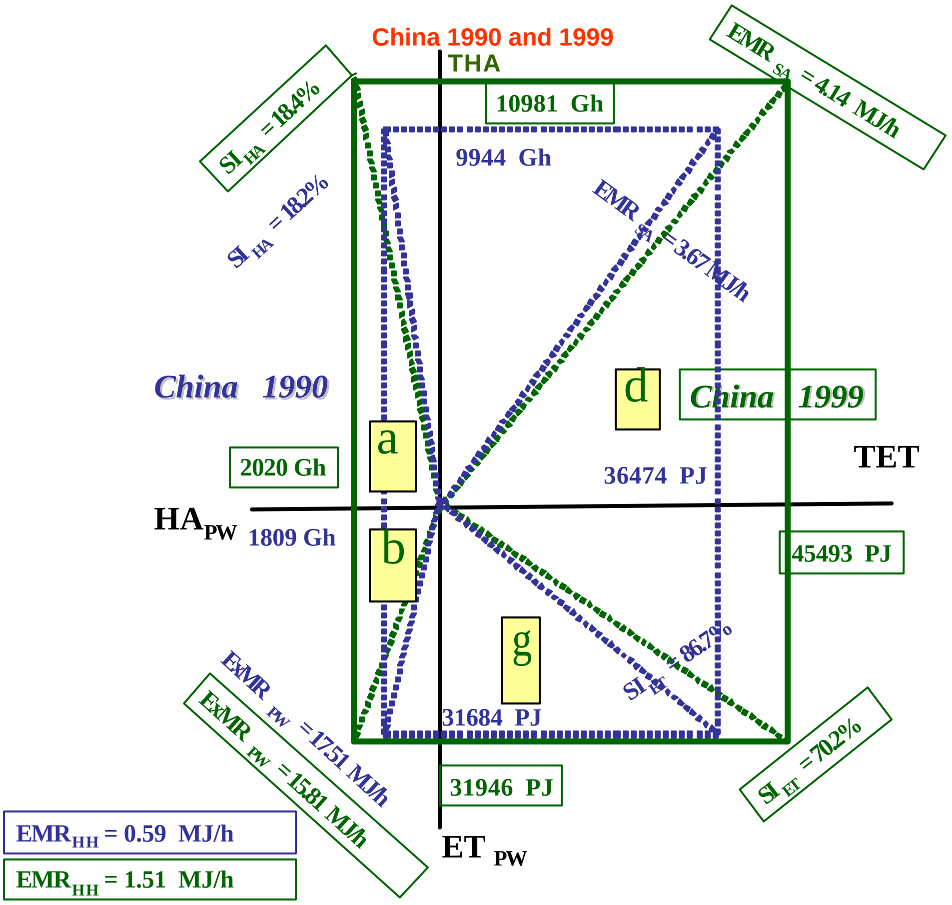
In this section we want to go back to the interface between the world level and the national level, to put in perspective not only the implications of the size of Chinese economy in biophysical terms, but also to briefly discuss of possible future scenarios of development for China.

Figure 51: ILA for OECD in 1990 and 1999



In this sense a first thing to do is compare the IL characterising the exosomatic metabolism of China with the IL characterising the exosomatic metabolism of the cluster of most developed economies, that is, the OECD. A representation of an IL characterising the exosomatic metabolism of OECD countries in both 1990 and 1999 is given in **Fig 51.**. Over this period of time we can see that there are very small changes in terms of "***development***" (= changes in the value taken by the intensive variables used as benchmark for the 4 angles). Instead, there is a slight change in terms of "***growth***" (= changes in the value taken by the set of extensive variables) in both economic and biophysical terms – e.g. total GDP, total Exosomatic energy throughput, population directly affecting the value of Total Human Activity. There is, however, a small increase in the level of exosomatic metabolism of the productive sectors that is therefore translated into a further increase in the level of EMR_{SA} of the society. It should be noted that however, when considering the final consumption, the exosomatic metabolic rate of the household sector increased almost of 10% - moving from 5.5 MJ/h in 1990 to 6.0 MJ/h in 1999.

Figure 52: ILA for China 1990 and 1999



The same ILA over the same period of time but applied to the exosomatic metabolism of China is given in **Fig. 52**. There we can see a few interesting points. Population has risen steadily (around 10% in the period) moving up the extensive variable THA. However, the level of energy consumption per capita - in our analysis the Exosomatic Metabolic Rate at the societal level (EMR_{SA}) has risen very little in the same period. Actually, there is a decrease in the level of EMR_{PW} of the productive sectors. That is, workers in the PW sector were harnessing less exosomatic energy per hour of work in 1999 than they did in 1990, due to the large expansion of textiles. This implies a negative effect in the possibility of increasing the level of economic productivity of labour (ELP_{PW} going from 0.60$/h in 1990 to only 2.16 $/h in 1999). The increase is important in relative terms, but remain very low in absolute terms (when comparing this benchmark value versus what is going on in other countries). As discussed before the increase in population (extensive variable THA) and the massive reduction of the fraction of work force in the agricultural sector lead to the point that the surplus generated by increases in EMR_{PW} and ELP_{PW} were invested not to further increase the level of capital accumulation of PS and SG sectors, but rather to provide the mass of workers moving away from the agriculture sector (with a lower EMR) the required capital assets in the industry and services sector (with a higher EMR). In spite of the fact that the share of the GDP re-invested into the economy has been over 35% in the period - according to the OECD statistics mentioned in Table 1 – the EMR_{PW} has decreased from 17.5 MJ/h in 1990 to 15.8 MJ/h in 1990. The opposite pattern is found for EMR_{HH} – in our analysis the energy investment for sustaining the material standard of living experienced at the household sector - which went from 0.6 MJ/h in 1990 to 1.5 MJ/h in 1999. Similar to what was said for the benchmark of Economic Labour Productivity, such a relative increase can appear impressive, but remains in a range of very low values, when compared with the analogous value of OECD countries (4 times higher).

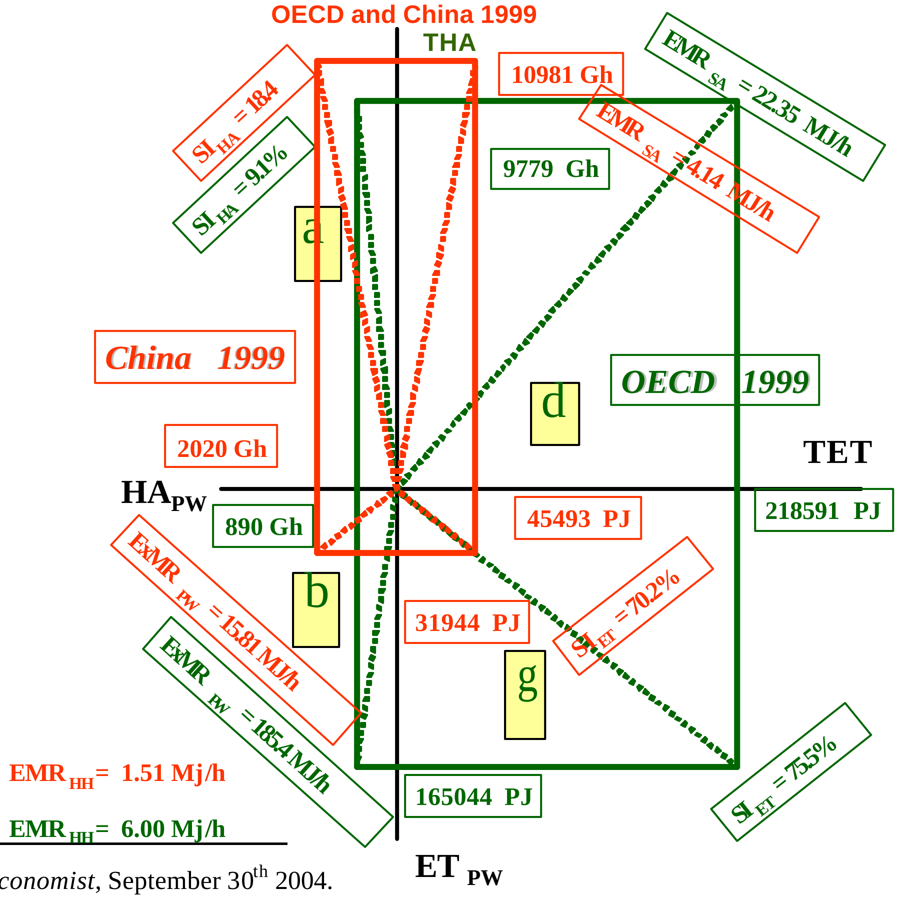
At this point, it is possible to have a visual comparison of the two ILAs (and the relative differences of benchmarks values). This comparison is given in **Fig 53**. There we can clearly see key structural differences between the characteristics of the exosomatic metabolism of China and the OECD countries. The former is based on cheap labour and on a large fraction of THA invested in labour, whereas the latter is based on both heavy energy consumption associated with a high level of exosomatic energy metabolism of the economy. The combination of these two factors is driving economic productivity. Using MSIASM benchmark system we can detect these difference by looking at the huge differences in:

* a angle – the intensive variable SI_{HA}- which is more than the double in China (18.4) than in the OECD cluster (9.1);

* b angle – the intensive variable EMR_{PW} – which is almost twelve time higher in the OECD cluster (185.4 MJ/h) than in China (15.8 MJ/h).

The two development models are different in essence, but it is well known that the Chinese government wants to move towards the “occidental” model, by first focussing on both light and heavy industry, hoping to move later on to the tertiary sector. From a world point of view, this move may have, and actually is already having, tremendous side effects on other countries economies. For example, China has already become a net importer of those materials needed to supply their increasing industry and local consumption. As result, China is already the world’s biggest consumer of many raw materials and commodities such as steel, copper, coal and cement, and the second biggest consumer of oil, after the USA[94].

Figure 53: ILA for OECD and China 1999



---

[94] *The Economist*, September 30th 2004.

Table 2: ILA for OECD and China 1999

	THA Gh	TET PJ	HA_{PW} Gh	ET_{PW} PJ	EMR_{SA} MJ/h	$ExMR_{PW}$ MJ/h	SI_{HA} %	SI_{ET} %
China	10.981	45.493	2.020	31.944	4.14	15.81	18.4	70.2
OECD	9.779	218.591	890	165.044	22.35	185.4	9.1	75.5

In addition to the implications for other countries (China/rest of the world) there are important internal implications (China/lower level elements). We discussed already the dilemma implied by the transition from an economy mainly based on agriculture to an economy based on a full take over of the secondary and tertiary sectors. This transition impose a dilemma between the need of investing in the necessary capital assets for the workers moved away from the agricultural sector to conduct their new set of economic activities versus the need of increasing investments and consumption in the household sector to improve the material standard of living of population. For instance, there is already a huge problem of hidden unemployment in the industrial rustbelt of the northeast. There the figure is more like 20 per cent. This goes hand in hand with the closing of government-owned enterprises, which implied that between 1996 and 2000 the government laid-off 31.4 million workers from public enterprises (ASRI, 2002: 27).

On the other hand, leaving the market free to organize the exosomatic metabolism of China, means expecting in the future that autocatalytic loop in societal metabolism (more profit making possible to invest more effectively in generating more profit) will enhance the already important gradients of development within the country. That is, we can expect that in a regime of total economic freedom for the market, sooner or later at the level n-1 (inside different parts of China) we will find an increasing difference in the pace of exosomatic metabolic rates and capital formation in different regions. For instance, in the year 2000, the gross capital formation of the Beijing region was 61%[95] of total gross capital formation in China. Obviously, this figure makes evident a widening gap with other rural regions that are able to invest only a smaller fraction of a smaller regional GDP. It is well known that behind the incident experience at Tiananmen square, at that time China was

---

[95] China Statistical Yearbook 2001, China Statistics Press, available at http://chinadatacenter.org/

experiencing a big tension between the rich provinces of the South willing to re-invest their profit in their local economies, rather than sharing these financial resources with less developed provinces.

10.5.2. Future scenarios for China

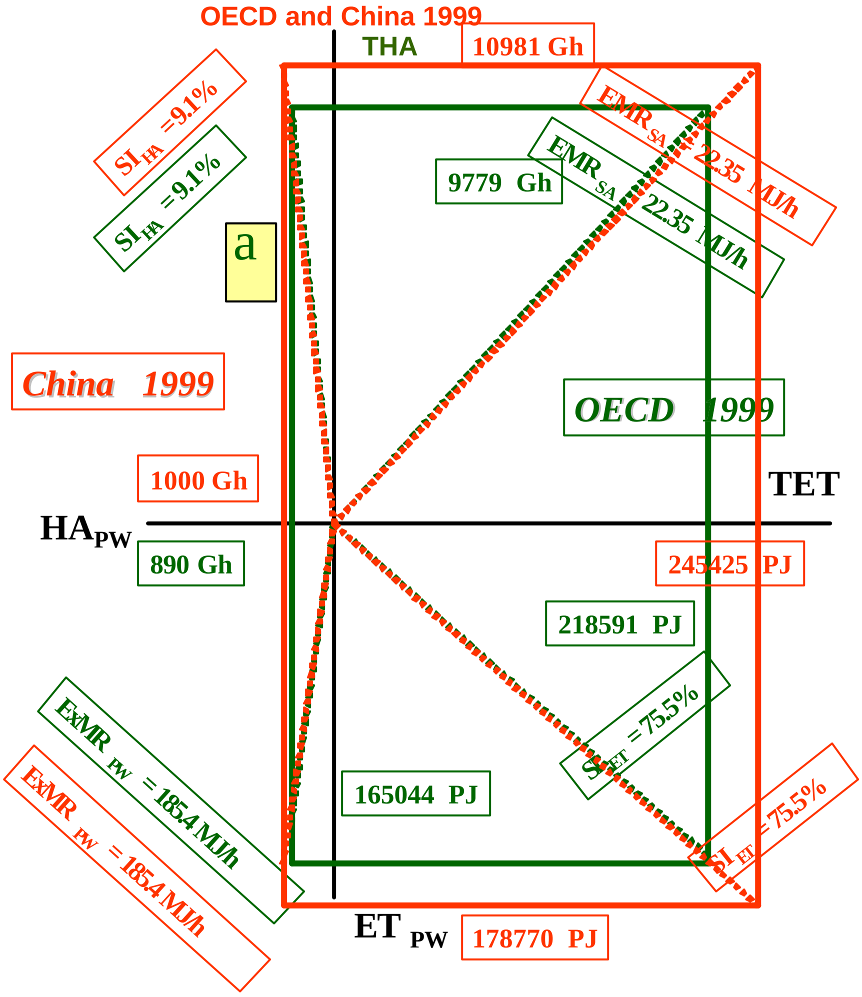
At this point, we can finally check the feasibility and likelihood of scenarios of future changes in the characteristics of the exosomatic metabolism of China. As we have already seen in previous figures, there are some values for the energy benchmarks that are found to be pretty stable for certain countries – as if they were the result of the existence of attractors determined by reciprocal constraints that lower-level characteristics impose on higher level characteristics and vice versa. Using this rationale, we can imagine that the future socio-economic development of China will follow the same development path of OECD countries. If this hypothesis is true, when China will reach the same level of economic development experienced by OECD countries today, then we should find for the benchmark values characterising the exosomatic metabolism of China, the same set of characteristics found for OECD countries today.

Table 3: Hypothetical ILA for OECD and China 1999

	THA Gh	TET PJ	HA_{PW} Gh	ET_{PW} PJ	EMR_{SA} MJ/h	$ExMR_{PW}$ MJ/h	SI_{HA} %	SI_{ET} %
China	10.981	***245.425***	***1.000***	***178.770***	***22.35***	***185.4***	***9.1***	***75.5***
OECD	9.779	218.591	890	165.044	22.35	185.4	9.1	75.5

To visualise such a possible future we can just impose the values typical of developed countries over the set of 4 benchmark expected for the 4 angles of the ILA to the population size – THA – of China today. This is done in **Fig 54**. In this way we can get, for China, the total exosomatic energy requirements associated with such a scenario (the resulting value of TET found on the right axis). This would imply that if China had today the same set of characteristics of its exosomatic metabolism found, as average, in the OECD countries, it would have a total consumption of 245,000 PJ. This would represent an increase of more than 5 times of the actual consumption of 45,500 PJ.

Figure 54: Hypothetical ILA for OECD and China 1999



Obviously, in order to be able to find this number, we did not need to get into the troubles of defining 4 angles for the ILA of both China and OECD countries. We could have just multiplied the level of consumption per capita of OECD countries by the population size of China. But at this point we can appreciate the peculiarity of the MSIASM approach. By looking at the whole set of different benchmarks it becomes possible to check whether a different path of development is possible for China. This can be done by looking at the feasibility and expected implications associated with the changing or the keeping of the value found for each one of the key benchmarks. Let us start by considering and explaining the characteristics associated with the benchmarks expressing the largest gradients in values.

* a angle – the intensive variable SI_{HA}- the value of this variable is more than the double in China (18.4) than in the OECD cluster (9.1). The characteristics that explain this difference are: (1) the dependency ratio. That is in China 40% of the population is dependent on 60% of the population that is working. This value is about 50/50 in OECD countries, with a tendency for those society at zero growth population (such as European Union and Japan) toward a reverse relation of 60% of population which is dependent on a 40% of population which is working. (2) the work load per year for working population. This value in China is absolutely high – around 2,800 hours of work/year – especially when compared with developed countries – where it ranges from 2,000 to 1,700 hours/year. What can we say about the future trends of these two characteristics that determine the peculiarity of the value of the for a angle China? In relation to the demographic structure that is determining a peculiar high fraction of working population, we must note that this is a temporary characteristics, generated by the implementation of policy of population control in the last 30 years. Not only this favourable situation is temporary, but implies an important and serious legacy.

“During the next 50 years China will experience a **dramatic population aging**. According to this most recent UN population projection (the 1998 Revision) China will have about 630 million people age 50 and above in 2050 - while there will be only some 78 million children below the age of 5 and just 324 million children and teenagers below the age of 20. In other words: by 2050 China will have almost twice as many people above age 50 than below age 20” - Heilig (1999). This means that a strategy of economic development based on cheap labour and fuelled by the abundant supply of human activity for working can no longer be feasible in the future. In relation to the second peculiarity – the incredibly high work load per year of Chinese workers – it should be noted that according to Zipf (1941) in order to be able to produce more, an economy must invest more of the available human activity in consuming. This must include an increase in the fraction of their human activity that adults can invest in leisure (= a reduction in the work load per year). When looking at both aspects it looks very improbable, that China will keep in the future the existing peculiarity in relation to this benchmark, and that sooner or later we can expect a movement toward the values found in developing countries.

* b angle – the intensive variable EMR_{PW} – the value of this variable is almost twelve times higher in the OECD cluster (185.4 MJ/h) than in China (15.8 MJ/h). We already discussed in details the reasons that are keeping the value of EMR_{PW} low. So that in this section we will focus on the consequences. A low value of EMR_{PW} translates into an obliged choice of a strategy based on export of labour intensive commodities. However, this strategy can become a trap if in the medium/long term the import of capital intensive goods fuelled by a growing internal demand is not replaced by an internal production of capital intensive goods. This requirement of an expansion of the supply of the PS sector (ET_{PS}) coupled to a decrease of HA_{PW} for the reasons discussed in the previous sector will result in an unavoidable dramatic increase in the value of EMR_{PS}. This can be easily guessed either by looking at the very low values found today for this benchmark in China even when looking at analogous values found in other developing countries, then by reasoning that much more products will have to be produced with less working time.

* d angle - the intensive variable EMR_{SA} – at this point it should be noted that Zipf's rational (if an economy wants to be able to produce more, it has to invest more in consuming) can also be applied to the overall balance between investments of both Human Activity and Exosomatic Energy over the compartments associated with producing (those belonging to PW) and with consuming (those belonging to HH). That is, the overall Exosomatic Metabolic Rate referring to the societal average (EMR_{SA}) will reflect the balance of investment among the two options: (i) producing more; versus (ii) consuming more. That is, this would imply a balancing over the two levels of metabolic rate of the PW and HH sectors (EMR_{PW} and EMR_{HH}). Huge differences of the values found for these two benchmarks from expected average can be used to explain peculiar behaviour of individual countries. For example, Ramos-Martin (2001), explained the peculiar behaviour of Spanish economy - the only developed economy that is not dematerialising [= reducing the

energy intensity of its economy in time] over the period 1980 – 1990 – with the peculiar low value of the benchmark EMR_{HH}. The value of EMR_{HH} for Spain in 1976 was 1.67 MJ/hour (much lower than in other European countries) whereas it raised to 3.27 MJ/hour in 1996. The big gradient when comparing to other similar countries is the explanation for the peculiar behavior of Spanish economy when coming to the energy intensity of its economy over the period 1976-1996. What are the consequences of this lesson learned about the past economic development of Spain for the future development of China, in which both the PW sector and the HH sector are heavily undercapitalised (= we mean sectors characterised by a benchmark value much lower than the one expected).

It is time to look at possible implications associated with the differences of values found for the characteristics of the exosomatic metabolism of China, in terms of future scenarios of development, options, risks and uncertainty.

Point #1 - a first crucial aspect will be the ability to keep coherence in the process of governance of the big transition ahead. As illustrated by the study of Ramos-Martin (2001) in Spain, in that country the combined effect of a limited population growth and a restrictive policy of the dictatorship in the previous decades (the so called 'Franco era') managed to compress the consumption. That is, the surplus generated by the Spanish economic process was mainly invested in providing energy availability for the PW sector (in increasing the EMR_{PW}) rather than increasing the material standard of living of the HH sector. This left a mark in Spanish economy in the form of a very low level of EMR_{PW}, but made it possible for Spain to catch up with the average value found for EMR_{PW} in other OECD countries. The same strategy of compression of final consumption in favour of a fast capital accumulation of the economy was adopted by other countries during their transition toward a developed economy. For example, Italy, Germany, Japan, and now Korea are all examples of countries that used tough measures of control on personal freedom to get through the period of compression of final consumption used to boost the speed of capital accumulation of the economy. Would the same strategy be possible in China?

For sure boosting of the level of capital accumulation of the PW sector as fast as possible must be a key strategy for the Chinese government. Such a strategy is necessary to keep as high as possible the level of investment in capital and infrastructure. Otherwise, when the population boom will get to an end, China may face a failure, with an economic sector based on cheap and abundant labour, that would no longer be able to generate enough surplus of added value to support a larger fraction of dependent population. On the other hand, the opposite policy of boosting the material standard of living as fast as possible, also should represent a top priority. If China continues to hold down the material standard of living of a large fraction of the population (in rural areas, in marginal social groups in urban areas) we may see an increase in the level of social unrest (with even more demonstrations, strikes, and violence[96]).

Point #2 - a second crucial aspect will be the ability to prevent the possibility of a breakdown of the social fabric due to the increasing tension between the rich south-east coastal zones, and the poor interior and former industrial area of the north east. As discussed earlier, the forces of free market that are so good at boosting the efficiency of the production and consumption of goods and services within a socio-economic process, tends to preserve and amplify gradients. Again, the tension among different parts of China already generated a lot of troubles in the recent past (rural vs urban; South-East vs North). This forces the government to face another daunting dilemma: (i) going for a maximisation of economic efficiency by leaving the market forces operate free from constraints; or (ii) giving priority to the unity of the country, by reducing the generation of the much needed economic surplus, to avoid the exacerbation of existing gradients of development.

---

[96] The BBC June 8th 2004 reported in year 2003 more than three million people took part in protests according to Chinese official data. On July 19th 2004 BBC reported that in year 2003 poverty rose for the first time in 25 years, widening the gap between urban and rural incomes. This may explain why in year 2004 the government decided to increase subsidies for agriculture (10bn Yuan ($1.2bn) in subsidies for farmers who grow rice and other grains, BBC November 19th 2004). On September 9th 2004 *The Economist* reported that even though the official estimate for urban unemployment was of 4.7% the unofficial was closer to 8 %, with more than 150 million people living in countryside accounted as peasants who would otherwise be unemployed.

Point #3 – a third crucial aspect is related to what will happen in the future with demographic variables. Looking at the past changes of demographic structure of China and at future projections (**Fig. 55**), one can notice the presence of echo-effect. That is after 20 year of a baby boom it is likely to get another one. We can use again two quotes from Heilig (1999) to summarize the main implications of this situation:

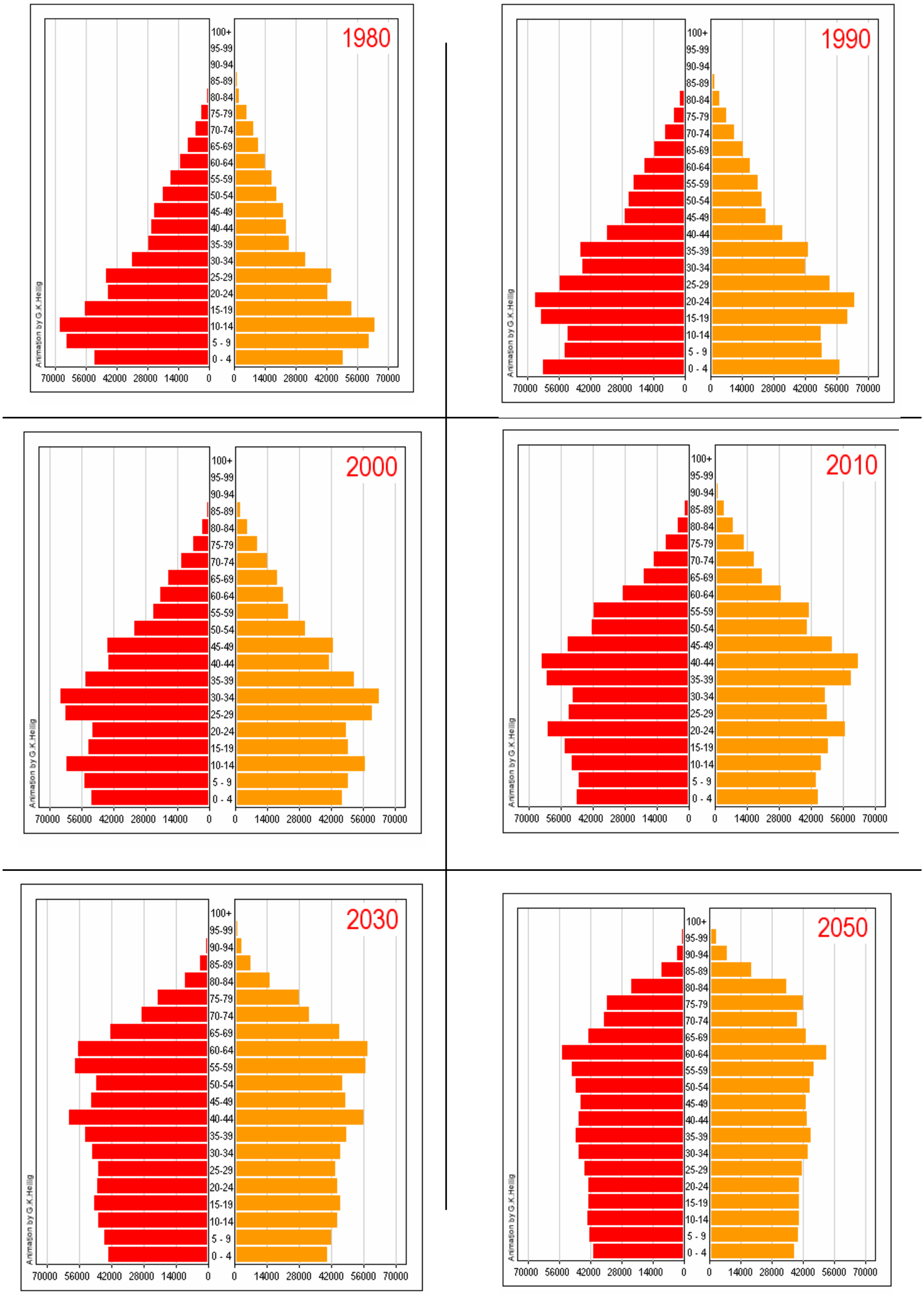
[1] “Looking at the change of the population pyramids one can see how the "baby boom" generation from the 1960s and early 1970s "moves up" the age pyramid. The animation also visualizes the *aging* of the Chinese population, which is caused by the significant fertility decline since the mid-1970s (and the further increase in life expectancy)”.

[2] “The number of young adults of *reproductive age* (20 - 50) will reach its maximum of more than 660 million around 2010. This explains why the **period between 1995 and 2025** is the **most critical** for the country's future population growth”.

These two quotes point at another daunting dilemma faced by Chinese government: (i) keeping a strong control on population to prevent a re-starting of high rate of population growth, but this implies getting into the problem of a large fraction of elderly; or (ii) increasing the number of young people entering into the Chinese economy, even if this can imply getting back to an increase of population size.

Concluding this overview of possible scenarios of development for China, we can say that the MSIASM approach does not represent a magic tool enabling analyst to predict the future. Rather, it makes possible to look at hidden relation, hidden biophysical constraints, and changes affected by lag-time that often tend to be neglected when perceiving and representing changes only on a single time scale.

Figure 55: China Population Pyramide 1980 – 2050



Source: Heilig 1999.

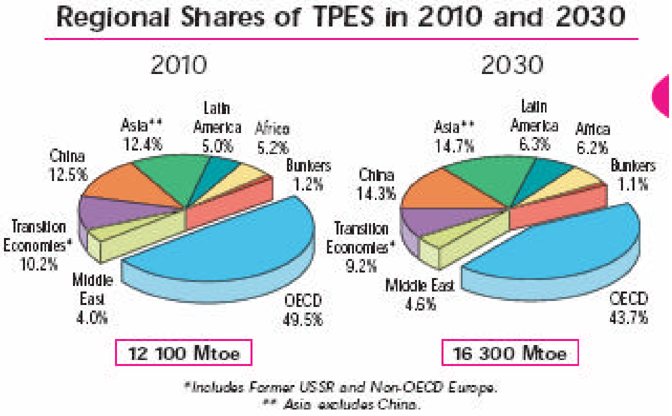
10.5.3. Possible impact of China development on world demand for oil

The present high price of oil in international markets is driven by several factors, among them spare capacity being currently tight, but also rising demand in China and other developing countries. This tendency goes back to late 1990s when China started its enormous economic growth.

As IEA (2003: 237) said, "China, the world's second-largest consumer of primary energy, is a key player in world energy markets, accounting for more than 10% of the world's total primary energy demand. It will continue to be an energy giant in the coming decades as strong economic growth drives up energy demand and imports"… "By 2030, net oil imports are projected to reach almost 10 mb/d – more than 8% of world oil demand. Imports will also have to meet 30% of the country's natural gas needs in 2030".

The result is, as *The New York Times* of February 18th reports based on IEA data, that Chinese oil imports have risen in the last ten years (from 1994 to 2004) a 31 % which translates into 3 million barrels a day. To make a comparison, Japanese imports are at the range of 5.3 million barrels a day. This "thirst for oil" is what is driving Chinese companies to bid for prospecting rights all over the world, as was mentioned before.

Figure 56: Regional Shares of TPES in 2010 and 2030



*Includes Former USSR and Non-OECD Europe.
** Asia excludes China.

Source: IEA 2004, p. 47.

The pressure by China and other developing countries over the available Total Primary Energy Supply is shown in **Figure 56**. There we can see how IEA is forecasting China accounting for 14.3% of world's energy demand by year 2030. What we want to emphasise here is the fact that at a global level, Chinese economic development is putting a lot of pressure on international markets for raw materials and oil in particular. Due to the size of both China and India, and the large room for expansion of their economies, this raising demand is very likely to continue for a long period of time. The Chinese strategy is very clear: they need to grow and they will do it by using and transforming increasing amounts of materials and energy. This is required in order to generate enough added value capable not only of absorbing huge amounts of redundant farmers, but also of providing the means to make a real Great Leap in technological terms. This pushes for an increase adoption of oil as a final energy carrier, but also for the development of better technologies in the use of coal. In fact, China has the third largest coal reserves in the world[97]. However, before being able to exploit such a potential what is needed is a proper technology (gasification) in order to generate high quality energy to be used throughout modern economic sectors. This implies that in the short/medium term, China will need to use huge and increasing amounts of existing high quality energy such as oil in order to run the economy and support such a technological change. These facts seem to support the hypothesis that the present situation of high prices at international level is going to be structural for a quite long period of time. That is, that oil prices to remain over 40 dollars a barrel in the short and medium term, if not higher. At this regard, the bank UBS at Hong Kong[98] studied the relation between Chinese oil imports and oil price. When the increase in oil prices is compared with the evolution of Chinese oil imports it is possible to note that the two lines go pretty parallel **Figure 57.** This in spite of the fact that China accounts for only 8% of global oil consumption. This seems to indicate that the relation between supply and demand of oil is affected not only by economic variables, but also by biophysical constraints. This entails that relative small increases in demand can have important

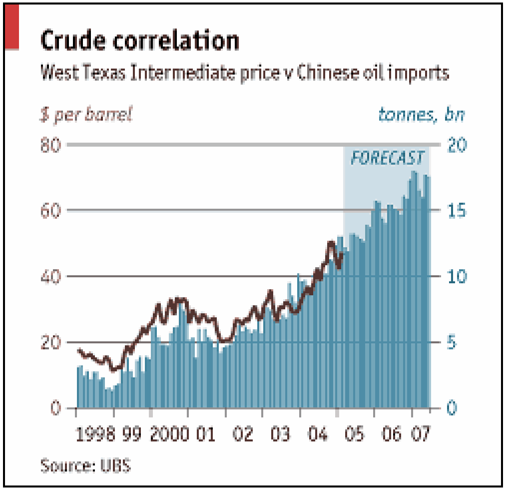
---

[97] According to the World Energy Council, http://www.worldenergy.org

[98] As reported by *The Economist* of February 17th 2005

consequences on the price. This is why the Secretary General of OPEC suggested in a press conference in February 2005[99] that oil prices may hit the 70$ a barrel mark in a couple of years.

Figure 57: oil real prices



Source: *The Economist*, February 17th 2005.

10.6. Conclusion

This chapter was aimed at analysing the characteristics of exosomatic energy metabolism of China by looking at the level of the nation on the interface with the world level, and at the level of the economic sectors of China interfaced with both the national level on the higher level and sub-economic sectors on the lower level. This exercise allowed us to show the potentialities of the methodology called MSIASM for the analysis of the relationship between economic development, population dynamics, technology, natural resources and environmental impact at different scales.

A similar analysis has been carried out before, but only looking at the national level and lower levels for the economies of Ecuador (Falconi, 2001), Spain (Ramos-Martin, 2001), and Vietnam (Ramos-Martin and Giampietro, in press).

In relation to the usefulness of MSIASM approach

---

[99] BBC News, March 4th 2005.

In our view the analysis presented so far shows that MSIASM is an useful tool for organising and performing an integrated and multi-scale analysis of changes in the characteristics of socio-economic systems. The information space generated by MSIASM implies the simultaneous use of different variables, which can be used to generate parallel descriptions of the same set of events at different levels and in relation to different selections of observable qualities. Of course, we do not claim nor believe that MSIASM is the only approach that should be used for integrated analysis of sustainability. Rather, we claim and believe that MSIASM allows a better understanding of the complexity of the sustainability problem and that it provides a very useful structuring of the information used to characterise the system under analysis. It defines benchmark values that can be related to lower level characteristics of the socioeconomic system and that can be compared with other socio-economic systems. It makes possible to formulate hypothesis to explain differences from expected values. It makes possible to blend historic series and variables belonging to different disciplinary fields. We believe that a MSIASM analysis helps in having an informed discussion on development scenarios.

In relation to the future of China

We firmly believe that the discussion of scenarios and policy options of China should be made by the Chinese people. One remarkable characteristics of the ILA approach is that it requires an input from the social system investigated to define how to best characterise it. Therefore, we do not believe that the analyses we presented here should be considered as substantive assessments of the Chinese dilemmas. Rather, the goal of this exercise was to show that by applying this type of analysis it is possible to gain coherence in the resulting integrated analysis across levels and disciplines. So far the Chinese government showed to be well aware of the intricate complex of constraints and opportunities and showed a remarkable ability to develop creative and effective policy. For sure, there are a lot of problems and challenges ahead.

Regarding the discussion over the future of China, which is going on among western scientists the data we show here clearly tend to indicate that China is not following the hypothesis of the inverted-U curve for energy intensity [= the so called dematerialisation hypothesis]. On the contrary, the huge development of China started when economic liberalisation was introduced in the economy priming a clear rise in energy and materials consumption. This is not a surprise for us, using MSIASM for some time now. According to the set of benchmark values found when characterising Chinese exosomatic metabolism China still belongs to the typology of developing countries. This is not good news for world resources, because of its huge size of population and enormous gradients for further increases of both energy and materials consumption per capita. We can expect that in spite of the fairy tales about tunnels under the Kuznets' curves, the amount of resources (both energy and material) metabolised by China in the future will grow dramatically, following Ostwald's predictions (Ostwald, 1909).

When analysing population structure and actual trends, we can individuate a very special characteristics of China in relation to the rest of developing countries. The large fraction of working force in the population. This fact, on one side provide an advantage for the country by reducing the societal overhead on Human Activity, that is cheap and abundant labour to be used to fuel labour intensive economic activities. On the other hand, this fact may represent an Achilles' heel for the future development of this society, when the large mass of adults will transform into a large mass of elderly. The combined effect of demographic growth and the distribution of the population over age classes has put China, despite the huge efforts of economic development, in the same side of Ecuador regarding the spiral of development (Falconi, 2001). That is, in spite of the high rate of investments in its economy China cannot get the necessary leap to bring it to the positive spiral of economic growth → investment in capital → making more energy available for the economy → the growing of EMR_{PW} → increasing ELP → generation of more surplus that can be used to further increase the value of EMR_{PW}.

In relation to the effect that the economic growth of China will have on world energy demand

From what said in the previous section, no matter if China wins or loose the battle to get into a positive spiral of growth, it will keep a high the pressure for natural resources in general, and energy in particular on the world market. China has the third largest coal reserves in the world, but for pollution and efficiency reasons, it must develop new technologies - such as gasification - for making a better use of it. Developing those technologies will require huge amounts of oil. Moreover, in spite of huge improvements in energy efficiency, Chinese economy is consuming more and more energy despite its shifting from coal to oil and gas. These facts explain why China is not only a key player at the international energy market as a buyer now, but why China is starting to buy prospecting rights everywhere, and oil and gas facilities to satiate its long term thirst for energy carriers. The conclusion is that unless the extraction and refining facilities are increased at the world level, and political agreements are reached among the producers to keep increasing the volume of oil extraction, Chinese pressure will keep oil, gas, coal, and construction materials prices high in the near future.

Conclusion

This conclusion is dedicated to four tasks: (i) pin-pointing some theoretical aspects relevant for the analysis presented in combining economics with complex systems, and thermodynamics; (ii) Developing on the usefulness of using MSIASM for analysing sustainability, with especial regard to the issue of multiple scales; (iii) Driving some non substantive conclusions for the case studies analysed in the text, particularly Spain, Viet Nam and China, and (iv) finally, grasping which may be the future direction of my research in the coming years in relation to the exosomatic energy metabolism of societies.

From a theoretical point of view

The thesis has shown how when analysing economic development and its relationship with the relative environmental impact one has to deal with the interaction of ecosystems and economic systems considered both as complex, nested, hierarchical systems. In this case, an integrated approach such as the one presented here offers some advantages since it links the economic reading to the biophysical reading, as well as it offers the possibility to gather data on different hierarchical levels.

This multi-scale integrated approach does not give as a result, substantive findings on how systems evolve, and therefore does not allow making predictions. However, as it was said in the text, such kind of approaches allow us to prevent Rosen's *global failure* since we are not adapting reality to our categories of analysis by means of policy, but rather we are adapting our categories of analysis to reality.

This approach is useful therefore for discussing about the present and for evaluating future scenarios. We believe that the selection and discussion of scenarios has more to do with the selection of useful narratives (i.e. soft modelling) rather than with forecasting (i.e. hard modelling). This is so because of the nature of complex adaptive systems, characterised by irreversibility and stochasticity in their evolution. The existence of numerous possible future trajectories associated with high levels of uncertainty (the sure emergence of novelties) implies that their future is largely unpredictable. We have to admit that there are no deterministic explanations (universal and a-historical) for the present states of complex adaptive systems. Rather we can describe and understand these systems by finding historical and spatial regularities, and by looking at the emergence of specific systems' properties. This still requires finding useful types for conducting research at the different levels. However, the selection of types must be later on tailored for coping with the particularities of specific situations. In this way, we can inform the decision process about the possible constraints implied by different courses of action. In our view, this translates into improving the quality of the narratives used to characterise, analyse, and describe the behaviour of complex system such as ecosystems, economies, and their interaction.

On the usefulness of MSIASM

In our view the analysis presented in this thesis shows that MSIASM is an useful tool for organising and performing an integrated and multi-scale analysis of changes in the characteristics of socio-economic systems. The information space generated by MSIASM implies the simultaneous use of different variables, which can be used to generate parallel descriptions of the same set of events at different levels and in relation to different selections of observable qualities.

The generation of a "mosaic effect" among the various pieces of information improves the robustness of the analysis and the possibility of getting new insights generating synergism in the parallel use of different disciplines.

MSIASM therefore can provide:

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

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

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

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

These characteristics of the MSIASM approach make it suitable for both carrying out historical analysis and for prospective analysis.

On the case studies analysed

The particular results for each of the countries analysed are presented in each of the chapters, however, putting together some words for each of them may allow grasping some of the potentialities of this accounting system.

In the case of Spain, it was clear that the country was not following the so-called hypothesis of dematerialisation. With MSIASM we were able of giving some of the reasons why.

When considering the dynamic of economic development, we have shown Spain was able to take the other side of the bifurcation (when compared to Ecuador), thanks to the different characteristics of its energy budget. In particular low population growth was crucial in setting the trajectory into a positive spiral.

We also showed how the household sector was responsible for such behaviour, by showing the evolution, and increase, in the level of energy use of the household sector.

In the case of Ecuador, MSIASM allowed to better understand, apart of the typical evolution of energy flows and the causes of that evolution, some demographic tendencies such as emigration. Just looking at the graphs presented in Chapters 7 and 9, one could interpret that the major problem of Ecuador has been generated by a sudden increase in population that has induced a stagnation of the economic productivity of labour due to a low exosomatic energy metabolic rate of economic sectors. Therefore, one of the ways out of this impasse was that of allowing a fraction of the work force to emigrate. This is exactly what happened in Ecuador in the recent years. However, the mistery remains of why an energy-exporting (and net material exporter) such as Ecuador, could not use *internally* such natural resources for domestic capital accumulation.

In the case of Viet Nam, the analysis showed the biophysical constraints that are limiting not only current development in the country, but also that are going to impose severe pre-requisites for future action delimiting a reduced degree of freedom in the policies to be taken in order of escaping the fatal spiral of more population growth, more dependence on low skills labour intensive exports that the country is heading to nowadays.

Regarding the discussion over the future of China, which is going on among western scientists, the data we showed here clearly indicated that China, as Spain, is not following the dematerialisation hypothesis. On the contrary, the huge development of China started when economic liberalisation was introduced in the economy priming a clear rise in energy and materials consumption. MSIASM also allowed seeing which were the likely repercussions of Chinese development upon other economies, mainly in regard to the world energy market, and particularly that of oil. We can expect that in spite of the fairy tales about tunnels under the Kuznets' curves, the amount of resources (both energy and materials) metabolised by China in the future will grow dramatically.

The approach also helped us to interpret Chinese evolution in terms of its demographic behaviour. The combined effect of demographic growth and the distribution of the population over age classes have put China, despite the huge efforts of economic development, in the same side of Ecuador regarding the spiral of development. That is, in spite of the high rate of investments in its economy China cannot get the necessary leap to bring it to the positive spiral of economic growth → investment in capital → making more energy available for the economy → the growing of EMR_{PW} → increasing ELP → generation of more surplus that can be used to further increase the value of EMR_{PW}.

On future research

As it has been said throughout the text, this thesis does not have the aim of being comprehensive, or substituting other kinds of analyses in regard to the role of energy for economic development. Rather it represented an innovative contribution to the always increasing research on economies as complex systems. However, maybe because of its innovative character, the analysis has some lacks. For instance, it could have been improved if we accounted for energy quality. That is, different energy carriers are better suited than others for different activities. For instance, we cannot use oil directly for feeding us, but we can transform that energy carrier, to help in the industrial process of food production. But we can neither use oil for running the computer with which this thesis was written, and we need to convert it into electricity. These examples imply energy is not heterogeneous at all. Different energy carriers imply that different economies may have the same economic results in terms of added value with totally different energy mix. Therefore, future research must tackle the issue of energy quality to improve the quality of the information generated for describing the behaviour of economies.

Another issue which could have improved the work presented here would be not focusing on energy consumption at the different levels of the system (even if accounting for different energy quality), but on power. Ayres and Warr (2005) have done something similar for the US economy by using final energy and physical work done. As explained in the first part of this thesis, energy analysts have considered, since long ago, that the relevant variable when analysing systems is power, or the ability to carry out work. This is related to the previous issue, since different carriers deliver different power. In our case, and this is an issue the author is well aware, particularly after long discussions with the developers of the MSIASM methodology Mario Giampietro and Kozo Mayumi, accounting for power would better represents systems' behaviour. The hypothesis is that when accounting for power, we are using a better proxy variable for dealing with the organisation of societies. Let us use an example. The Russian levels of consumption of energy are closer to those of the USA than to those of the EU, whereas one can easily see that the material standard of living of Russia is closer (though lower) to the EU than to the USA. This might be because when considering just energy consumption, we are not accounting for differences in efficiency, which is crucial for the final outcome. Our belief is that accounting for power would even make more evident there are some clear typologies of countries in regard to energy metabolism. Of course, data on power is not available, and building up databases is time costly and requires a high degree of subjectivism which was out of the scope of this thesis, but which is fundamental for my future research on the topic.

A third aspect that could have improved the analysis is that of the spatial scale. When using the national level as the focus level of analysis, one losses lot of relevant information on the regional differences one might find within a country. This fact, relevant by itself, is of particular importance when dealing with huge economies such as China. As it was said in the text, data permitting, one could find different typologies at the sub-national level, which would improve the resulting analysis.

A last observation is with regard to the impact upon the environment. So far, energy consumption is used in this work as a kind of proxy for environmental impact. This assertion has many criticisms. First, as said before, environmental problems are nowadays more related to sinks (and waste disposal) than to resource scarcity. Second, unless we account for both the energy quality, and the efficiency of the different processes of energy conversion, straight value judgements on the use of certain amount of energy can not be made.

In any case, all these limitations of the present analysis do not reduce the credit of what was presented here, but rather must be taken as ways of improving it.

Therefore, there is still a lot to do in the field of exosomatic energy metabolism of societies, and I hope I can still contribute somehow in the future.

Bibliography

Adams, R.N. (1987) "Some observations on social evolution from an energy structure approach", *European Journal of Operational Research*, 30: 193-202.

Adams, F. G. and Miovic, P. (1968): "On relative fuel efficiency and the output elasticity of energy consumption in western Europe". *Journal of Industrial Economics*, 17: 41-56.

Adriaanse, A. et al. 1997. *Resource Flows: The Material Basis of Industrial Economies* (a joint publication of the World Resources Institute (WRI); the Wuppertal Institute; the Netherlands Ministry of Housing, Spatial Planning, and Environment; and the National Institute for Environmental Studies, Washington, DC).

Agras, J., and Chapman, D. (1999) "A dynamic approach to the Environmental Kuznets Curve hypothesis", *Ecological Economics*, 28: 267-277.

Anguiano-Téllez, M.E. (2002) "Emigración reciente de latinoamericanos a España: trayectorias laborales y movilidad ocupacional", *Papeles de Población*, num. 33: 101-115, Julio/Septiembre. México.

Arrow, K., Bolin, B., Costanza, R., Dasgupta, P., Folke, C., Holling, C.S., Jansson, B., Levin, S., Mäler, K., Perrings, C., and Pimentel, D. (1995) "Economic growth, carrying capacity, and the environment", *Science*, 268: 520-521.

ASRI (2002): *Labour Standards in China, the Business and Investment Challenge*, December 2002, Association for Sustainable and Responsible Investment in Asia.

Ayres, R.U. (1995) "Economic growth: politically necessary but *not* environmentally friendly", *Ecological Economics*, 15: 97-99.

Ayres, R.U. (1997) "The Kuznets curve and the life cycle analogy", *Structural Change and Economic Dynamics*, 8: 413-426.

Ayres, R.U. (1998) "Eco-thermodynamics: economics and the second law", *Ecological Economics*, 26: 189-209.

Ayres, R.U (1999) "The second law, the fourth law, recycling and limits to growth", *Ecological Economics*, 29: 473-483.

Ayres, R. U. and Kneese, A.V. (1969) "Production, Consumption and Externalities." *American Economic Review* 59(3):282-297.

Ayres, R.U., and Simonis, U., (eds.) (1994). *Industrial Metabolism: Restructuring for Sustainable Development*. Tokyo: United Nations University Press.

Ayres, R.U., and Warr, B. (2005) "Accounting for growth: the role of physical work", *Structural Change and Economic Dynamics*, 16: 181-209.

Barbé-Duran, Ll. (1996) *El curso de la economía. Grandes escuelas, autores y temas del discurso económico.* Ariel, Barcelona.

Barbier, E.B., and Markandya, A. (1990) "The conditions for achieving environmentally sustainable growth", *European Economic Review,* 34: 659-669.

Barnett, H.J., and Morse, C. (1963) *Scarcity and Growth: The Economics of Natural Resource Availability.* John Hopkins, Baltimore.

Baumgärtner, S., Dyckhoff, H., Faber, M., Proops, J., and Schiller, J. (2001) "The concept of joint production and ecological economics", *Ecological Economics* 36: 365-372.

BBC News http://news.bbc.co.uk June 8th 2004, July 19th 2004, November 19th 2004.

Beard, T.R., and Lozada, G.A. (1999) *Economics, Entropy and the Environment. The Extraordinary Economics of Nicholas Georgescu-Roegen.* Edward Elgar, Cheltenham.

Bergh, J., and Gowdy, J.M. (2003) "The microfoundations of macroeconomics: An evolutionary perspective", *Cambridge Journal of Economics*, 27 (1): 65-84.

Bertalanffy, L. (1949) "The concepts of systems in physics and biology", *Bulletin of the British Society for the History of Science*, 1:44-45.

Bertalanffy, L. (1950) "An outline of General Systems Theory", *British Journal for the Philosophy of Science*, 1:139-164.

Bertalanffy, L. (1968) *General Systems Theory: Foundations, Development, Applications*. George Braziller, New York.

Binswanger, M. (1993) "From microscopic to macroscopic theories: entropic aspects of ecological and economic processes", *Ecological Economics*, 8: 209-234.

Boltzmann, L. (1872) "Weitere Studien über das Wärmegleichgewicht unter Gasmolekülen, Sitzungsber. Kais. Akad. Wiss. Wien Math. Naturwiss. Classe 66 (1872) 275–370. "Further Studies on Thermal Equilibrium between Gas Molecules" Wien Ber., 66, p. 275-370.

Boulding, K.E. (1987) "The epistemology of complex systems", *European Journal of Operational Research*, 30: 110-116.

Bruyn, S.M. (1999) "The need to change attractors", *Ökologisches Wirtschaften,* 3: 15-17.

Bruyn, S.M., and Opschoor, J.B. (1997) "Developments in the throughput-income relationship: theoretical and empirical observations", *Ecological Economics*, 20: 255-268.

Bruyn, S.M., van den Bergh, J.C.J.M., and Opschoor, J.B. (1998) "Economic growth and emissions: reconsidering the empirical basis of environmental Kuznets curves", *Ecological Economics*, 25: 161-175.

Buenstorf, G. (2000) "Self-organization and sustainability: energetics of evolution and implications for ecological economics", *Ecological Economics*, 33: 119-134.

Cabeza, M. (1996) "The concept of weak sustainability", *Ecological Economics*. 17: 147-156.

Cañellas, S., González, A.C., Puig, I., Russi, D., Sendra, C., and Sojo, A. (2004): "Material flow accounting of Spain", *International Journal of Global Environmental Issues*, Vol. 4(4): 229-241.

Carnot, S. (1824) *Reflexions sur la Puissance Motrice du Feu et sur les Machines Propres à Développer cette Puissance*. Chez Bachelier Libraire, Paris.

Carpintero, O. (2003a): "Los requerimientos totales de materials en la economía española. Una visión a largo plazo : 1955-2000", Revista de Economía Industrial, 351(III): 27-58.

Carpintero, O. (2003a): "Los costes ambientales del sector servicios y la nueva economía : entre la desmaterialización y el "efecto rebote"", Revista de Economía Industrial, 352(IV): 59-76.

Casler, S.D., and Blair, P.D. (1997) "Economic structure, fuel combustion, and pollution emissions", *Ecological Economics* 22: 19-27.

China Statistical Yearbook 2001, China Statistics Press, available at http://chinadatacenter.org/

Christensen, P.P. (1989) "Historical roots for ecological economics – biophysical versus allocative approaches", *Ecological Economics*, 1: 17-36.

Clark, N., Pérez-Trejo, F., and Allen, P. (1995) *Evolutionary Dynamics and Sustainable Development: A Systems Approach*. Edward Elgar, Aldershot.

Clausius, R. (1865) *Abhandlungen über die Mechanische Wärmetheorie*. F. Vieweg, Braunschweig.

Cleveland, C.J. (1987) "Biophysical economics: historical perspective and current research trend", *Ecological Modelling*, 38: 47-73.

Cleveland, C.J. (1999): "Biophysical economics: from physiocracy to ecological economics and industrial ecology", in Mayumi, K. and Gowdy, J.M (Eds.): *Bioeconomics and Sustainability.* Edward Elgar. Cheltenham, UK.

Cleveland, C.J., and Ruth, M. (1997) “When, where, and by how much do biophysical limits constraint the economic process: A survey of Nicholas Georgescu-Roegen’s contribution to ecological economics”, *Ecological Economics*, 22: 203-224.

Cleveland, C.J., Costanza, R., Hall, C.A.S., and Kaufmann, R. (1984) “Energy and the U.S. economy: a biophysical perspective”, *Science*, 225: 890-897.

Cleveland, C.J., Kaufmann, R.K., and Stern, D.I. (1998) “The aggregation of energy and materials in economic indicators of sustainability: thermodynamic, biophysical, and economic approaches”, in Ulgiati, S. (ed.): *Advances in Energy Studies*. Musis, Rome.

Cline, W.R. (1992) *The Economics of Global Warming*. Institute for International Economics, Washington DC.

Colectivo Ioé (Walter Actis, Carlos Pereda y Miguel Ángel de Prada) (2002): *Inmigración, escuela y mercado de trabajo: Una radiografía actualizada*. Fundación “La Caixa”. Colección Estudios Sociales num. 11. http://www.estudios.lacaixa.es

Costanza, R. (1980) “Embodied energy and economic valuation”, *Science* 210: 1219-1224.

Costanza, R. (1989) “What is ecological economics?”, *Ecological Economics*, 1: 1-7.

Costanza, R. (ed.)(1991) *Ecological Economics: The Science and Management of Sustainability.* Columbia University Press, New York.

Cottrell, W.F., (1955) *Energy and Society: The Relation between Energy, Social Change, and Economic Development*, McGraw-Hill, New York.

Cuc, L.T., and Chi, T.K. (2003) “Vietnam: Socio-Economic Development Strategy 2001-2020”, Presented at the *3rd Project Workshop Southeast Asia in Transition*, 2-6 June 2003, Vienna, Austria.

Dalmazzone, S. (1999) *Economic Activity and the Resilience of Ecological Systems.* PhD Thesis, University of York.

Daly, H.E. (ed.)(1973) *Toward a Steady-State Economics*. W.H. Freeman, San Francisco.

Daly, H.E. (1985) “The circular flow of exchange value and the linear throughput of matter-energy: a case of misplaced concreteness”, *Review of Social Economy,* 44: 279-297.

Daly, H.E. (1990) “Toward some operational principles of sustainable development”, *Ecological Economics* 2:1-6.

Daly, H.E. (1991) *Steady State Economics: Second Edition with New Essays*. Island Press, Washington DC.

Daly, H.E. (1992) *Steady-State Economics*. Earthscan Publications, London.

Daly, H.E. (1996) “Consumption: value added, physical transformation and welfare”, in Costanza, R., Segura, O., and Martinez-Alier, J. (eds.): *Getting Down to Earth*. Island Press, Washington DC.

Daly, H.E., and Cobb, J.B. (1989) *For the Common Good: Redirecting the Economy Toward Community, the Environment and a Sustainable Future*. Beacon Press, Boston.

Denzen, N. (1994) “The art and politics of interpretation”, in Denzen, N., and Lincoln, Y. (Eds.): *Handbook of Qualitative Research*. Sage Publications, London.

Denzen, N., and Lincoln, Y. (1994) “Introduction: entering the field of qualitative research”, in Denzen, N., and Lincoln, Y. (eds.): *Handbook of Qualitative Research*. Sage Publications, London.

Dobb, M. (1973) *Theories of Value and Distribution since Adam Smith*. Cambridge University Press, Cambridge.

Dopfer, K. (1991) “The generation of novelty in the economic process: An evolutionary concept”, in Dragan, J.C., Seifert, E.K., and Demetrescu, M.C. (eds.): *Entropy and Bioeconomics*. Nagard, Rome.

Duchin, F. (1988) “Analyzing structural change in the economy”, in Ciaschini, M. (ed.): *Input-Output Analysis: Current Developments*. Chapman and Hall, London.

Duchin, F. (1996) “Ecological economics: the second stage”, in Costanza, R., Segura, O., and Martinez-Alier, J. (eds.): *Getting Down to Earth*. Island Press, Washington DC.

Duchin, F., and Lange, G. (1994) *The Future of the Environment: Ecological Economics and Technological Change*. Oxford University Press, New York.

Duchin, F., and Szyld, D. (1985) “A dynamic input-output model with assured positive output”, *Metroeconomica* 37: 269-282.

Dyke, C. (1994) “From entropy to economy: a thorny path”, in Burley, P., and Foster, J. (eds.): *Economics and Thermodynamics. New Perspectives on Economic Analysis*. Kluwer, Boston.

Eddington, A.S. (1928) *The Nature of the Physical World*. Cambridge University Press, Cambridge.

Eldredge, N., and Gould, J.S. (1972) “Punctuated equilibria: an alternative to phyletic gradualism”, in Schopf, T.J.M. (ed.): *Models in Paleobiology*. Freeman, Cooper and Co., San Francisco.

Faber, M. (1985) “A biophysical approach to the economy entropy, environment and resources”, in van Gool, W., and Bruggink, J. (eds.): *Energy and Time in Economic and Physical Sciences*. North-Holland, Amsterdam.

Faber, M., and Proops, J.L.R. (1998) *Evolution, Time, Production and the Environment*. Springer, Berlin.

Faber, M., Manstetten, R., and Proops, J.L.R. (1996) *Ecological Economics: Concepts and Methods*. Edward Elgar, Cheltenham.

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

Fischer-Kowalski, M. (1997) “Society’s metabolism: on the childhood and adolescence of a rising conceptual star”, in Redclift, M., and Woodgate, G. (eds.): *The International Handbook of Environmental Sociology*. Edward Elgar, Cheltenham.

Forrester, J.W. (1987) “Nonlinearity in high-order models of social systems”, *European Journal of Operational Research*, 30: 104-109.

Foster, J. (1997) “The analytical foundations of evolutionary economics: from biological analogy to economic self-organization”, *Structural Change and Economic Dynamics*, 8: 427-451.

Foster, J., Kay, J., and Roe, P. (2001) “Teaching complexity and systems thinking to engineers”, paper presented at the *4th UICEE Annual Conference on Engineering Education*, Bangkok, Thailand, 7-10 February 2001.

Funtowicz, S.O., and Ravetz, J.R. (1991) “A new scientific methodology for global environmental issues”, in Costanza, R. (ed.): *Ecological Economics: The Science and Management of Sustainability*. Columbia University Press, New York.

Funtowicz, S.O., and Ravetz, J.R. (1994) “The worth of a songbird: Ecological economics as a post-normal science”, *Ecological Economics*, 10: 197-207.

Funtowicz, S.O., and Ravetz, J.R. (1997) “The poetry of thermodynamics”, *Futures*, 29 (9): 791-810.

Georgescu-Roegen, N. (1970) “The economics of production. The Richard T. Ely Lecture”. *American Economic Review* 60, 1–9.

Georgescu-Roegen, N. (1971) *The Entropy Law and the Economic Process*. Harvard University Press, Cambridge, Massachusetts.

Georgescu-Roegen, N. (1975) “Energy and economic myths”, *Southern Economic Journal*, 41:347-381.

Georgescu-Roegen, N. (1977) “The steady state and ecological salvation: a thermodynamic analysis”, *Bioscience* 27: 266-270.

Giampietro, M. (1991) “Escaping the Georgescu-Roegen paradox on development: equilibrium and non-equilibrium thermodynamics to describe technological evolution”, in Dragan, J.C., Seifert, E.K., and Demetrescu, M.C. (eds.): *Entropy and Bioeconomics*. Nagard, Rome.

Giampietro, M. (1994) “Sustainability and technological development in agriculture: a critical appraisal of genetic engineering”, *Bioscience* 44(10): 677-689.

Giampietro, M. (1997) “Linking technology, natural resources, and the socioeconomic structure of human society: a theoretical model”, *Advances in Human Ecology*, vol. 6: 75-130.

Giampietro, M. (guest editor) (2000). Special issue of *Population and Environment* on Societal Metabolism Part 1 of 2: Introduction of the Analytical Tool in Theory, Examples, and Validation of Basic Assumptions. *Population and Environment* 22 (No. 2): 97-254.

Giampietro, M. (guest editor) (2001). Special issue of *Population and Environment* on Societal Metabolism-Part 2 of 2: Specific Applications to Case Studies. *Population and Environment* 22 (No. 3): 257-352.

Giampietro, M., (2001), Fossil energy in world agriculture, in *Encyclopedia of Life Sciences,* Macmillan Reference Limited, available at http://www.els.net/.

Giampietro M. (2003). *Multi-Scale Integrated Analysis of Agro-ecosystems* CRC Press Boca Raton 472 pp.

Giampietro, M., and Mayumi, K. (1997) “A dynamic model of socioeconomic systems based on hierarchy theory and its application to sustainability”, *Structural Change and Economic Dynamics,* 8: 453-469.

Giampietro, M. and Mayumi, K. (2000). "Jevons' paradox. Scaling in Societal Metabolism and the fairy tale of Kuznets curves", Proceedings of the 3rd Biannual Conference of the European Society for Ecological Economics, Vienna 3-6 May 2000: "Transitions towards a Sustainable Europe. Ecology-Economy-Policy".

Giampietro, M. and Mayumi, K., (2000a): Multiple-scale integrated assessment of societal metabolism: Introducing the approach, *Population and Environment*, 22 (2): 109-153.

Giampietro, M. and Mayumi, K., (2000b): Multiple-scale integrated assessment of societal metabolism: Integrating biophysical and economic representations across scales, *Population and Environment*, 22 (2): 155-210.

Giampietro, M., and Mayumi, K. (2001) "Integrated assessment of sustainability trade-offs: Methodological challenges for Ecological Economics", paper presented at the ESEE conference *Frontiers 1: Fundamental issues of Ecological Economics*, Cambridge, UK, 4-7 July 2001.

Giampietro, M. and Mayumi, K. (2004): "Complex Systems and Energy", in C. Cleveland (Editor) *Encyclopaedia of Energy*, Elsevier, San Diego. Volume 1: 617-631.

Giampietro, M., and Pastore, G. (1999) "Biophysical roots of 'enjoyment of life' according to Georgescu-Roegen's bioeconomic paradigm", in Mayumi, K., and Gowdy, J.M. (eds.): *Bioeconomics and Sustainability.* Edward Elgar, Cheltenham.

Giampietro, M., and Pimentel, D. (1991) "Energy efficiency: assessing the interaction between humans and their environment", *Ecological Economics*, 4: 117-144.

Giampietro, M., and Ramos-Martin, J. (2005) "Multi-Scale Integrated Analysis of Sustainability: a methodological tool to improve the quality of narratives", *International Journal of Global Environmental Issues*, in press.

Giampietro, M., Bukkens, S., Pimentel, D. (1999): "General trends of technological change in agriculture", *Crit. Rev. Plant Sci.*, 18, 261-282.

Giampietro, M., Mayumi, K., and Bukkens, S.G.F. (2001) "Multiple-Scale Integrated Assessment of Societal Metabolism: An Innovative Approach to Development and Sustainability", mimeo.

Giampietro, M. Mayumi, K. and Ramos-Martin, J. (in press): "Using quantitative analyses to improve the quality of the narratives about sustainability: Multi-Scale Integrated Analysis of Societal Metabolism". Paper Presented at the 6th conference of the European Society for Ecological Economics, Lisbon, 14 - 17 June, 2005.

Glansdorff, P. and Prigogine, I., (1971), *Thermodynamics Theory of Structure, Stability and Fluctuations,* John Wiley & Sons, New York.

Gleick, J. (1987) *Chaos: Making a New Science*. Penguin, Harmondsworth.

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

Gomiero, T., and Giampietro, M. (2005) "Overview of graphic tools for data representation in integrated analysis of farming systems", *International Journal of Global Environmental Issues,* in press.

Gould, S.J. (1992) "Life in punctuation", *Natural History*, 101: 10-21.

Gould, S.J., and Eldredge, N. (1993) "Punctuated equilibrium comes of age", *Nature* 366: 223-227.

Gowdy, J.M. (1994) *Coevolutionary Economics: The Economy, Society, and the Environment*. Kluwer Academic Publishers, Amsterdam.

Gowdy, J.M., and Ferrer-i-Carbonell, A. (1999) "Toward consilience between biology and economics: the contribution of Ecological Economics", *Ecological Economics*, 29: 337-348.

Gray, L.C. (1913) "The economic possibilities of conservation", *Quarterly Journal of Economics*, 27: 497-519.

Gray, L.C. (1914) "Rent under the presumption of exhaustibility", *Quarterly Journal of Economics*, 28: 466-489.

Grubb, M.; Sebenius, J.; Magalhaes, A.; Subak, S. (1992): "Sharing the burden", in I.M. Mintzer (Ed.): *Confronting Climate Change*. Stockholm Environment Institute. Cambridge University Press: Cambridge.

Haberl, H. (2001a) "The energetic metabolism of societies, part I: accounting concepts", *Journal of Industrial Ecology*. 5(1): 11-33.

Haberl, H. (2001b) "The energetic metabolism of societies, part II: empirical examples", *Journal of Industrial Ecology*. 5(2): 71-88.

Haken, H., and Knyazeva, H. (2000) "Arbitrariness in nature: synergetics and evolutionary laws of prohibition", *Journal for General Philosophy of Science* 31: 57-73.

Hall, C.A.S.; Cleveland, C.J.; and Kaufman, R. (1986). *Energy and Resource Quality.* New York: John Wiley & Sons.

Heckman, J.J. (2001) "Econometrics and empirical economics", *Journal of Econometrics* 100: 3-5.

Heilig, G.K. (1999): *Can China feed itself? A system for evaluation of policy options*. IIASA, Laxenburg, Austria.

Herring, H. (1999) “Does energy efficiency save energy? The debate and its consequences”, *Applied Energy*, 63: 209-226.

Hinterberger, F., and Schmidt-Bleek, F. (1999) “Dematerialization, MIPS and Factor 10. Physical sustainability indicators as a social device”, *Ecological Economics*, 29: 53-56.

Holling, C.S. (1996) “Engineering resilience versus ecological resilience”, in Schulze, P. (ed.): *Engineering Within Ecological Constraints*. National Academy of Engineering. National Academy Press, Washington DC.

Hotelling, H.C. (1931) “The economics of exhaustible resources”, *The Journal of Political Economy*, 39: 137-175.

Houghton, J.T. et al. (eds.) (1990) *Climate Change: The IPCC Scientific Assessment. Report from Working Group I*, Cambridge University Press, New York.

Houghton, J.T. et al. (eds.) (1992) *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment*, Cambridge University Press, New York.

Houghton, J.T. et al. (eds.) (1996) *Climate Change 1995. The Science of Climate Change*. Cambridge University Press, New York.

Hueting, R., and Reijnders, L. (1998) “Sustainability is an objective concept”, *Ecological Economics* 27 (139-147).

ILO Statistics. Laborsta data base, www.ilo.org

Instituto Nacional de Estadística (1992). *Contabilidad Nacional de España. Serie enlazada 1964-1991. Base 1986.* Madrid.

Instituto Nacional de Estadística (Spanish National Statistics Institute) (1998). *Serie contable 1992-1997*. Madrid. www.ine.es

International Energy Agency (2003) *Key World Energy Statistics*. Paris.

International Energy Agency (2004) *Key World Energy Statistics*. Paris.

Jackson, T., and Marks, N. (1999) “Consumption, sustainable welfare and human needs – with reference to UK expenditure patterns between 1954 and 1994”, *Ecological Economics* 28(3): 421-441.

James, W.P.T. and Schopheld, E.C., (1990), *Human Energy Requirement*, Oxford University Press, Oxford.

Jänicke, M., H. Mönch, T. Ranneberg, U.E. Simonis (1989). "Economic Structure and Environmental Impacts: East-West Comparisons". *The Environmentalist*, Vol. 9, p. 171-182.

Jantsch, E. (1987) *The Self-Organizing Universe*. Pergamon Press, Oxford.

Jevons, F. (1990). "Greenhouse: A paradox", *Search* 21 (5).

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

Judson, D.H. (1989) "The convergence of neo-Ricardian and embodied energy theories of value and price", *Ecological Economics*, 1: 261-281.

Kåberger, T., and Månsson, B. (2001) "Entropy and economic process – physics perspectives", *Ecological Economics* 36: 165-179.

Kampis, G., (1991), *Self-Modifying Systems in Biology and Cognitive Science: A New Framework for Dynamics, Information, and Complexity*, Pergamon Press, Oxford, 543 pp.

Kaufmann, R.K.(1992) "A biophysical analysis of the energy/real GDP ratio: implications for substitution and technical change", *Ecological Economics*, 6: 35-56.

Kaufmann, R. K. (1994): "The relation between marginal product and price in U.S. energy markets". *Energy Economics*, 16: 145-158.

Kaufmann, R.K., and Cleveland, C.J. (1995) "Measuring sustainability: needed – an interdisciplinary approach to an interdisciplinary concept", *Ecological Economics*, 15: 109-112.

Kay, J.J., and Regier, H. (2000) "Uncertainty, complexity, and ecological integrity: insights from an ecosystem approach", in Crabbé, P., Holland, A., Ryszkowski, L., and Westra, L. (eds.), *Implementing Ecological Integrity: Restoring Regional and Global Environmental and Human Health*, Kluwer, NATO Science Series.

Kay, J.J., Regier, A.H., Boyle, M., and Francis, G. (1999) "An ecosystem approach for sustainability: addressing the challenge for complexity", *Futures* 31: 721-742.

Keynes, J.M. (1936), *The General Theory of Employement, Interest, and Money*, London: Macmillan for the Royal Economic Society

Khalil, E.L. (1990) "Entropy law and exhaustion of natural resources: is Nicholas Georgescu-Roegen paradigm defensible?", *Ecological Economics*, 2: 163-178.

Koestler, A. (1969) "Beyond atomism and holism: the concept of the holon", in Koestler, A., and Smythies, J.R. (eds.): *Beyond Reductionism*. Hutchinson, London.

Kopolo, G. (1999). *Surrogate emissions. Could this be a new twist to the carbon-trading debate?* MSc Thesis, Environmental Change Unit, University of Oxford.

Krausmann, F.; Haberl, H. (2002): The process of industrialization from the perspective of energetic metabolism. Socioeconomic energy flows in Austria 1830-1995. In: *Ecological Economics* 41(2): 177-201.

Kuhn, T.S. (1962) *The Structure of Scientific Revolutions*, Chicago University Press, Chicago.

Kurz, H.D., and Salvadori, N. (2003) "Fund-flow versus flow-flow in production theory: Reflections on Georgscu-Roegen's contribution", *Journal of Economic Behavior & Organization* Vol. 51: 487-505.

Lavoisier, A. (1789) *Traité élémentaire de chimie, présenté dans un ordre nouveau et d'après les découvertes modernes*, 2 vols. Paris: Chez Cuchet. Reprinted Bruxelles: Cultures et Civilisations, 1965.

Lorenz, E.N. (1963) "Deterministic non-period flows", *Journal of Atmospheric Sciences*, 20: 130-141.

Lotka, A.J. (1922) "Contribution to the energetics of evolution". *Proc. Nat. Acad. Sci.* 8: 147-154.

Lotka, A.J. (1956) *Elements of Mathematical Biology*. Dover Publications, New York.

Machado, G., Schaeffer, R., and Worrell, E. (2001): "Energy and carbon embodied in the international trade of Brazil: an input – output approach", *Ecological Economics* 39: 409-424.

Malenbaum, W. (1978) *World Demand for Raw Materials in 1985 and 2000*. McGraw-Hill, New York.

Malthus, T.R. (1798) *An Essay on Population*. Ward, Lock and Company, London.

Mandelbrot, B.B. (1967) "How long is the coast of Britain? Statistical self-similarity and fractal dimensions", *Science* 155: 636-638.

Marshall, A. (1920) *Principles of Economics*. Macmillan, London.

Martinez-Alier, J. (1987) *Ecological Economics: Energy, Environment, and Society.* Blackwell's Book Services, Oxford.

Martínez Alier, J., Munda, G. and O'Neill, J., (1998): "Weak comparability of values as a foundation for ecological economics". *Ecological Economics*, 26: 277-286.

Martinez-Alier, J., and O'Connor, M. (1999) "Distributional issues: an overview", in van den Bergh, J. (ed.): *Handbook of Environmental and Resource Economics*. Edward Elgar, Cheltenham.

Matthews, E. et al. (2000): *The Weight of Nations: Material Outflows from Industrial* Economies (a joint publication of the World Resources Institute (WRI); the Wuppertal Institute; the National Institute for Environmental Studies; the Institute for Interdisciplinary Studies of Austrian Universities; and the Centre of Environmental Science, Leiden University, Washington, DC).

Maturana, H.R., and Varela, F. (1980) *Autopoiesis and Cognition: The Realization of the Living*, D. Reidel, Boston.

May, R.M., and Oster, G.F. (1976) "Bifurcations and dynamic complexity in simple ecological models", *American Naturalist*, 110: 573-599.

Mayumi, K. (1993) "Georgescu-Roegen's 'Fourth Law of Thermodynamics', the modern energetic dogma, and ecological salvation", in Bonati, L., Lasagni, M., Moro, G., Pitea, D., and Schiraldi, A. (eds.): *Trends in Ecological Physical Chemistry*. Elsevier, Amsterdam.

Mayumi, K. (1995) "Nicholas Georgescu-Roegen (1906-1994): An admirable epistemologist", *Structural Change and Economic Dynamics*, 6: 261-265.

Mayumi, K. (2001) *The Origins of Ecological Economics: The Bioeconomics of Georgescu-Roegen*, Routledge, London.

Mayumi, K., and Giampietro, M. (2001) "The epistemological challenge of modeling sustainability: risk, uncertainty and ignorance", paper presented at the ESEE conference *Frontiers 1: Fundamental issues of Ecological Economics*, Cambridge, UK, 4-7 July 2001.

Mayumi, K. and Giampietro M. (2004): "Entropy in Ecological Economics", in J. Proops and P. Safonov (Editors): *Modeling in Ecological Economics*, Edward Elgar, Cheltenham (UK). pp.80-101.

Mayumi, K. and Giampietro M. (in press): "Uncertainty, modeling relation theory, and the epistemological challenge of self-modifying systems: governance and sustainability in the post-normal science era", *Ecological Economics*.

Meadows, D.H., Meadows, D.L., Randers, J., and Behrens, W.W. (1972) *The Limits to Growth*. PAN Books Ltd., London and Sydney.

Mesner, S., and Gowdy, J.M. (1999) "Georgescu-Roegen's evolutionary economics", in Mayumi, K., and Gowdy, J.M. (eds.): *Bioeconomics and Sustainability*. Edward Elgar, Cheltenham.

Mielnik, O., and Goldemberg, J. (1999) "The evolution of the 'carbonization index' in developing countries”, *Energy Policy*, 27: 307-308.

Mill, J.S. (1866) *Principles of Political Economy,* Longman-Green, London.

Mirowski, P. (1989) *More Heat Than Light*. Cambridge University Press, Cambridge.

Munda, G. (2000) *Conceptualising and Responding to Complexity.* EVE Policy Research Brief Series, Cambridge Research for the Environment, Cambridge.

Munda, G. (2004) “Social Multi-Criteria Evaluation: Methodological foundations and operational consequences”, *European Journal of Operational Research*. Vol. 158: 662-677.

Muradian, R., and Martinez-Alier, J. (2001) “Trade and the environment: from a ‘Southern’ perspective”, *Ecological Economics* 36: 281-297.

Neurath, O. (1944) *Foundations of the Social Sciences*. University of Chicago Press, Chicago.

Nicolis, G., and Prigogine, I. (1977) *Self-Organization in Nonequilibrium Systems.* John Wiley & Sons, New York.

Noël, J.F., and O’Connor, M. (1998) “Strong Sustainability and Critical Natural Capital”, in Faucheux, S., and O’Connor, M. (eds.) *Valuation for Sustainable Development. Methods and Policy Indicators***.** Edward Elgar, Cheltenham.

Norgaard, R.B. (1989) “The case for methodological pluralism”, *Ecological Economics*, 1: 37-57.

Norgaard, R.B. (1994) *Development Betrayed*. Routledge, London.

Norton, B.G. (1991) *Toward Unity among Environmentalists.* Oxford University Press, New York.

O’Connor, J. (1988) “Capitalism, nature, socialism: a theoretical introduction”, *Capitalism, Nature, Socialism*, 1: 11-38.

O’Connor, M. (1991) “Entropy, structure, and organisational change”, *Ecological Economics*, 3: 95-122.

O’Connor, M. (1994) “Entropy, liberty and catastrophe: the physics and metaphysics of waste disposal”, in Burley, P., and Foster, J. (eds.): *Economics and Thermodynamics. New Perspectives on Economic Analysis*. Kluwer, Boston.

O’Riordan, T. (1996) “Democracy and the sustainable transition”, in Lafferty, W.M., and Meadowcroft, J. (eds.): *Democracy and the Environment. Problems and Prospects.* Edward Elgar, Cheltenham.

Odum, E.P. (1989) *Ecology and Our Endangered Life-Support Systems*. Sinuauer associates, Sunderland, Massachusetts.

Odum, H.T. (1971) *Environment, Power, and Society*. John Wiley & Sons, New York.

Odum, H.T. (1973) “Energy, ecology, and economics”, *Ambio* 2: 220-227.

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

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

Odum, H.T. (2000) *The Prosperous Way Down*. The University Press of Colorado, Niwot.

Odum, H.T., and Pinkerton, R.C. (1955) “Time’s speed regulator: the optimum efficiency for maximum power output in the physical and biological systems”, *American Scientist* 43: 331-343.

OECD (1999). *OECD Statistical Compendium on CD-ROM*, Paris.

OECD (2002): *OECD Statistical Compendium on CD-ROM*, Paris.

OECD (2004): *OECD Employment Outlook 2004*, Paris.

Opschoor, J.B. (1997) “Industrial metabolism, economic growth and institutional change”, in Redclift, M., and Woodgate, G. (eds.): *The International Handbook of Environmental Sociology*. Edward Elgar, Cheltenham.

Ostwald, W. (1907), The modern theory of energetics, *The Monist*, 17, 481-515.

Ostwald, W. (1909). *Energetische Grundlagen der Kulturwissenschaft* [Energetic foundations of sociology]. Leipzig: Klinkhardt.

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

Paterson, M. (1996) *Global Warming and Global Politics*. Routledge, London.

Pearce, D., and Atkinson, G.D. (1993) “Capital theory and the measurement of weak sustainable development: and indicator of ‘weak’ sustainability”, *Ecological Economics*, 8: 103-108.

Pearce, D., and Turner, K. (1990) *Economics of Natural Resources and the Environment*. Harvester Wheatsheaf, Great Britain.

Perrings, C. (1994) "Conservation of mass and the time behaviour of ecological-economic systems", in Burley, P., and Foster, J. (eds.): *Economics and Thermodynamics. New Perspectives on Economic Analysis*. Kluwer, Boston.

Perrings, C., and Walker, B. (1997) "Biodiversity, resilience and the control of ecological-economic systems: the case of fire-driven rangelands", *Ecological Economics* 22: 73-83.

Podolinsky, S. (1883). "Menschliche Arbeit und Einheit der Kraft", *Die Neue Zeit*, (Stuttgart), 1(9), 413-424; 1(10), 449-457.

Prigogine, I. (1962) *Introduction to Non-Equilibrium Thermodynamics*. Wiley, New York.

Prigogine, I., (1978), *From Being to Becoming*, W.H. Freeman and Co., San Francisco.

Prigogine, I. (1987) "Exploring complexity", *European Journal of Operational Research*, 30: 97-103.

Prigogine, I. and Stengers, I., (1981), *Order out of Chaos*, Bantam Books, New York.

Prigogine, I., and Stengers, I. (1984) *Order Out of Chaos*. Heinemann, London.

Proops, J.L.R. (1979) *Energy, Entropy and Economic Structure*. PhD Thesis, Keele University.

Proops, J.L.R. (1979): *Energy, Entropy and Economic Structure*. PhD Thesis. Keele University.

Proops, J.L.R. (1983) "Organisation and dissipation in economic systems", *Journal of Social Biological Structures*, 6: 353-366.

Proops, J.L.R. (1985) "Thermodynamics and economics: from analogy to physical functioning", in van Gool, W., and Bruggink, J. (eds.): *Energy and Time in Economics and Physical Sciences*. Elsevier, Amsterdam.

Proops, J.L.R. (1988) "Energy intensities, input-output analysis and economic development", in Ciaschini, M. (ed.): *Input-Output Analysis: Current Developments*. Chapman & Hall, London.

Proops, J.L.R., Atkinson, G., Schlotheim, B.F., and Simon, S. (1999) "International trade and the sustainability footprint: a practical criterion for its assessment", *Ecological Economics* 28: 75-97.

Proops, J.L.R., Faber, M., and Wagenhals, G. (1993) *Reducing CO_2 Emissions. A Comparative Input-Output Study for Germany and the UK*. Springer-Verlag, Berlin.

Quesnay, F. (1758) “Tableau Economique”, in Kuczynski, M., and Meek, R.L. (1972)(eds.): *Quesnay’s Tableau Economique*. Macmillan, London.

Ramos-Martin, J., (1999): “Breve comentario sobre la desmaterialización en el estado español”, *Ecología Política*, 18: 61-64.

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

Ramos-Martin, J., (2001b): “Non-linearity in energy metabolism of Spain: “Attractor Points” for the Development of Energy Intensity”, in S. Ulgiati, M. Brown, M. Giampietro and K. Mayumi (Editors), *Advances in Energy Studies. Exploring Supplies, Constraints, and Strategies*, Modesti Publisher, Padova.

Ramos-Martin, J. (2003a) “Empiricism in ecological economics: a perspective from complex systems theory”, *Ecological Economics* 46: 387-398.

Ramos-Martin, J. (2003b): “Intensidad energética de la economía española: una perspectiva integrada”, in *Revista de Economía Industrial*, Number 351(III): 59-72

Ramos-Martin, J. (2003c): “Empirismo en economía ecológica: una visión desde la teoría de sistemas complejos”, *Revista de Economía Crítica*. Vol. 1: 75-93.

Ramos-Martin, J. (2004a): “La perspectiva biofísica del proceso económico: Economía Ecológica”. In F. Falconi, M. Hercowitz, R. Muradian (Eds.): *Globalización y Desarrollo en América Latina*. FLACSO, Quito, Ecuador.

Ramos-Martin, J. (2004b): “La perspectiva biofísica de la relació home-natura: Economia Ecològica”, in J. Valdivielso (comp.), *Les dimensions socials de la crisis ecològica*, Ed. UIB, Palma de Mallorca.

Ramos-Martin, J., and Giampietro, M. (in press): “ Multi-Scale Integrated Analysis of Societal Metabolism: Learning from trajectories of development and building robust scenarios”, *International Journal of Global Environmental Issues*.

Ramsay, J. (1998) “Problems with empiricism and the philosophy of science: implications for purchasing research”, *European Journal of Purchasing & Supply Management* 4: 163-173.

Rappaport, R.A. (1971), “The flow of energy in an agricultural society”, *Scientific American*, 224, 117-133.

Redclift, M (1986) “Redefining the environmental ‘crisis’ in the South”, in Weston, J. (ed.): *Red and Green. The New Politics of the Environment*. Pluto Press, London.

Rist, R.C. (1994) “Influencing the policy process with qualitative research”, in

Denzen, N., and Lincoln, Y. (eds.): *Handbook of Qualitative Research*. Sage Publications, London.

Robbins, L. (1932) *An Essay on the Nature and Significance of Economic Science*. Macmillan, London.

Rosen, R., (1958a), A relational theory of biological systems, *Bull. Math. Biophys.*, 20, 245.260.

Rosen, R., (1958b), The representation of biological systems from the standpoint of the theory of categories, *Bull. Math. Biophys.*, 20, 317.341.

Rosen, R. (1972): "Some relational cell models: The metabolism-repais systems", in R. Rosen (editor): *Foundation of Mathematical Biology* Vol. 2. Academic Press: New York pp. 217-253.

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

Rosen, R. (1987) "On complex systems", *European Journal of Operational Research*, 30: 129-134.

Rosen, R., (2000), *Essays on Life Itself*, Columbia University Press, New York, 361 pp.

Rothman, D.S. (1998) "Environmental Kuznets curve – real progress or passing the buck? A case for consumption-based approaches", *Ecological Economics* 25: 177-194.

Rotmans, J. and Rothman, D. (2003), *Scaling Issues in Integrated Assessment*, Swets & Zeitlinger Publishers, Lisse, The Netherlands.

Ruth, M. (1993) *Integrating Economics, Ecology and Thermodynamics*. Kluwer, Dordrecht.

Ruth, M. (1996) "Evolutionary economics at the crossroads of biology and physics", *Journal of Social and Evolutionary Systems*, 19: 125-144.

Sanne, C. (2000) "Dealing with environmental savings in a dynamical economy – how to stop chasing your tail in the pursuit of sustainability", *Energy Policy*, 28: 487-495.

Schandl, H., Grünbühel, C.M., Haberl, H. and Weisz, H. (2002) *A handbook on methodologies to describe the physical dimension of socio-economic activities with respect to environmental change – Accounting for Society's Metabolism and Appropriation of Net Primary Production*. Mimeo. IFF – Dept. Social Ecology. Vienna.

Schipper, L. (1996) "Life-styles and the environment: The case of energy", *Daedalus*, 125: 113-138.

Schneider, E.D., and Kay, J.K. (1994) “Life as a manifestation of the second law of thermodynamics”, *Mathematical and Computer Modelling*, Vol. 19, No 6-8: 25-48.

Schrödinger, E. (1945) *What Is Life?* Cambridge University Press, Cambridge.

Schumpeter, J.A. (1949). *The Theory of Economic Development*. Harvard University Press, Cambridge, Massachusetts, 3rd edition.

Schumpeter, J.A. (1954) *History of Economic Analysis*, George Allen & Unwin, London.

Scott, A. (1985) *Progress in Natural Resource Economics*. Clarendon Press, Oxford.

Simon, H.A. (1983) *Reason in Human Affairs*. Stanford University Press, Stanford.

Simon, S. (1997) *Sustainability, National Accounting, and the Environment*. PhD Thesis, Keele University.

Simonis, U.E. (1989). *Industrial restructuring for sustainable development: three points of departure.* Science Centre Berlin. FS II 89-401, Berlin.

Soddy, F. (1922) *Cartesian Economics*. Hendersons, London.

Spencer, H. (1880) *First Principles*. Appleton, New York.

Sraffa, P. (1960) *Production of Commodities by Means of Commodities*. Cambridge University Press, Cambridge.

Stern D. I. (1993): “Energy use and economic growth in the USA: A multivariate approach”, *Energy Economics* 15, 137-150.

Stern, D.I., Common, M.S., and Barbier, E.B. (1996) “Economic growth and environmental degradation: The environmental Kuznets curve and sustainable development”, *World Development*, 24: 1151-1160.

Stock, G.B., and Campbell, J.H. (1996) “Human society as an emerging global superorganism”, in Khalil, A.L., and Boulding, K.E. (eds.): *Evolution, Order and Complexity*. Routledge, London.

Sun, J.W. (1999) “The nature of CO_2 emissions Kuznets curve”, *Energy Policy*, 27: 691-694.

Suri, V., and Chapman, D. (1998) “Economic growth, trade and energy: implications for the environmental Kuznets curve”, *Ecological Economics*, 25: 195-208.

Tainter, J., (1988), *The Collapse of Complex Societies*, Cambridge University Press, Cambridge, U.K.

Tam, T.T.B., and Hien, H.M. (1998) “Land use and cover change in Vietnam”, Paper presented at the “Land use / cover change – Data and information systems (LUCC-DIS) Workshop”, 13-18 August 1998, Chulalongkorn University, Bangkok, Thailand.

The Economist: July 12th 2001, February 19th 2004, April 29th 2004, September 9th 2004, September 30th 2004, November 25th 2004, February 17th 2005.

The New York Times, February 18th 2005.

Ulanowicz, R.E. (1980) “An hypothesis on the development of natural communities”, *Journal of Theoretical Biology*, 85: 223-245.

Ulanowicz, R.E. (1986) *Growth and Development: Ecosystem Phenomenology*. Springer, New York.

Ulanowicz, R.E. (1996) “The propensities of evolving systems”, in Khalil, E.L., and Boulding, K.E. (eds.): *Evolution, Order and Complexity.* Routledge, London.

Unruh, G.C. & Moomaw, W.R. (1998). “An alternative analysis of apparent EKC-type transitions”, *Ecological Economics,* 25: 221-229.

Unruh, G.C. (2000) “Understanding carbon lock-in”, *Energy Policy*, 28 (12): 817-830.

Varela, F., Maturana, H.R., and Uribe, R. (1974) “Autopoiesis: the organization of living systems, its characterization, and a model”, *Biosystems* 5: 187-196.

Walker, B.H., Ludwig, D., Holling, C.S., and Peterman, R.M. (1969) “Stability of semi-arid savanna grazing systems”, *Ecology* 69: 473-498.

Weissmahr, J.A. (1991) “On the importance of energy for evolutionary and ecological economics”, in Dragan, J.C., Seifert, E.K., and Demetrescu, M.C. (eds.): *Entropy and Bioeconomics*. Nagard, Rome.

Wëizsacker, E.U., Lovins, A.B., and Lovins, L.H. (1997) *Factor Four. Doubling Wealth, Halving Resource Use.* Earthscan, London.

Weston, R.F., and Ruth, M. (1997) “A dynamic, hierarchical approach to understanding and managing natural economic systems”, *Ecological Economics*, 21: 1-17.

White, L.A. (1943), Energy and evolution of culture, *Am. Anthropol.*, 14, 335.356.

White, L.A. (1959), *The Evolution of Culture: The Development of Civilization to the Fall of Rome*, McGraw-Hill, New York.

Wilson, E.O. (1993) *The Diversity of Life.* Penguin, London.

Wilson, E.O. (1998) *Consilience*. Alfred Knopf, New York.

Witt, U. (1992) "Evolutionary concepts in economics", *Eastern Economic Journal*, 18: 405-419.

Witt, U. (1997) "Self-organization and economics – what is new?", *Structural Change and Economic Dynamics*, 8: 489-507.

World Energy Council, http://www.worldenergy.org

Zeleny, M. (1996) "On the social nature of autopoietic systems", in Khalil, A.L., and Boulding, K.E. (eds.): *Evolution, Order and Complexity.* Routledge, London.

Zipf, G.K. (1941): *National Unity and Disunity: The Nation as a Bio-Social Organism.* The Principia Press, Bloomington, IN.

ANNEX I: CURRICULUM VITAE

Jesus Ramos-Martin
Lerchenfelder Strasse 76/1/10
A-1080 Vienna, Austria
Tel: + 43 676 4424233
jesusramosmartin@yahoo.es
http://www.txusramos.tk

Nationality: Spanish
Passport: AA315363
Born: 17th April 1974
Santa Coloma, Spain

ACADEMIC DETAILS

2001- : PhD (c) in Environmental Sciences (Ecological Economics) at Autonomous University of Barcelona. Title of the Thesis: "*Complex systems and exosomatic energy metabolism of human societies*". To be discussed in November 2005.

2000-2001: MPhil researcher at Keele University. Topic of the research: "Analysing Energy Metabolism of Societies from a Complex-Systems Perspective". Scholarship given by Caja de Ahorros del Mediterraneo (CAM) and the British Council.

1999-2000: MA in "Environmental Politics" at Keele University, UK. Topic of the research: "Equity issues regarding the CO_2 emissions property rights under the FCCC". Scholarship given by Caja de Ahorros del Mediterraneo (CAM) and the British Council.

1998-1999: MSc in "Ecological Economics, Territory and Environmental Management" within the PhD Programme in Environmental Sciences at the Autonomous University of Barcelona. My research focused on Climate Change, mainly GHGs abatement measures in the Metropolitan Area of Barcelona through Joint Implementation projects.

1992-1996: "Economics" degree (Development and International Economics) at the Autonomous University of Barcelona.

OTHER RELEVANT COURSES

September 1999: Advanced Course in "Decision Tools and Processes for Integrated Environmental Assessment", focusing on Multicriteria Decision Aid. Environment and Climate Programme. European Commission. Universitat Autònoma de Barcelona.

From 26th to 30th July 1999, Seminar "Environment as a competitive factor. Economic ideas for the next century", organised by the Menéndez Pelayo International University in Santander (Spain).

June-December of 1998: Course *Management and Development of Renewable and Alternative Energy* organised jointly by the Catalan Institute of Technology and by the Industrial Organisation School of Madrid.

From 4th to 8th of August 1997, "Course: The Public Sector in a Market Economy: redistribution, regulation, and stabilisation" at the Menéndez Pelayo International University Summer Courses', in Santander.

In 1997 Course: *Solar Energy Designing and Installing*, organised by CENSOLAR.

CONFERENCES AND WORKSHOPS

17th – 23rd July 2005, presentation at the "2nd Liphe4 Summer School on Participatory Integrated Assessment of Sustainability". Title: "Multi-Scale Integrated Analysis of Societal Metabolism (MSIASM): Examples of applications at the national level".

14th – 17th June 2005, 2 presentations jointly with Mario Giampietro and Kozo Mayumi at the 6th International Conference of the European Society for Ecological Economics "Science & Governance: The Ecological Economics Perspective", held in Lisbon, 2005. Titles, "Using quantitative analysis to improve the quality of the narratives about sustainability: Multi-Scale Integrated Analysis of Societal Metabolism (MSIASM)", and "Addressing the Implications of Scales when analysing the evolution of economies using Multi-Scale Integrated Analysis of Societal Metabolism (MSIASM): The case of China".

20th – 27th August 2004, presentation at the "Liphe4 Summer Workshop on Participatory Integrated Assessment of Sustainability". Title: "Multi-Scale Integrated Analysis of Societal Metabolism".

17th – 20th March 2004, paper presented at the International Conference "Bridging Scales and Epistemologies: Linking Local Knowledge and Global Science in Multi-Scale Assessments" within the activities of the UN Millennium Ecosystem Assessment. Title: "Multi-Scale Integrated Analysis of Societal Metabolism: Learning from Trajectories of Development and Building Robust Scenarios".

3rd March 2004, seminar at the University of Pisa (Italy) on "Multi-Scale Integrated Analysis of Societal Metabolism: The Theory and Practice"

27th – 28th November 2003, seminar given at the International Workshop "Interfaces between Science & Society", organised by the Joint Research Centre of the European Commission at Ispra, held in Milano. Title: "Multiple-Scale Integrated Analysis of Societal Metabolism: Examples of Applications".

12th to 15th of February 2003, paper presented jointly with Miquel Ortega Cerdà at the ESEE Conference Frontiers 2, held in Tenerife, Spain. Title: "Non-linear relationship between energy intensity and economic growth".

18th - 20th of November 2002, paper presented at the Encuentro Nacional Rio + 10: II Cumbre de la Tierra held at the University of Almeria. Title: "Johannesburg '02: La política ambiental en venta".

6th and 7th of June 2002, paper presented jointly with Miquel Ortega Cerdà at the IX Symposium on Economic History held at the Autonomous University of Barcelona. Title: "Energy intensity and economic growth: attractor points for both developed and developing countries".

25th-29th of April 2002, seminar given at the workshop SOCIAL METABOLISM. Physical indicators of unsustainability Universitat Autònoma de Barcelona. Title: "Multiple-Scale Integrated Assessment of Societal Metabolism".

From 6th to 9th March 2002, two papers given at the 7th Biennial Conference of the ISEE (International Society for Ecological Economics), held in Sousse, Tunisia. Titles: "Grandfathering vs. equitable allocations: The case for CO_2 emission rights", and "Integrated assessment of development trajectories: the two sides of the bifurcation of economic development (Spain versus Ecuador)", this latter jointly with Fander Falconí.

30th- 31st August 2001, paper given at the Conservation and Sustainable Development – Comparative Perspectives workshop, held at the Yale Center for Comparative Research, Yale University, New Haven, USA. Title: "Empiricism in Ecological Economics: A Vision from Complex Systems Theory".

From 4th to 7th of July 2001, paper given with John Proops at the EC High Level Scientific Conference, "Frontiers 1: Fundamental Issues of Ecological Economics", organised by the ESEE (European Society for Ecological Economics), Cambridge, UK. Title: "Empiricism in ecological economics: can there be a predictive ecological econometrics?".

From 18th to 22nd of June 2001, paper given at the Tercera Convención Internacional sobre Medio Ambiente y Desarrollo. Tercer Congreso de Economía y Medio Ambiente. La Habana, Cuba. Title: "Empirismo en economía ecológica: una visión desde la teoría de los sistemas complejos".

From 23rd to 27th of May 2000, poster presented at the Second International Workshop *Advances in Energy Studies* "Exploring Supplies, Constraints, and Strategies". Porto Venere, Italy. Title: Non-linearity in energy metabolism of Spain: "Attractor Points" for the Development of Energy Intensity.

From 3rd to 6th of May 2000, 2 communications presented at the Third International Conference of the *European Society for Ecological Economics* "Transitions to a Sustainable Europe: Ecology-Economy-Policy", University of Vienna, Austria. Titles: "The Role of the Different Groups of Countries in the International Negotiations on Climate Change", and "Brief comment on dematerialization and the energy intensity in Spain".

From 12th to 16th July 1999: communication, jointly with Professor Joan Subirats "Ejercicio de simulación de las negociaciones de Cambio Climático. Negociación de un protocolo que limite las emisiones de gases de efecto invernadero", at the *I Curs Internacional d'Estiu de Medi Ambient. Medi i societat: noves tendències,* Canillo, Andorra. Organised by the Institut d'Estudis Andorrans.

January 1999: "Workshop on Complex Systems Analysis**,** European Project "Environmental Valuation in Europe". Barcelona.

From 4th to 7th of March 1998, participant at the Second International Conference of the *European Society for Ecological Economics* on: "Ecological Economics and Development" at the University of Geneva, Switzerland.

LANGUAGES

Spanish and Catalan: mother tongue.

English: Fluent in reading, writing and speaking. TOEFL and IELTS. Two years living in the UK. Several publications in English.
Italian: Fluent in reading, writing and speaking, 2 years living and working in Italy.

Portuguese: reading and understanding.

COMPUTER KNOWLEDGE

Knowledge of the MS Office package, including the word processor Word; the spreadsheet Excel, the presentation assistant PowerPoint, web editor Front-Page, as well as Netscape Navigator and Microsoft Internet Explorer, for Internet. Moreover, I have used Access database and the statistical program SPSS. Programming in HTML language as well.

PROFESSIONAL DETAILS

From May 2005: Researcher at the Institute for Social Ecology, Faculty for Interdisciplinary Studies of the University of Klagenfurt (Klagenfurt-Graz-Wien), Austria.

September 2003 – April 2005: Researcher at the Istituto Nazionale di Ricerca per gli Alimenti e la Nutrizione (Italian National Institute of Research on Food and Nutrition), Roma, Italy. Working on a Participatory Integrated Assessment of the use of GMOs in agriculture.

August 2002: Associated lecturer of "Ecological Economics" and "Economics and Politics of Climate Change" at Facultad Latinoamericana de Ciencias Sociales (FLACSO), in Quito, Ecuador.

Since February 2002, founding partner and Manager of the environmental consultancy **ENT Environment and Management** (http://www.ent-consulting.com), in charge of the Administration and Finances.

October 2000 – September 2003 and October 1998 - September 1999: associated lecturer of the degree course subject "Economics of Natural Resources" to both Economics and Environmental Sciences students at the Autonomous University of Barcelona.

August 1998: Co-ordinator and lecturer of the subject "Environmental Management Systems", in the Summer Courses of the Open University of Catalonia, dealing with the relationship between the environment and firms in general, and the environmental standards EMAS and ISO 14001 in particular.

March-June 1998: assistant lecturer of the degree course subject "Economics of Natural Resources" in the framework of the "New Project of Joint Subjects in Videoconference between the Polytechnic University of Madrid and the Autonomous University of Barcelona", monitoring and assessing the students of the Polytechnic University of Madrid.

February-June 1998: Rugby instructor in some primary and secondary schools of Santa Coloma de Gramenet, within the Sport Club Puig Castellar and Santa Coloma City Council Joint Programme on "Initiation and Promotion of Rugby in schools 1998".

March-April 1998: Co-author and chairperson of the virtual discussion forum on "Industry and the Environment" in the Open University of Catalonia web page within the framework of the ECOCAMPUS project.

From September 1996 to June 1997 I have done the Military Service as an Officer, specifically as a second lieutenant.

From October 1995 to June 1996 I have been scholarship holder in the Library Service of the Autonomous University of Barcelona.

RESEARCH PROJECTS

2005: Researcher for the EU funded project “MATISSE: Methods and Tools for Integrated Sustainability Assessment”.

2005: Researcher for the EU funded project (INTERREG IIIB Programme) “MARS: Monitoring the Alpine Region’s Sustainability”.

2003-2004: Researcher for the Italian Ministry of Agriculture project “Developing procedures for improving the quality of scientific information used for diffusion on GMOs”.

2002-2003: Researcher for the EU funded project “Development and application of a multi-criteria software decision analysis tool for renewable energy sources”, contract NNE5-1999-NNE5/273/2001, under the supervision of Professor Giuseppe Munda.

2002: Participant in the Integrated Action between the Spanish Ministry for Science and Technology and the Austrian Government, contract HU2000-0025: “Integración del análisis de flujos de materia y energía en el análisis multicriterial (Integrating materials and energy flows analysis into multicriteria analysis)”.

2002: Participant at the project EASY-ECO (Evaluation of Sustainability in Europe), coordinated by the University of Economics and business Administration of Vienna, and funded by the European Commission (Contract HPCF-CT-2001-00286).

1999-2002: Member of the research group at Autonomous University of Barcelona in the project “Evaluación económico-ambiental en un marco internacional (Environmental-economic evaluation in an international framework)”, funded by the Spanish Ministry of Education and Science, DGICYT (Sectorial Program of General Promotion of Knowledge), contract P98-0868.

ORGANISATION OF EVENTS

Member of the Organising Committee of the 2nd Liphe4 *Summer School on Participatory Integrated Assessment of Sustainability* (www.liphe4.org/school.html), held in Sangonera la Verde (Murcia, Spain), from 17th to 23rd July 2005.

Member of the Scientific Committee of the *6th International Conference of the European Society for Ecological Economics* (http://www.esee2005.org/), to be held in Lisbon, 14th-17th June 2005.

Member of the Scientific Committee of the International Conference *Complexity, Science & Society* (http://www.liv.ac.uk/ccr/2005_conf/), organised by the Center for Complexity Research, The University of Liverpool, to be held in Liverpool, 11th-14th September 2005.

Member of the Organising Committee of the Second *Iberoamerican Congress on Development and Environment*, to be held in Mexico DF, Mexico, in November 2005.

Member of the Organising Committee of the Liphe4 *Summer Workshop on Participatory Integrated Assessment of Sustainability* (www.liphe4.org/school), held in Deutschlandsberg (Austria), from 20th to 27th August 2004.

Member of the Organising Committee of the *Iberoamerican Congress on Development and Environment* (http://www.ent-consulting.com/cidma), held in Quito, Ecuador, from 9th to 12th April 2003.

SCIENTIFIC ASSOCIATIONS

Member of the Board of the European Society for Ecological Economics.

Member of the International Society for Ecological Economics.

Member of the European Working Group "Multiple Criteria Decision Aiding".

Founding member of the Asociación Hispano Portuguesa de Economía de los Recursos Naturales (Portuguese-Spanish Association of Natural Resource Economics).

Founding member of the Red Iberoamericana de Economía Ecológica (Iberoamerican Network for Ecological Economics).

Founding member of the Scientific Society LIPHE[4]

Member of the Editorial Board of the Revista Iberoamericana de Economía Ecológica (Iberoamerican Journal of Ecological Economics).

LIST OF PUBLICATIONS

(1) Ramos-Martin, J. (1999b): "New role of Flexibility Mechanisms for improving equity under a new burden sharing scheme", *Joint Implementation Quarterly,* Vol. 5 (4).

(2) Ramos-Martin, J. (1999a): "Breve comentario sobre la desmaterialización en el estado español", *Ecología Política*, 18: 61-64.

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

(4) Ramos-Martin, J. (2001b): "Non-linearity in energy metabolism of Spain: "Attractor Points" for the Development of Energy Intensity", in S. Ulgiati et al. (eds), *Advances in Energy Studies. Exploring Supplies, Constraints, and Strategies,* Padova (Italy), SGE Editoriali. Pp: 535-542.

(5) Ramos-Martin, J. and J. Proops (2001): "Empiricism in ecological economics: can there be a predictive ecological econometrics?". *ISEE Working Paper*.

(6) Ramos-Martin, J. (2001c): "De Kyoto a Marrakech: historia de una flexibilización anunciada", *Ecología Política* 22: 45-56.

(7) Ramos-Martin, J. (2003a): "Empiricism in Ecological Economics: A Perspective from Complex Systems Theory", *Ecological Economics* Vol 46/3 pp 387-398.

(8) Ramos-Martin, J. (2003b). "Intensidad energética de la economía española: una perspectiva integrada", *Revista de Economía Industrial*. Number 351(III): 59-72.

(9) Ramos-Martin, J. (2003c): "Empirismo en economía ecológica: una visión desde la teoría de sistemas complejos", *Revista de Economía Crítica.* Vol. 1: 75-93.

(10) Falconí, F., Ramos-Martin, J. (2003). "Societal Metabolism of Societies: The bifurcation between Spain and Ecuador". In: *Advances in Energy Studies. Reconsidering the Importance of Energy,* S. Ulgiati, M.T. Brown, M. Giampietro, R.A. Herendeen, and K. Mayumi, Editors. SGE Publisher Padova, Italy, 2003, pp.45/61.

(11) Ramos-Martin, J., Russi, D., Puig, I., Ortega, M., and Ungar, P. (2003): *Deuda Ecológica. ¿Quién debe a quién?* Icaria Editorial, Barcelona. Also published in Catalan by the same Publisher, and in Italian (DEBITO ECOLOGICO Chi deve a chi? Editrice Missionaria Italiana. 2003).

(12) Ramos-Martin, J. (2004a): “La perspectiva biofísica del proceso económico: Economía Ecológica”. In F. Falconi, M. Hercowitz, R. Muradian (Eds.): *Globalización y Desarrollo en América Latina*. FLACSO, Quito, Ecuador, pp. 19/47.

(13) Ramos-Martin, J. (2004b): “La perspectiva biofísica de la relació home-natura: Economia Ecològica”, in J. Valdivielso (Ed.), *Les dimensions socials de la crisi ecològica*, Edicions UIB, Palma de Mallorca, Spain, 2004.

(14) Iraegui, J., and Ramos-Martin, J. (2004). *Gestió Energètica Local (Local Energy Management).* Fundació Pi i Sunyer i Diputació de Barcelona.

(15) Giampietro, M., and Ramos-Martin, J. (2005): “Multi-Scale Integrated Analysis of Sustainability: a methodological tool to improve the quality of narratives”, *International Journal of Global Environmental Issues*, in press.

(16) Ramos-Martin, J., and Giampietro, M. (2005): “Multi-Scale Integrated Analysis of Societal Metabolism: Learning from trajectories of development and building robust scenarios”, *International Journal of Global Environmental Issues*, in press.