ECOLOGY AND ECONOMY: A SYSTEMS PERSPECTIVE

By: Andrew M. Losos

Supervisor: Dr. Peter A. Victor

Volume 10, Number 5
FES Outstanding Graduate Student Paper Series
September 2005
ISSN 1702-3548 (online)
ISSN 1702-3521 (print)

Faculty of Environmental Studies
York University
Toronto, Ontario
M3J 1P3

I. Abstract

This paper presents a theoretical analysis of an economy from the perspective of systems and hierarchy theory. Economic systems are examined in two dimensions – the material and the functional – each of which is regarded as one aspect of a dual hierarchy. The issue of proper scaling is addressed. Throughout this examination, efforts are made to compare the organisation of economic systems with that of ecosystems. Finally, similarities and differences between the two are discussed.

TABLE OF CONTENTS

II. Introduction

> "Arguably the most critical problem that any of us face is recognizing causal relationships in the complex systems in which we work and live. The systems approach… allows us to identify causal relationships in complex systems that cannot be identified by other methods of problem solving."
>
> (Grant, 1998: 67)

Economies and ecosystems have certain common characteristics. Both allocate material and energy between interacting entities to satisfy certain needs. There are also very intimate and important connections between them, as ecosystems supply the material and energy inputs that economies need, while economies dispose of their wastes back into ecosystems. On the other hand, there are some ways in which the two are quite distinct: for example, the existence in economies of money for exchange. This paper explores the reasons for and extent of these apparent similarities and differences in the organisation of ecosystems and economies from a systems perspective. It also attempts to put the interface between them into the same context.

This paper has its origins in an intuitive sense of the apparent similarities between these two kinds of systems. Overall, can it or can it not be said that ecosystems and economies have something in common? There is a sense that some of the principles at work in one may also be at work in the other, and that understanding of either might be increased by study of the characteristics common to both. Many researchers do not make many fundamental distinctions between economic and ecological system organisation (see Boulding, 1978, Matutinovic, 2002, Weston and Ruth, 1997). From their perspective, the two are merely variants of a general organisational pattern – different species of the same genus, as it were. This paper will investigate one potential basis for such a view.

Economic systems are subject to similar constraints of analysis as apply to ecosystems, though economics has generally enjoyed better predictive success than ecology to date. Most easily conceptualised in either the abstracted aggregate or in the detailed microscopic instance, the field of economic research nevertheless has yet to devote much attention to consideration of economies as complex systems or to the application of systems theory to them. Using hierarchy theory as a tool, this paper will present a systemic analysis of economic organisational structures as nested hierarchies in similar fashion to the treatment of ecosystems. In this case, two perspectives will be considered: a material perspective, and a functional perspective.

III. The Economy as a Hierarchical System

Are economies hierarchically organised? There is a growing school of thought within the discipline of economics that believes that economies are in fact complex adaptive systems similar to ecosystems. Theorists such as Boulding (1978, 1993), Daly (1992), Giampietro and Mayumi (1997), and Odum et al. (2000), among others, have collectively produced the kernel of a body of literature on the subject.

What is an Economy?

Economies must be regarded more as a concept than as a strictly physical thing. As is the case with systems, the question of subjectivity is relevant: is "the economy" something which exists "out there" or not? Boulding (1993: 1) states that though the economy is an incredibly complex structure to contemplate in its entirety, the mind "can form some picture of the immensely complicated system that constitutes our world, with interacting and moving objects ranging from quarks to continents" – in other words, a mental map (Vanderburg, 2000). Reference to "the economy" is best explained as a representation of the mental map of the person making the reference.

An economy is not an entirely symbolic entity, however. It is a functioning system, with real and measurable inputs, outputs and components underlying the subjectivity of the observer (Ogle, 2000). Boulding (1993: 2) reinforces this interpretation: "An economy … is what mathematicians call a 'fuzzy set'. The boundary that divides what is in the economy from what is not may not always be clear, but this does not mean that it is not real or important."

Interestingly, the task of defining what is meant by "economy" is rarely addressed directly in the economic literature (Fisher, 1913, Levine, 1978a, 1978b, and Marshall, 1961). Lipsey (1979) approximates an actual definition as a network of interrelated markets. This definition assumes a great deal, however. For example, it assumes that an economy contains markets, while command economies do not. A more recent definition seems to capture the consensus popular definition: "[An economy is] a set of interrelated production and consumption activities." (Lipsey et al., 1997: G-5). This is still a very broad stroke.

A more detailed definition is therefore proposed: *The economy is the system of material and functional relationships involved in the transformation of raw materials into goods and services and their distribution for consumption and disposal.* This definition has three main advantages: first, it makes explicit the interrelation of material and social elements of the system, emphasising that an economy is neither completely concrete nor completely conceptual. Second, it includes the full material life cycle from extraction of natural resources to disposal of wastes. Third, it includes the functional elements of the economy: transformation, distribution, consumption and disposal.

In the absence of a detailed and explicit definition from economists of the economy, the following section sketches the framework of Kenneth Boulding's unique understanding of an economy and of economic processes. Boulding, more than almost any other economist, tried to bridge the gap between economics and ecology using systems theory.

Boulding on the Nature of Economies

Boulding expressly blurs the lines between economy and ecosystem, encompassing both human (economic) and non-human (ecological) production systems:

> [C]ommodities are produced in ways that are not essentially different from the ways in which living organisms are produced – by the operation of some kind of *knowledge* structure or know-how or plan, which has the ability to direct *energy* toward the selection, transportation, and transformation of *materials* into the appropriate forms, whether this is a chicken or an automobile. (Boulding, 1978: 173-174, emphases not added)

Indeed, this is one of the most intriguing and unique characteristics of Boulding's theory as outlined here and of his broad approach to economics in general: it is not strictly limited to the traditional realm of economic activity. His vision is inherently integrative:

> All production, whether of a plant from a seed or of a clay pot by a potter, involves the 'know-how' to direct energy of appropriate kinds and information to the selection, transportation and transformation of material into a particular phenotype – a tree, a bird, a cat or a human being – or into a house, a car or a clay pot. (Boulding, 1993: 3)

Boulding's contention is very elegant indeed as it points to a common root of all productive processes and breaks through the intellectual compartmentalisation that studies the human production processes as being somehow fundamentally different than their natural counterparts. Thus he presents as fact the parallels identified in this paper: rather than being distinct, ecological and economic systems share essential similarities in form and function.

This does not imply, however, that there are no significant differences between the nature of production between ecological and economic systems. For Boulding, these differences are anchored in his dual concept of evolution (1978: 14-15). The era of the early hominids was governed mainly by biogenetic evolution, in which adaptations occur mainly through mutation and natural selection helps to perpetuate favourable adaptations while eliminating unfavourable ones. Adaptations spread throughout the population through breeding, propagating further with each new generation. This is what is traditionally understood by the term "evolution", as it is the evolutionary process which is common to all organisms. Ecological systems are still governed by this form of evolution.

In the case of organisms with sufficiently advanced intellectual capacities, however, a second process of evolution can emerge. This process is the evolution of cognitive processes, which Boulding terms "noogenetics" – not merely the emergence of cognitive processes where none existed before, but also the evolution of those processes from simpler to more complex configurations (Boulding, 1978: 14). Noogenetic evolution is distinct from genetics in that it can occur much more rapidly. Indeed, learning can occur within the space of a few moments for simple tasks, or over a period of years for more complex studies.

The unique way in which Boulding frames the economy leads to some novel and interesting considerations. For example, could a forest be considered to be an organisation within the context of the economy? It can hardly be said that economies produce forests. However, if one expands one's definition of "the economy" beyond the strictly conventional, one might consider the process of maintaining and regenerating the forest as an economic activity in its own right. Does it not contribute to the economy? A growing forest is producing natural capital in the form of biomass, which is not strictly a human artefact, but can be used as an input to a human economic system. It also provides environmental services: sequestration of atmospheric carbon, prevention of soil erosion, filtration and retention of groundwater, etc., which benefit humans and contribute in indirect ways to conventional economic processes. These activities are fundamental to the sustenance of "the economy" but they occur in nature. A managed forest, for example, or indeed any cultivated land, is simultaneously part of an ecosystem and of the economy. This example illustrates the great advantage of this theory: it permits productive processes to be viewed as a seamless continuum, all but erasing the artificial nature-economy boundary and emphasising the integration and interdependence of the ecological with the economic.

Boulding's theories are informative as a background against which to investigate hierarchical interpretations of economic systems, as we shall see in the following sections.

Complexity in Economic Systems

Much of the basis for comparison lies in the fact that existing methods for modelling economic systems have – like those for ecosystems – been predominantly based on reductionist approaches which seek to treat economies as small-number systems – microeconomics – or to aggregate them so that they may be analysed with statistical methods – macroeconomics (Boulding, 1950: 3). As with ecology, these approaches have increasingly proven inadequate to explain observed phenomena or as a guide for planning interventions. Also as with ecology, the result has been a determined search for new models which may prove more suitable. The search for new models appears so far to be less advanced among economists than among ecologists.

Unlike large-number systems, economies cannot be conveniently divided into subunits. This is due partly to the heterogeneity of the system components themselves: within any given economy, even firms performing similar functions can have widely differing compositions and behaviours. It is also due in part to the overlap in roles between firms and their components. For example, for some purposes, the output of individuals' labour can reasonably be aggregated and treated as a single firm with an economic throughput equal to the sum of the throughputs of its component individuals. However, those individuals are also economic agents in their own right: each conducts personal economic transactions of buying and selling to meet his or her needs independently of the needs of the firm to which he or she belongs. This undermines the assumption of the firm as a coherent subunit for aggregation. Most importantly, however – and this is the reason for the apparent contradiction – it is also compelling evidence of a hierarchical structure, as components on one scale are acting as holons on a lower scale. Hierarchically organised systems tend characteristically to defy reductive and aggregative methods of observation.

At the opposite end of the spectrum, economies cannot practically be treated as small-number systems either, because they share with ecosystems the heterogeneity of components and relative strength of interactions which make reduction unviable as an effective modelling technique on all but the most limited scales. Economic systems are not readily described using deterministic mathematical models. Unlike Newton's Law of Gravitation, for example, it is difficult to see how a universal (i.e. applicable in all situations and therefore usable to predict system behaviour accurately) mathematical law could be derived to describe the behaviour of firms or markets. Though microeconomic theory may derive some mathematical rules – subject to some significant assumptions – which govern relationships between a small number of entities, those rules are not sufficient to explain the properties of the whole. The high degree of organisation of the world economy combined with the number of interacting components make the system too complex; overall behaviour takes the form of emergent properties which cannot be described in terms of the properties of individual entities. Economies must therefore be considered middle-number systems like ecosystems – and for the same reasons.

There is a growing consensus in the ecological economics community that economies can be understood as complex adaptive systems. (see for example Boulding 1993, Giampietro and Mayumi 1997, Leijonhufvud 1999). Matutinovic (2002) places economies alongside ecosystems, immune systems, embryos, nervous systems and computer networks under the heading of complex adaptive systems, giving us at the very least some hope that observing economies from a systems perspective may have value: "Describing different systems from the same conceptual perspective opens ground for insights, understanding and analogy building. Different systems having the same properties and mechanisms are expected to have similar organizational patterns, regardless of the details of the agents composing the system." (Matutinovic, 2002: 422).

It seems that there is at least some basis in the literature and in the theory of complexity for a comparison to be drawn on these grounds between economies and ecosystems. The sections which follow will explore that comparison further, looking at these similarities through the lens of hierarchy theory.

Dual Hierarchy in Economies

There is, according to Matutinovic (2002: 423), a growing consensus that many ecological concepts may be successfully employed to describe human social systems, which implies that an analogy between ecological and economic models could be found. For the purposes of comparison with ecosystems, a material-functional dual hierarchy will be explored for economic systems.

Important research has been done on the hierarchical structure of economic systems from the independent material and functional perspectives. In this paper the work of Matutinovic (2002) and of Giampietro and Mayumi (1997) shall be examined.

Material Hierarchy Components

This most directly perceivable of the two hierarchies contains the physical components of the economy. As a consequence of its relative ease of perception, the material hierarchy is the more likely to form a part of the mental maps of most people than is a hierarchy based on function.

Matutinovic (2002) presents a model of the material economy based in part on the work of Holland (1988, 1995). This model is explicitly hierarchical:

> The economy is composed of many agents, which can be regarded as building blocks: people, departments, firms, industrial sectors and national economies, forming hierarchical aggregates that can be extended up to the world economy. These heterogeneous agents are interconnected with flows – exchanging goods, services, information, and money. They are embedded in the natural environment, which provides the very basis for their survival with its source and sink functions. (Matutinovic, 2002: 422)

Here we have the essentials needed to understand the material economic hierarchy: the so-called "building blocks" or holons, the nature of the relationship between them, the "environment" beyond the system boundary, and the flows across that boundary. This model does not adopt the explicit continuity of ecosystem and economy of Boulding's theory, but acknowledges the strong interdependence of the two:

> Both ecologies and economies are constituent parts of the larger meta-system, the ecosphere. In this meta-system we can observe how its different building blocks – biological and cultural – aggregate to form local subsystems – biotic and social. The exchange of matter and energy between the global economy and the ecosphere produces a complex feedback, which has the possibility of affecting the functioning and stability of the meta-system and the human subsystem. (Matutinovic, 2002: 422)

Such local subsystems can take many different forms, depending on the scale at which they occur. Note also that they need not be strictly material in nature; they could potentially take the form of organisations, for example.

Figures 1a and 1b, below, illustrate the parallel structure of physical flows in the context of ecological and economic systems, respectively. In 1a, internal flows (T_{ij}, T_{jk}, …) of material and energy occur between arbitrary compartments or holons (C_i, C_j) of an ecosystem and from those components to the environment in the form of "useful exports or detritus" ($T_{i,n+1}$, $T_{j,n+1}$), inputs of raw materials (T_{0i}), or dissipation through respiration ($T_{i,n+2}$, $T_{j,n+2}$). This accounts for the complete material balance in the ecosystem – all inputs are conserved in outputs or wastes.

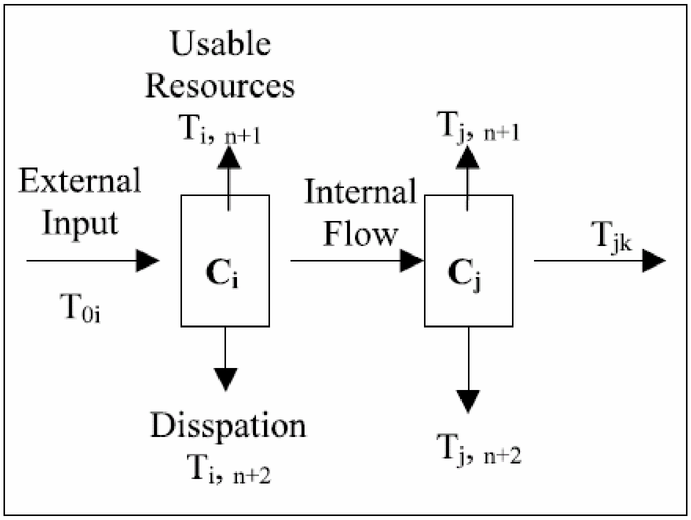

Figure 1a - Ecosystem flow diagram (Matutinovic, 2002: 423)

It is interesting to note that little distinction is made between flows of matter and energy in this model. In ecological systems, energy is transferred almost exclusively through a material medium (Krebs, 2001: 514). The internal flows (T_{ij}, T_{jk}, etc.) in an ecosystem consist of the transfer of matter and energy through predatory relationships. If one takes the compartments in the example to be individual organisms, the product of one organism C_i is its own body mass and total embodied energy. Through predation, this becomes the input to another organism C_j. Organisms consume one another not only because they need inputs of certain materials to maintain their own physical structure, but also because they need the energy stored in the tissues of the prey to maintain their energetic structure. For this reason, it is not necessary to make great distinctions between flows of matter and of energy: their mechanisms are essentially the same, and indeed any given transfer will involve elements of both. Primary producers, who receive their energy inputs directly from solar radiation and store it in complex molecules through photosynthesis, are a notable exception because they do not receive their inputs of material or energy through predation. Hence their role as producers: all predation at higher trophic levels is in essence a contest to possess and consume the complex molecules that photosynthesis invests with trapped solar energy. The roles of materials in energy transfer will be discussed below, along with the functional hierarchy.

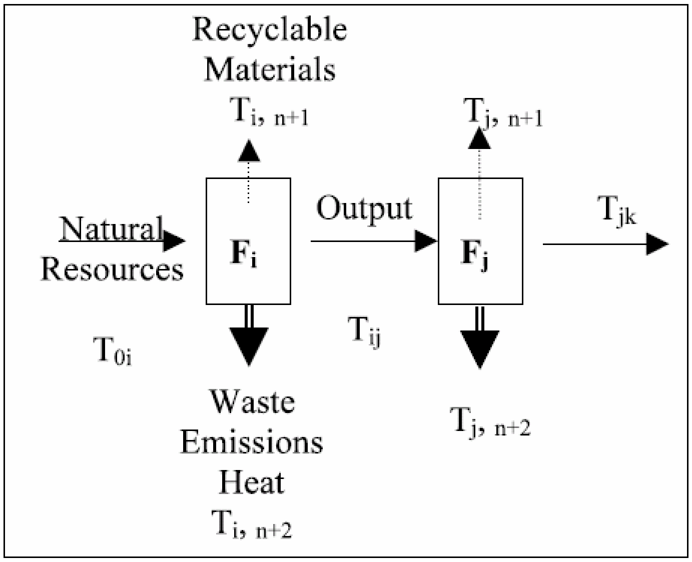

Figure 1b - Economic flow diagram (Matutinovic, 2002: 423)

The case of human economic systems is only marginally different from that of ecosystems. As it does in ecosystems, energy circulates within human systems and is transformed by the system's component entities. This is the economy's metabolism (De Rosnay, 1975). Technology – electricity in particular – has made it possible in some cases for energy to flow without a corresponding transfer of materials, but this merely spatially separates cause from effect as the energy is still generated from a material carrier. Even for most technological applications, it is often most practical to use materials to store energy for use. Fossil fuels are an example of this – the "food" of choice of the modern industrial economy. Even fossil fuels are products of ecological processes – ultimately of photosynthesis – and economies have as yet no substitute for them.

No human technology has yet been able to duplicate the feat accomplished by chlorophyll, which is to make energy bioavailable. For their own internal, organic energy needs, humans must still rely on energy resident in material vehicles (i.e. food). As we shall now see in discussion of economic material flows, technology does not free humans or their economies of the operating constraints of ecological systems. Though technology may appear to make economic systems qualitatively different from ecosystems, when one examines their material bases, their similarities outweigh the differences.

Figure 1b, above, depicts the material and energy flows in a generic economic system. As in the ecological model of Figure 1a, transfers occur between the environment and entities within the economy – in this case, firms (F_i, F_j) which may represent holons at any level – from individual consumers to national economies as this illustration is not scale-specific. Scaling of the model will be discussed below.

In this model of the material economy, the lines between energy and material flows are blurred once again. As in Figure 1a, no distinction need be made between flow types. Flows of natural resources (T_{0i}) can include materials gathered for their physical properties (e.g. steel, silicon, lumber, etc.) or their stored energy (e.g. oil, coal, firewood, foodstuffs). Some materials can possess both of these properties, making them more versatile and consequently more valuable. Wood, for example, can be used as lumber or as firewood. Petroleum can be burned as fuel or used as feedstock for plastics. These inputs cross the environment-economy boundary when they enter the "economic process" (Matutinovic, 2002: 424). Recyclable materials are those by-products of processing which can be used as inputs to other processes – an analogue to detritus in the ecosystem model.

Internal flows generally consist of an output from one firm which serves as an input to another. Unlike in ecosystems, "predation" in economies need not result in the consumption of one firm by another – though firms can be merged into one another or "die" and their physical components (assets) incorporated into other firms. Instead, the product is separate from the firm itself. Another very important distinction of economic flows is that they generally involve some kind of exchange, unlike the unidirectional flows within ecosystems. A flow of material in one direction is compensated by a flow of exchange goods – money, material goods, and/or energy – in the opposite direction. However, the overall flow through the economy is from natural resources through firms to waste which then returns to the environment.

Unlike ecological systems, economies generally do not have dedicated analogues to decomposers. As a result, not all waste produced by an economy can be recycled and there is a net flow of wastes to the environment, where they will break down. The environment, therefore, functions as the ultimate decomposer for the material wastes produced by economies. Depending on the nature of those wastes and the relationship between their rate of production and the rate at which ecological processes can break them down, such a situation can result in a net build-up of economic wastes in the environment.

Therefore, where ecosystems have a circular flow of materials cycling through organisms, being broken down through decomposition and being taken up into biomass again, economies have a predominantly linear material flow pattern – raw materials from the environment into the economic process within and between firms and then out to the environment again as wastes in an economically unusable, high-entropy state. With regard to energy, however, both economies and ecosystems ride the same thermodynamic "arrow of time": energy cannot be recycled in the same way that matter can. Low-entropy (i.e. useful) energy is taken in as exergy and broken down by the metabolism of successive entities, leaving only high-entropy, degraded energy to be dissipated when it is no longer useful. In the context of the Earth, all exergy available to both ecosystems and economies can be traced back to solar radiation made chemically available through photosynthesis, whether embodied in living organisms or transformed through geological processes into fossil fuels. Waste energy is dissipated through radiation into space (Georgescu-Roegen, 1971: 243-244).

Gradients (Muller, 1998) are useful in analysing the organisation of economies – as they are for ecosystems. The most obvious evidence of this can be found in the continual demand for “raw materials” – which is in essence a term meaning “low-entropy material inputs” for economic processes. Consider for example the production of iron. First, a deposit of iron ore is located in an accessible location within the earth’s crust. Such a deposit already represents a gradient: a concentration of relatively high abundance of iron within a limited area. Iron can of course be found in non-economical quantities in any handful of soil or sand one may choose, but in order to be economically useful, there must already be an existing natural gradient. From that deposit, then, the ore is removed from the ground and through the process of smelting, energy is applied to remove impurities from it until only the purified iron is left. This is the process of making the concentration gradient steeper. Indeed, economic value is often associated with the steepness of this gradient: purer substances are typically valued more highly than less pure ones – unless the purer substance carries a negative economic value as in the case of a contaminant, for example. This is an example of the economic process doing with inanimate objects what living organisms do with their own bodies: using a continual flow of exergy to reduce local entropy.

Scaling

How does scaling work in the material hierarchy? In the context of an economy, it is likely to be useful to observe systems at scales as low as individual people, which may be regarded as the basic coherent unit of economic action. At the level of the firm, however, the composition and nature of individual holons may be highly variable as firms can be quite heterogeneous. A firm might represent one person individually producing and consuming in her home workshop in connection with other firms, or it might represent a large corporation with thousands of employees and many material assets. Matutinovic (2002: 424) designates firms as the analogues of biological species, and national economic sectors as analogues of higher trophic aggregations. This model, he writes, can be extended up to the level of international trade where the individual holons represent national economies.

There is some ambiguity in where meaningful distinctions between levels may be found. It is not clear, for example, how many levels may exist in the modern, global economy of today. In theory, it is possible to conceive of economic holons at the level of individual firms, neighbourhoods (e.g. street market), cities, regions, meta-regions, and finally, the largest possible meta-region: the globe. Note that these spatiotemporal scales do not necessarily correspond to political boundaries, raising some interesting management challenges. Even the status of the national economy – a mainstay of existing macroeconomic theory – is somewhat unclear in this hierarchy, a fact which has played a central part in the debate over globalisation. When political jurisdictions are added to the picture, the hierarchy is no longer completely nested. When left to their own devices, economies do not naturally conform to non-economic boundaries. From a systems point of view, it is this tension between the natural tendency of economies to obey their own self-defined organisational structure and the tendency of human societies to construct boundaries based on non-economic criteria that forms the core of the worldwide conflict regarding globalisation.

What then can be the role of the familiar city-province-country-continent structure? There is not, as yet, any comprehensive answer to this question in the literature on the theory of economic systems. However, if one considers that the hierarchy of political jurisdictions represents just one dimension of the economic hierarchy, one might see how the complicated, semi-nested structure that currently exists could in fact be decomposed into two interlaced hierarchies as O'Neill et al. (1986: 198) did for ecosystems. Each dimension examined – political, functional, material, or other – may reveal a different configuration. The union of those configurations constitutes the actual system.

Signals are passed vertically between levels of this hierarchy as well as horizontally within each level. Within an arbitrarily chosen focal Level 0 of the material hierarchy, the ongoing economic processes will be the interactions of supply and demand between holons, represented by internal flows T_{ij} in Figure 1b. These flows can be of matter, energy, or money. The most common mechanism for these flows is that of exchange – the trading of goods between entities. Other mechanisms are possible, however (Boulding,1978: 222-224). In the process of producing and delivering these goods, materials will be consumed, energy will be dissipated, and waste will be generated. Economic activity also involves significant transfer of information by means of language within Level 0, as orders are sent, prices signalled, etc.

Vertical signals travelling upward from Level -1 to Level 0 are the enablers of activity at Level 0. These will often be the aggregated outputs of holons on the lower level: for example, the combined output of a number of production line workers at Level -1 enable supply to flow from the firm at Level 0, which in turn supplies other firms through exchange. Signals from Level 0 to Level +1 display this same pattern, except that firms act as holons within higher groupings – such as a market, for example.

Downward signals act as constraints on the enablers manifested at lower levels. In this context, those signals are likely to be represented as demand: the firm (Level 0) controls the workers (Level -1) through production orders – a manifestation of demand. The demand at level 0 is in turn influenced by demand at higher levels. There may also be other constraints; for instance, shortages of materials, wars, high energy prices, labour unrest, etc. Overall, upward signals generally correspond to supply or potential supply, while downward signals represent demand, which both limits and stimulates supply. The higher levels therefore moderate the activity occurring at lower levels. This raises some interesting questions about social structures and hierarchies, since it apparently means that those who exercise control of the higher levels can also thereby control the lower ones. An inquiry based on political economic theory would be of benefit here.

Holons and processes at Level 0 will operate at lower frequencies than those at Level -1, and those at Level +1 lower still, since distances at higher levels tend to be greater and therefore movement of materials slower. The past century or so, in which rapid, long-distance communication has become increasingly accessible until now it is very widely available through the internet and telephones, has seen the potential lag times between demand creation and demand satisfaction shortened. An intriguing possibility for further research would be to study the effects of this acceleration of communications on the vertical and horizontal signals and structure of the economic hierarchies.

The material hierarchy described here shows some similarities with the biotic hierarchy described above for ecological systems. Difficulties in establishing spatial scales in particular seem to be common to both. The next section will examine the economy from the perspective of function.

Functional Hierarchy Components

The functional approach to understanding the economic hierarchy has been addressed by Giampietro and Mayumi (1997). This chapter examines and expands on the hierarchy they propose. Rather than assessing levels of the hierarchy on the basis of space and time, level differentiation is accomplished based on nesting of functions. The authors set the whole society as the focal level – Level 0. Level +1 is the global ecosystem, which enfolds society and encompasses "the ensemble of biophysical processes on which society depends." (455). Level -1 can be a number of subsets of society, be they specific economic sectors, social groups or individuals whose interactions with the whole society are of interest. This sets the stage for an analysis of the functional structure of the economy within society.

The overall function of the economy is to maintain and improve the structures of society, as part of the ongoing self-organisation process of society as a whole, (Giampietro and Mayumi, 1997: 455). Within this overarching process, economic processes may be grouped into two categories. The first deals with *efficiency* according to present boundary conditions, or the process of "sustaining the short-term stability of the [self-organisation] process by taking advantage of existing favourable gradients" (455). The second relates to *adaptability* in the face of long-term unpredictable change in boundary conditions, or "sustaining the long-term stability of such a process by maintaining a high compatibility in the face of a changing environment." (455). Figure 2, below, illustrates how exosomatic energy – that useful energy available outside human bodies, as opposed to endosomatic energy which is used to maintain the body – and human time are divided between economic functions within this context:

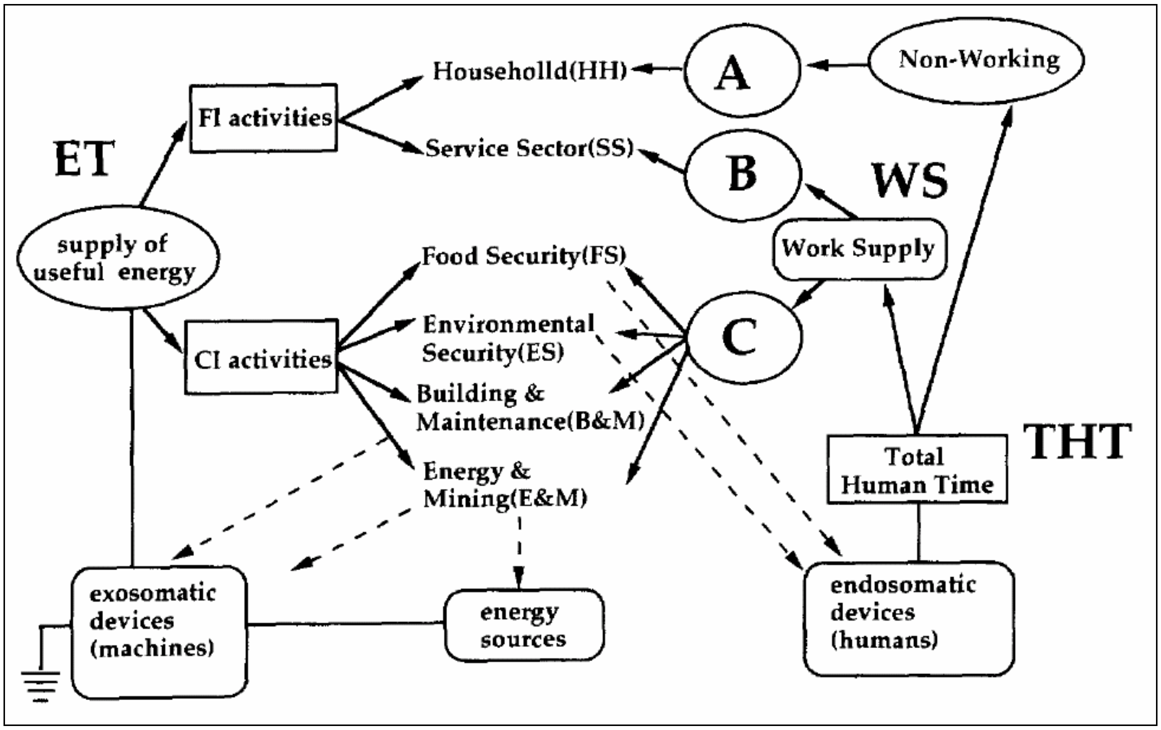

Figure 2 - Parallel allocation of useful energy and human time between various economic functions (Giampietro and Mayumi, 1997: 456)

In this model, on the left side of this diagram, exosomatic energy is allocated by humans to either of two types of activities. Circulating investment (CI) activities support the pursuit of efficiency and correspond to the primary or productive sectors of the economy, while fixed investment (FI) activities support adaptation and correspond roughly to service sectors. This is equivalent to the dual metabolism described by de Rosnay (1975: Chapter 3): energy for living things plus energy for machines. It is not sufficient to allocate energy, however. Humans must also participate in the control of these activities. For this purpose, the right side of the diagram shows the parallel allocation of human time into categories A, B, and C, representing the total labour needed to drive all FI and CI activities. Taken together, the total useful energy in the economy is symbolised as ET and the total available labour as “total human time” or THT.

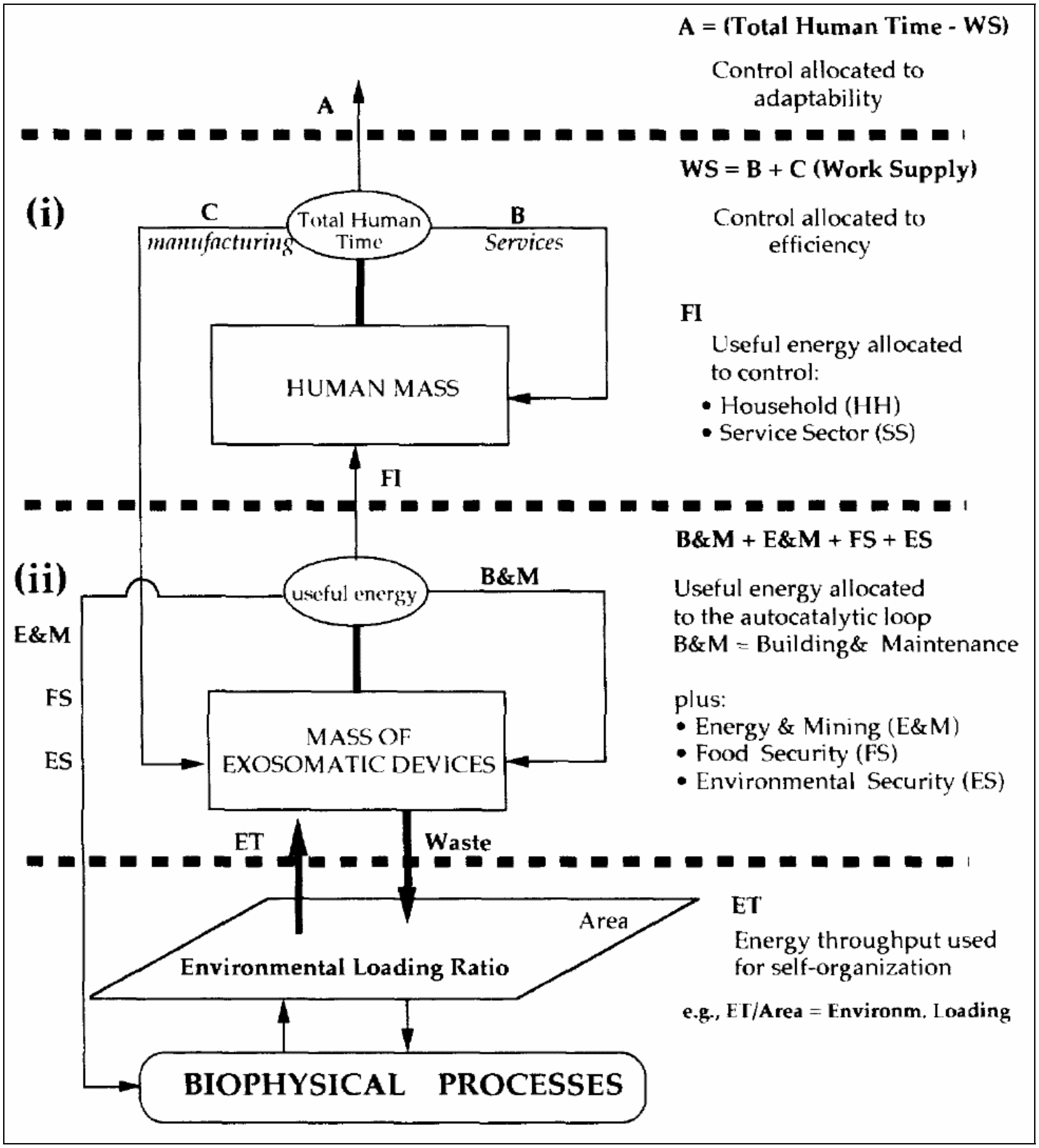

Figure 3 - Functional hierarchy of economic systems (Giampietro and Mayumi, 1997:463)

Exosomatic energy and human time when invested together into each of these activities allows them to take place.

Figure 3, above, shows more explicitly the configuration of the functional hierarchy within an economy. The focal level is that of society, denoted in the diagram by (i). At this level, most processes focus on the maintenance of the "human mass" or aggregate of all persons in society. Most processes internal to this level can be regarded as service-type activities which sustain and build the human elements of the economy: for example, education and health care. This is the autocatalytic loop of human activity

(Giampietro and Mayumi, 1997: 462) – the processes which constitute autopoiesis within the human element of society. The activities at this level constrain the level below through direct control of machines by humans – demanding an investment of human labour – and through signals indicating society's demand for useful energy. Human processes such as birth, growth, education, development, and death at Level 0 are of a lower frequency on average than those of the machines on Level -1. Level 0 processes influence events at Level +1 through observation and analysis of material and energy demand, socio-political trends, and cultural interpretation of events.

The next lower level, Level -1, indicated in the diagram by (ii) comprises the mass of exosomatic devices or machines which are created by humans and are functionally subordinate to humans in the economic hierarchy. The primary function of the machines is to make useful energy available to be applied under the guidance of human control. The allocation of energy between CI and FI is explicitly shown at this level. Processes at Level -1 primarily involve the exosomatic autocatalytic loop (Giampietro and Mayumi, 1997: 464): the process of self-generation or autopoiesis of the mass of machines, also known as capital replacement. This is the use of machines to build and maintain their own structure (Giampietro and Mayumi, 1997: 464). The activities occurring at this level provide Level 0 with the useful energy needed to maintain the autocatalytic loop of human activity. The frequency of activity among machines is higher and the average cycle times shorter than among humans. Machine processes act in a downward direction on the biophysical level by investing energy in mining, food security, and environmental security. These may be collectively understood as the extractive resource industries: mining is the most obvious, but farming, fishing, forestry, etc. are also included. This investment of energy maintains the biophysical processes useful to the economy.

In turn, the machine level depends for its initial conditions on those biophysical processes, which form the lowest level of this hierarchy – Level -2. At Level -2, internal processes focus on regeneration of the resources harvested for use in the economy, as well as disposal of wastes generated by the latter – in other words, the traditional economic source/sink role of "the environment". Its tribute paid to Level -1 comprises the raw materials and energy needed by the machines for further their own maintenance or for transmission to Level 0. This is the lowest level of this hierarchy and thus the highest frequencies and shortest activity cycle times are found here.

The level immediately above Level 0 is that functional layer which is concerned with adaptability, or modification to the economic process or structure in anticipation of future conditions – Level +1. Here are processes focused on predicting what those future conditions might be and what changes in society may be necessary to adjust to them. This includes much academic and intellectual work, as well as political activity. Activities on this level have lower frequencies and longer cycle times than at the human scale. This level provides society at Level 0 with its functional constraints: accumulated knowledge including that of science and technology, cultural frameworks, cognitive interpretations of the universe. Looking up the hierarchy, this level acts in an upward direction by modifying the overall relationship of the economy to the biosphere – a practical example of this would be the currently ongoing Kyoto Protocol process, whose role in the functional hierarchy merits examination.

Though it is not represented in Figure 3, there is one higher level of function in the economic hierarchy: that of the biosphere, which might be viewed as Level +2. It is the biosphere which sets the conditions to which activities on Level +1 must adapt. Processes at Level +2 are the large-scale environmental factors: for instance, climate change. These processes have the cumulative effect of exerting downward constraints to Level +1. Activities at Level +1 can have an effect on Level +2: to continue the example of climate change, the Kyoto Protocol is a process which can occur at Level +1 and if faithfully implemented (at Levels 0 and -1) can over time have an impact on climate change, which occurs at Level +2. The high level at which these processes operate means that the amount of time involved will be relatively large. This is consistent with the fact that these are broad, systemic changes. Examples would include long-term changes in climate, atmospheric composition, ocean currents, vegetation, soil nutrients, or richness and abundance of species.

An interesting conundrum arises in setting the role of the biosphere in this hierarchy, because the biosphere can be seen to have two seemingly contradictory roles with regard to the economy. The biosphere can be seen as it traditionally has been – as the lowest level of the hierarchy: the source of components, mechanisms and initial conditions, as well as the spatial location of the economy. However, as has been increasingly recognised in recent decades, the biosphere can also apply constraints, control and boundary conditions to the economy, a role which is normally fulfilled by higher levels. The apparent contradiction arises because it is difficult to conceive of a single entity acting as "bookends" to the economic process, especially within a hierarchical context: how can an entity be nested inside an entity which is nested within itself? The apparent paradox is in fact no paradox at all, as it derives from a confusion of physical and functional concepts. While this "nesting paradox" would be impossible in the case of a physical system, it is quite possible for the *functions* of the biosphere to be manifested at and to nest within one another at different levels of the *functional* hierarchy. The apparent contradiction does, however, serve to illustrate the unique position of the biosphere with regard to the economic hierarchy. As both enabler and controller, its importance to the function of the economy is clear.

Materials are not mentioned explicitly in Giampietro and Mayumi's model, which may invite some misleading interpretations. This model places the emphasis almost entirely on the transfer and investment of useful energy – exergy – and labour, but materials do in fact have their own distinct and irreducible role in the economy. As has been discussed above, materials can serve as vehicles for energy transfer. However, some materials are needed by the economy for their structural or chemical properties. Examples of these would be steel for the construction of new machines or amino acids needed by the body for the construction and maintenance of proteins. Not all materials can be substituted for energy, and this must be made explicitly clear in interpreting this functional model. Materials can have multiple functions, but not all functions can be performed equally by all materials.

The functional hierarchy outlined here for economic systems differs somewhat from the functional hierarchy of ecosystems. Further study might reveal the reasons for this discrepancy, whether it is a function of the epistemological approach taken or whether it is an intrinsic difference between the two.

IV. Conclusion

The inquiry upon which this paper initially set out was to determine whether a basis existed for comparison between ecosystems and economies through the theoretical framework of systems theory – more precisely, through the framework of hierarchy theory. In this stated objective, it has been only partly successful, and as a result, few actual conclusions about the nature of economies and/or ecosystems can be drawn. However, some interesting results will be highlighted here.

One of the most interesting results of the conceptual studies conducted for this paper is the role of the biosphere as both enabler and controller in the economic context, as discussed in section VII (d) ii, above. The functional economic hierarchy shows that there are two functional points of contact between the economy and the ecosystem: one at the lowest scale, where high-frequency activity feeds the material and energy needs of the higher scales, and another at the highest level, where the low-frequency processes of the biosphere exert constraints in a downward direction upon the economy. The appeal of such an insight is that it serves to highlight a fact which is widely understood, but just as widely denied or ignored, particularly in the mainstream: economic activity depends on the participation of a healthy biosphere. The way in which this model presents this issue, with the biosphere occupying both the highest and the lowest levels in the functional economic hierarchy, puts the importance of the biosphere clearly into perspective.

A second, related insight that can be gained from this model is that humans are, from the functional perspective at least, an integral part of the biosphere and dependent upon it. The fact that the biological human mass is represented as one level in the functional hierarchy of the economy does not mean that humans can be viewed as separate from the biosphere. Quite the opposite is true: the position of the biosphere as the highest level of that hierarchy shows that humans are, from a functional point of view, a component of and subordinate to the constraints of the biosphere.

Another conceptual similarity between economies and ecosystems is that economies do with inanimate objects what living organisms do with their own bodies: they apply energy to reduce entropy locally, exporting high-entropy wastes as externalities. On the surface at least, this seems to be an extension of the open autopoietic system outside the boundaries of living systems. Are humans the only species that creates this kind of external open system for the purpose of exchange? This parallel remains an intriguing one.

It seems to be much easier to explicitly define the levels of organisation in the functional hierarchies than it is in the physical ones. It would be interesting to investigate why this is. Perhaps this is due to the fact that humans can perceive the physical components more easily but their organisation is less easily understood. Perhaps this is one of the reasons why no compelling explanation is yet forthcoming.

A very important lesson learned is that systems such as those examined here are not necessarily objective entities. Neither are some of the tools employed to model them: systems and systems theory are subjective concepts. Even the designation of boundaries between levels in the various hierarchies is open to a great deal of interpretation on the part of the observer. Boulding's (1985) implication appears to have been correct: humans may indeed perceive a system in anything that possesses organisation. This is one of the primary reasons that this paper cannot make the conclusions which it originally sought; the perspectives from which the various systems are examined, from which the models are formulated, are not necessarily sufficiently comparable to warrant such conclusions. One of the similarities that this paper has highlighted is that economies and ecosystems can both be described as hierarchies, and analysed and decomposed in accordance with hierarchy theory. However, it is not clear whether this is because these systems share some fundamental, objective similarities or simply because the mind of the human observer projects the same systemic organisational model onto subjects which may have only a superficial resemblance. Is the pattern "out there" or is it in the mind of the observer? A new epistemological approach would have to be formulated to make it possible to answer that question. This approach would need to be sufficiently rigorous to ensure that the subjectivity of the models influenced each of the four hierarchies (functional and structural for ecosystems and economies) in the same way. This has not been accomplished in this paper, but it could be done in a second iteration.

Another interesting and surprising discovery to which this paper has led is the realisation that "the economy" is also a subjective construct akin to systems. One of the main flaws in the approach taken during the initial research was to assume that there was actually an objective definition for "the economy" as a set of material relations which could be dispassionately observed. This is, after all, how it is presented in mainstream discourse and in the media. The difficulty of locating an explicit definition and the apparent reluctance of economic texts to openly address the question of what an economy is paint a very different picture, indeed. Ogle's (2000) characterisation of the economy as a hologram whose image changes depending on one's point of view now seems a very apt description. Perhaps an economy could be considered in the same way as Vanderburg (2000) considers technology: as an entity which changes people as people change the entity.

Though this paper aims to underline the similarities in organisation between the two types of systems of interest, it can also necessarily identify the differences between them. A very salient difference is the mode of organisation for interactions between entities: in the economy, the preferred mode is generally exchange, though threats and integrative interactions can also occur. In ecosystems, exchange is a possibility; take for example mutualism (Krebs, 2001: 179). However, most interactions between species do not involve two-way exchanges but rather one-way appropriations: predation of carnivores on herbivores, or herbivory of the latter on primary producers are examples of this. An interesting spin-off from this paper would be to compare the types of interactions from each of the two contexts.

One of the most important apparent distinctions is the role of information and of communication in each. Communication, taken to mean the transmission of information from one entity to another, seems to be much more prolific in economic systems, perhaps because as subsets of human social systems, economies can benefit from the use of language to transmit information, whereas ecological communication mechanisms are apparently less able to transmit complex information. This too could form the basis for an interesting research project.

GLOSSARY

Adaptability: That part of society's process of self-organisation which deals with adjusting over the long term to boundary conditions which change in an unpredictable way. Complementary to "efficiency".

Autopoiesis: The continual process of self-making which is a characteristic property of living systems.

Boundary: The division that circumscribes a given holon. Separates the holon from its "environment". In hierarchy theory, boundaries are identified based on rates of interaction within the holon as compared to interactions with other holons.

Decomposability: The ability of a system to be disassembled into its constituent levels and holons without incurring a significant loss of information.

Ecological system: Interchangeable with "ecosystem".

Economy: The system of material and functional relationships involved in the transformation of raw materials into goods and services and their distribution for consumption and disposal.

Ecosystem: An organized, integrated and persistent aggregation of ecological entities standing out in the matrix of other ecological objects.

Efficiency: That part of society's process of self-organisation which deals with operating in the short term within the boundary conditions existing at present. Complementary to "adaptability".

Element: Interchangeable with "entity". A system which is a component of a larger suprasystem.

Emergent property: A property of the system that is not a property its components. "The whole is greater than the sum of its parts."

Endosomatic energy: That energy available to and used by humans to maintain the metabolism of the body. Contrast with "exosomatic" energy.

Entity: Interchangeable with "element". A system which is a component of a larger suprasystem.

Entropy: A measure of the amount of disorder in a thermodynamic system. High entropy implies a highly degraded state (high disorder). Low-entropy materials and energy have greater potential for use than those with high entropy.

Exergy: The fraction of a system's energy which has a high potential to be transformed into mechanical work or into other forms of energy.

Exosomatic energy: Useful energy available to humans outside of the body's metabolism. Effectively, all available energy which can be allocated by humans for designed purposes. Contrast with "endosomatic energy".

Firm: The basic coherent unit of economic action. The smallest unit capable of acting in economic systems.

Focal level: The level at which the phenomena of interest occur for any given question.

Herbivore: An organism which meets its energy and material needs by consuming plants.

Holon: Within a larger system, a holon is a subsystem defined in terms of a boundary which separates the holon from components (other holons) in the rest of the system. Within the holon, components interact frequently or strongly with each other, but only infrequently or weakly with components of other holons. (From O'Neill et al., 1986: 79-80).

Horizontal structure: Structure existing between holons within any single level of a hierarchy.

Level -1: The level below the focal level. Also called the reductionist level.

Level 0: Interchangeable with the focal level. Also called the operational level.

Level +1: The level above the focal level. Also called the macro level.

Nested hierarchy: A hierarchically-organised system in which holons at one level are entirely composed of subsystems which are themselves holons at the next lower level.

Rate: A primary distinguishing characteristic of hierarchical systems, rates can represent, among other things, behavioural frequencies, relaxation times, cycle times, or response times of system entities.

Scale: Spatiotemporally-defined level of a hierarchy.

Subsystem: Relative term used to describe a system at a lower level than the current frame of reference. A lower-level system for which the system under observation is a suprasystem.

Suprasystem: Relative term used to describe a system at a higher level than the current frame of reference. The higher-level system of which the system under observation is a subsystem.

Surface: Any boundary between levels or between holons.

System: A set of any two or more elements or components which form an integrated whole.

System principle: The principle that a whole system is greater than the sum of its parts. One of the fundamental principles of systems theory.

Vertical structure: Structure existing between levels within a hierarchy.

REFERENCES

Boulding, Kenneth Ewart. (1950). *A Reconstruction of Economics.* New York: John Wiley & Sons.

Boulding, Kenneth Ewart. (1978). *Ecodynamics: A new theory of societal evolution.* Beverly Hills: Sage Publications.

Boulding, Kenneth Ewart. (1985). *The World as a Total System.* Beverly Hills: Sage Publications.

Boulding, Kenneth Ewart. (1993). *The Structure of a Modern Economy: The United States, 1929-1989.* New York: New York University Press.

Daly, Herman E. (1992). Allocation, distribution and scale: Towards an economics that is efficient, just, and sustainable. *Ecological Economics* 6, pp. 185-193.

De Rosnay, Joel. (1975). *The Macroscope: A new world scientific system.* Translated from the French by Robert Edwards (1979). New York: Harper & Row. Full text HTML version available from Principia Cybernetica Project at: http://pespmc1.vub.ac.be/macroscope/

Fisher, Irving. (1913). *Elementary Principles of Economics*. New York: MacMillan.

Georgescu-Roegen, Nicholas. (1971). The Entropy Law and the Economic Problem. In Herman E. Daly, ed., (1973), *Economics, Ecology, Ethics: Essays Toward a Steady-State.* W.H. Freeman, pp. 236-247.

Giampietro, Mario, and Kozo Mayumi. (1997). A dynamic model of socioeconomic systems based on hierarchy theory and its application to sustainability. *Structural Change and Economic Dynamics* 8, pp. 453-469.

Grant, W.E. (1998). Ecology and natural resource management: reflections from a systems perspective. *Ecological Modelling* 108, pp. 67-76.

Holland, J.H. (1988). The global economy as an adaptive process. In P.W. Anderson, K.J. Arrow, D. Pines (Eds.), *The Economy as an Evolving Complex System*. Reading, MA: Addison Wesley, pp. 117–124.

Holland, J.H. (1995). *Hidden Order: How Adaptation Builds Complexity*. Reading, MA: Helix Books.

Krebs, Charles J. (2001). *Ecology: The experimental analysis of distribution and abundance.* Fifth edition. San Francisco: Benjamin Cummings.

Leijonhufvud, Axel. (1999). Adaptive Behavior, Market Processes and the Computable Approach. *Brazilian Electronic Journal of Economics* 2(2), June 1999.

Levine, David P. (1978a). *Economic Theory Volume 1: The elementary relations of economic life.* London: Routledge and Kegan Paul.

Levine, David P. (1978b). *Economic Theory Volume 2: The system of economic relations as a whole.* London: Routledge and Kegan Paul.

Lipsey, Richard G. (1979). *An Introduction to Positive Economics.* Fifth edition. London: Weidenfeld and Nicolson.

Lipsey, Richard G., Christopher T.S. Ragan, and Paul N. Courant. (1997). *Macroeconomics*. Ninth Canadian edition. Don Mills: Addison-Wesley.

Marshall, Alfred. (1961). *Principles of Economics*. 9th edition. London: Macmillan.

Matutinovic, Igor. (2002). Organizational patterns of economies: an ecological perspective. *Ecological Economics* 40, pp. 421-440.

Muller, Felix. (1998). Gradients in ecological systems. *Ecological Modelling* 108, pp. 3-21.

Odum, Howard T., M.T. Brown and S. Ulgiati. (2000). Ecosystems as Energetic Systems. In S.E. Jorgensen and Felix Muller (eds.) *Handbook of Ecosystem Theories and Management*, pp. 281-302. New York: Lewis.

Ogle, Greg. (2000). *Between Statistical Imperatives and Theoretical Obsessions: An inquiry into the definition and measurement of the economy.* Doctoral thesis. University of Adelaide, Australia. Published online: http://users.senet.com.au/~gregogle/PhD_home.html (accessed 27 July 2004).

O'Neill, R.V., D.L. DeAngelis, J.B. Waide and T.F.H. Allen. (1986). *A Hierarchical Concept of Ecosystems.* Princeton: Princeton University Press.

Vanderburg, Willem H. (2000). *The Labyrinth of Technology.* Toronto: University of Toronto Press.

Weston, Roy F., and Matthias Ruth. (1997). A dynamic, hierarchical approach to understanding and managing natural economic systems. *Ecological Economics* 21, pp. 1-17.