On Complexity Theory, Exergy and Industrial Ecology: Some Implications for Construction Ecology

James J. Kay
Environment and Resource Studies,
University of Waterloo,
Waterloo, Ontario,
Canada N2L 3G1

Reference:
Kay, J.J., 2002, "On Complexity Theory, Exergy and Industrial Ecology: Some Implications for Construction Ecology" in Kibert, C., Sendzimir, J., Guy, B. (eds), *Construction Ecology: Nature as the Basis for Green Buildings,* Spon Press, pp.72-107

INTRODUCTION

Industrial ecology has been defined by Graedel and Allenby as "… the means by which humanity can deliberately and rationally approach and maintain a desirable carrying capacity, given continued economic, cultural and technological evolution. The concept requires that an industrial system be viewed not in isolation from its surrounding systems, but in concert with them." (Graedel and Allenby, 1995). The Institute of Electrical and Electronic Engineers (IEEE) has defined industrial ecology as "… the objective, multidisciplinary study of industrial and economic systems, and their linkages with fundamental natural systems." (IEEE electronics and the environment committee, 1995). Tibbs describes industrial ecology as follows: "..industrial ecology involves designing industrial infrastructures as if they were a series of interlocking manmade ecosystems interfacing with the natural global ecosystem" (Tibbs, 1992). And O'Rourke et al characterize industrial ecology as "..bringing systems thinking in ecology together with systems engineering (for design of products and processes) and economics" (O'Rourke; Connelly, and Koshland, 1996).

While much of the literature on industrial ecology suggests that it originated in the early 1990's, Erkman and O'Rourke et al. trace its roots back to the early 1970's (Erkman, 1997; O'Rourke and others, 1996). One thread of development, which has been largely overlooked, can be traced to the Institute of Electrical and Electronic Engineers; Systems, Man, Cybernetics Society. In the early 1970's Koenig and later his son and their students at Michigan State, in collaboration with Chandrashekar and his students at University of Waterloo, developed analytical tools, based on systems theory. These tools are for analysing and designing engineering systems so that they are as efficient and effective as possible, while minimizing their environmental impact. These tools are more sophisticated than any this author has seen in the industrial ecology literature. (Chinneck, 1983; Chinneck and Chandrashekar, 1984; Koenig and Tummala, 1991; Koenig and Cantlon, 1998; Koenig and Cantlon, 1999; Koenig and others, 1972; Koenig and others, 1975; Koenig and Tummala, 1972; Saama and others, 1994; Tummala and Koenig, 1993; Wong, 1979; Wong and Chandrashekar, 1982; Wong and Chandrashekar, 1982)

As part of Chandrashekar's team, this author undertook a master's thesis in Systems Design Engineering entitled *An Investigation into the Design Principles for a Conserver Society* (Kay, 1977). (Today it would be called *Engineering Design Principles for Industrial Ecology*.) The basic premise of the thesis was that all man-made systems must contribute to the survival potential of natural ecosystems. This thesis proposed that "a new branch of engineering to investigate and implement design strategies that are in line with this premise should be started. It would seem appropriate to call this branch ecosystems engineering, where ecosystems is used in the broad sense of H. T. Odum to include industrial systems. This branch will bring together the disciplines of ecology, economics, engineering design, systems theory, and thermodynamics. This branch would be responsible for providing engineers in the field with the tables, rules of thumb and models (in other words the methodology) necessary for designing, implementing, and maintaining eco-compatible systems." (p.75 (Kay, 1977).

In this regard, it was proposed in this thesis that hierarchical production-consumption models of all engineering systems be constructed and that their design as production-consumption systems be such that:

- the interface between man-made systems and natural ecosystems reflects the limited ability of natural ecosystems to provide energy and absorb waste before their survival potential is significantly altered, and that the survival potential of natural ecosystems must be maintained. This is referred to as the problem of *interfacing*.
- the behavior and structure of large scale (i.e. involving several different mass-energy transformation processes) man-made systems should be as similar as possible to those exhibited by natural ecosystems. This is referred to, after Papanek (Papanek, 1970), as the *principle of bionics*.
- whenever feasible the function of a component of a man-made system should be carried out by a subsystem of the natural biosphere. This is referred to as *using appropriate biotechnology.*
- non-renewable resources be used only as capital expenditures to bring renewable resources on line.

All of this suggests a root definition of industrial ecology. It is fundamentally about dealing with human transformations of mass and energy (i.e. industrial activities) from an ecosystem perspective. This begs the question: what is an ecosystem approach and to what end? An ecosystem approach is about the application of systems thinking to the analysis and design of biophysical mass and energy transformation systems. The point of an ecosystem approach is to maintain a situation which is ecologically sound, that is, has integrity, while providing humans with a sustainable livelihood (Kay, 1991; Kay and Regier, 2000; UNDP, 1998). This chapter is about exploring an ecosystem approach for industrial ecology.

The challenges

O'Rourke et al observe that "many of the concepts of IE are not new. None the less, the IE literature fails to examine the lessons of the 1970s and 1980s attempts to reform industry" (p.108, (O'Rourke and others, 1996). During the late 70s and early 80s, others efforts, besides the ones of this author, were made to advance design principles and methodologies for what we now call industrial ecology. (Besides the work of Koenig and his colleagues, see for example, O'Callaghan and Edgerton (Edgerton, 1982; O'Callaghan, 1981).) So why do our designs not reflect these ideas?

There are three reasons. First, our society simply does not see the need for these design principles, at least not in a wholesale way. It is for this reason that I think that development of ecological economics is critical. Second, we do not grasp how to analyze mass-energy flow systems. Our ability to build production-consumption models is quite limited. Thus our competence in dealing with the interfacing problem is wanting. Third, we really do not have a good understanding of how ecological systems work. Thus it is quite difficult for us to understand our effects on ecological systems or what properties of ecological systems we should mimic. So in the absence of clear direction on how to implement the four design principles mentioned above and other similar ones, and given that lack of perceived economic incentives to do so, it is convenient to simply ignore them.

So how to we rectify the situation? The first challenge is the recasting of economics such that it reflects the biophysical reality that humans are enmeshed in and dependent on a biosphere of natural ecosystems. This is the business of ecological economics and will not be dwelt on any further herein. Second is the need to develop thermodynamics so that we can adequately describe mass-energy flow systems. While we are quite competent in first law analysis (the analysis of the quantity of flow and efficiency), second law analysis (the analysis of the quality of flow and effectiveness) eludes us. Some very useful strides have been made in exergy (quality of energy) analysis (Brodyansky and others, 1994; Gaggioli, 1983; Moran, 1982; Szargut and others, 1988; Wall, 1986), particularly network thermodynamics (Chinneck, 1983; Chinneck and Chandrashekar, 1984; Peusner, 1986; Wong and Chandrashekar, 1982), but the development of similar analysis techniques for material flow quality still remains as a challenge. The third and massive challenge, the one that is the crucial to our survival, is to understand ecosystems.

It is this last challenge that I took up for my doctoral work (Kay, 1984). The key to this challenge is to understand ecosystems as complex adaptive self-organizing hierarchical open systems (SOHO systems for short) (Kay and others, 1999; Schneider and Kay, 1994b). This is an area of theory and practice that is in its infancy.

Most readers will be quite unfamiliar with the notions and the language of complexity and self-organization theory. Yet in this chapter it is only possible to provide a brief overview summary of this theory. It must be left to the reader to pursue other works which elaborate on this topic. In particular the following are written in a style for a general audience and are recommended for further reading: (Casti, 1994; Holling, 1986; Kay and others, 1999; Kay and Schneider, 1994; Kay, 1997). Hopefully the reader will be motivated to wade through the brief theoretical synopsis which follow. Valuable knowledge emerges from these theoretical considerations, as well as many important insights with direct practical implications for industrial ecology. These insights, with examples, are delved into in the discussion of the design principles and their application to construction ecology, later in this chapter. This chapter closes with a sketch of an ecosystem approach design methodology for construction ecology.

ECOSYSTEMS, SUSTAINABILITY AND COMPLEXITY.

The issue of complexity has attracted much attention in the past decade. This issue emerged in the wake of the new sciences which became prominent in the 1970's: catastrophe theory, chaos theory, non-equilibrium thermodynamics and self-organization theory, Jaynesian information theory, complexity theory etc. A number of authors have focused specifically on self-organizing systems (Casti, 1994; di Castri, 1987; Jantsch, 1980; Kay, 1984; Nicolis and Prigogine, 1977; Nicolis and Prigogine, 1989; Peacocke, 1983; Wicken, 1987). The term complex systems thinking is being used to refer to the body of knowledge that deals with complexity. Complex systems thinking has its origins in von Bertalanffy's general systems theory (von Bertalanffy, 1968; von Bertalanffy, 1975).

Complex adaptive self-organizing hierarchical open (SOHO) systems

Spontaneous coherent behaviour and organization occurs in open systems (such as natural ecosystems and human systems). Central to understanding such phenomena is the realization that open systems are processing an enduring flow of high quality energy (exergy). In these circumstances, coherent behaviour appears in systems for varying periods of time. However such behaviour can change suddenly whenever the system reaches a catastrophe threshold and “flips” into a new coherent behavioural state (Nicolis and Prigogine, 1977). (A “catastrophe threshold” is a point of discontinuity at which continuous change of some variables generates sudden discontinuous responses. A simple example is the vortex which spontaneously appears in water from draining a bathtub, or more dramatically, the appearance of tornadoes “from nowhere”. See Appendix 1 in (Kay, 1991).)

Kay and Schneider examined the energetics of open systems and have taken Prigogine's work one step further (Schneider and Kay, 1993; Schneider and Kay, 1994a; Schneider and Kay, 1994b). An open system with exergy (high quality energy) pumped into it is moved away from equilibrium, but nature resists movement away from equilibrium. This is the second law of thermodynamics restated for non-equilibrium situations. When the input of exergy and material pushes the system beyond a critical distance from equilibrium, the open system responds with the spontaneous emergence of new, reconfigured organized behaviour that uses the exergy to build, organize and maintain its new structure. This reduces the ability of the exergy to move the system further away from equilibrium. As more exergy is pumped into a system, more organization emerges, in a step-wise way, to dissipate the exergy. Furthermore, these systems tend to get better and better at "grabbing" resources and utilizing them to build more structure, thus enhancing their dissipating capability. There is however, in principle, an upper limit to this organizational response. Beyond a critical distance from equilibrium, the organizational capacity of the system is overwhelmed and the system's behaviour leaves the domain of self-organization and becomes chaotic. As noted by Ulanowicz there is a "window of vitality", that is, a minimum and maximum level between which self-organization can occur (Ulanowicz, 1997b).

Self-organizing dissipative processes emerge whenever sufficient exergy is available to support them. Once a dissipative process emerges and becomes established it manifests itself as a structure. These structures provide a new context, nested within which new processes can emerge, which in turn beget new structures, nested within which... Thus emerges a SOHO system, a nested constellation of self-organizing dissipative process/structures organized about a particular set of sources of exergy, materials, and information, embedded in a physical environment, that give rise to coherent self-perpetuating behaviours.

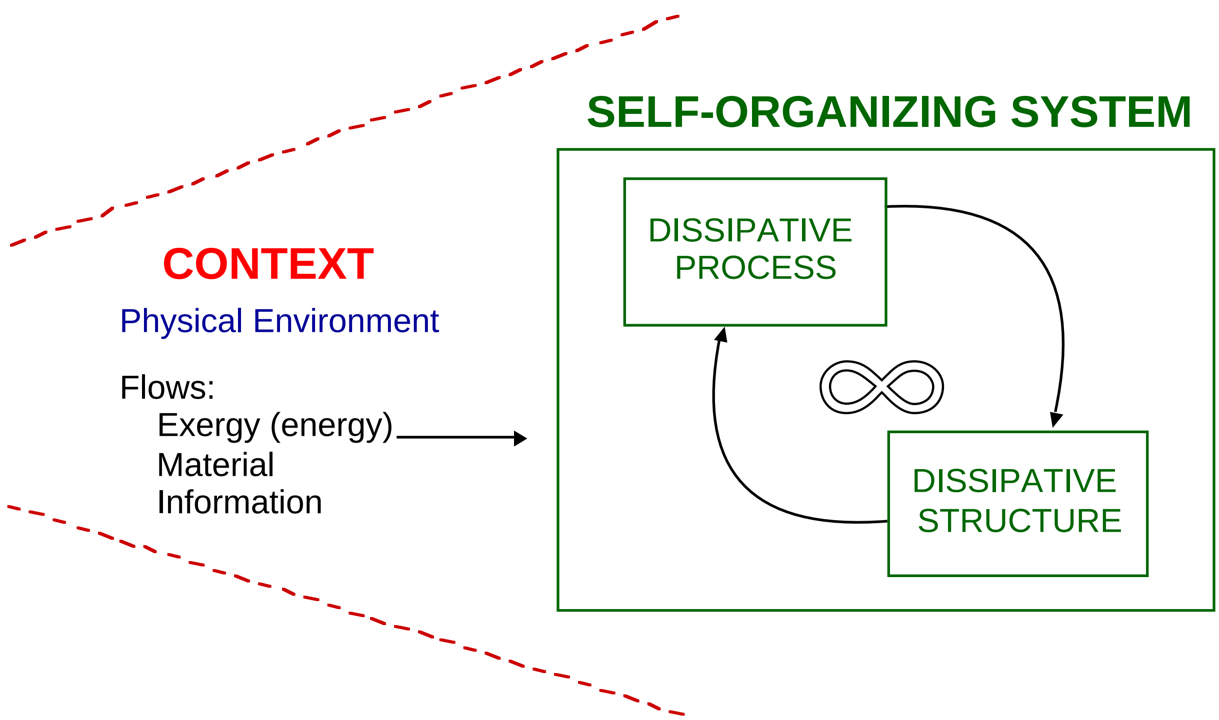
A common example is the emergence of a vortex in bathtub water as it drains. The exergy is the potential energy of the water (due to the height of water in the bathtub), the raw material is the water, the dissipative process is water draining, the dissipative structure is the vortex. The vortex will not form until enough height of water is in the bathtub, and if too much height of water is present, laminar flow occurs instead of a vortex.

The theory of non-equilibrium thermodynamics suggests that the self-organization process in SOHO systems proceeds in a way that captures increasing resources (exergy and material); makes ever more effective use of the resources; builds more structure; and enhances survivability (Kay and Schneider, 1992; Kay, 1984; Schneider and Kay, 1994b). These seem to be the kernel of the propensities of self-organization. This conception of self-organization, as a dissipative system, is presented in Figure 1.

How these propensities manifest themselves as morphogenetic causal loops and dissipative processes is a function of the given environment (context) in which the system is imbedded, as well as the available materials, exergy and “information”, the latter defined as factors embedded internally within the system that constrain and guide the self-organization. The interplay of these factors defines the context and associated constraints on the set of processes which may emerge. Generally speaking, which specific processes emerge from the potential set are uncertain.

This short sketch of a framework for discussing the dynamics of complex adaptive SOHO systems is meant to illustrate the very different kinds of dynamics associated with these systems and hence the very different kinds of considerations which need to be taken into account when examining them. Flips between attractors, organization about attractors, the spontaneous emergence of behaviours, their nested nature, and the importance of the second law of thermodynamics vis a vis exergy and nonequilibrium, requires a very different mindset for understanding dynamics (Caley and Sawada, 1994). A central tenet of our work is that natural ecosystems and societal systems cannot be understood without understanding them as SOHO systems. Industrial ecology must take into account these considerations of complexity and self-organization.

Figure 1: A conceptual model for self-organizing systems as dissipative structures. Self-organizing dissipative processes emerge whenever sufficient exergy is available to support them. Dissipative processes restructure the available raw materials in order to dissipate the exergy. Through catalyse, the information present enables and promotes some processes to the disadvantage of others . The physical environment will favour certain processes. The interplay of these factors defines the context for (i.e. constrains) the set of processes which may emerge. Once a dissipative process emerges and becomes established it manifests itself as a structure. These structures provide a new context, nested within which new processes can emerge, which in turn beget new structures, nested within which... Thus emerges a SOHO system, a nested constellation of self-organizing dissipative process/structures organized about a particular set of sources of exergy, materials, and information, embedded in a physical environment. The canon of the SOHO system is the complex nested interplay and relationships of the processes and structures, and their propensities, that give rise to coherent self-perpetuating behaviours, that define the attractor.



Ecosystems as Self-Organizing systems

Ecosystems can be viewed as the biotic, physical, and chemical components of nature acting together as nonequilibrium self-organizing dissipative systems . As ecosystems develop or mature they should develop more complex structures and processes with greater diversity, more cycling and more hierarchical levels all to abet exergy degradation. Species which survive in ecosystems are those that funnel energy into their own production and reproduction and contribute to autocatalytic processes which increase the total exergy degradation of the ecosystem. In short, ecosystems develop in a way which systematically increases their ability to degrade the incoming solar exergy (Kay and Schneider, 1992; Kay, 1984; Schneider and Kay, 1994a; Schneider and Kay, 1994b).

Keeping in mind that the more processes or reactions of material and energy that there are within a system, (i.e. metabolism, cycling, building higher trophic levels) the more the possibility for exergy degradation Schneider and Kay showed that most, if not all, of Odum's phenomenological attributes of maturing ecosystems can be explained by ecosystems behaving in such a manner as to degrade as much of the incoming exergy as possible (See Table 1) (Kay and Schneider, 1992; Odum, 1969; Schneider, 1988).

In terrestrial ecosystems, surface temperature measurements can be used to demonstrate that ecosystems develop so as to degrade exergy more effectively. The exergy degradation in a terrestrial ecosystem is a function of the difference in black body temperature between the captured solar energy and the energy reradiated by the ecosystem. (This is discussed in detail in Fraser and Kay (Fraser and Kay, 2000).) Thus if a group of ecosystems are bathed by the same incoming energy, the most mature ecosystem should reradiate its energy at the lowest exergy level, that is the ecosystem would have the coldest black body temperature. The black body temperature is determined by the surface temperature of the canopy of the ecosystem.

Consider the fate of solar energy impinging on five different surfaces, a mirror, a flat black surface, a piece of false grass carpet (e.g.. Astroturf), a natural grass lawn and a rain forest. The perfect mirror would reflect all the incoming energy back toward space with the same exergy content as the incoming radiation. The black surface will reradiate the energy outward at a lower quality than the incoming energy, because much of the exergy is converted to lower quality infra-red radiation and sensible heat. The green carpet will reradiate its energy similar to the black surface but will differ because of its surface quality and different emissivity. The natural grass surface will degrade the incoming radiation more completely than the green carpet surface, because processes associated with life, (i.e. growth, metabolism and transpiration) degrade exergy (Ulanowicz and Hannon, 1987). Its surface temperature will be colder than the black surface or the Astroturf. The rain forest should degrade the incoming exergy most effectively because of the many pathways (i.e. more species, canopy construction) available for degradation. It will be even colder than the grass.

In previous papers Kay and Schneider have discussed Luvall et al's experiments in which they overflew terrestrial ecosystems and measured surface temperatures (Kay and Schneider, 1994; Luvall and others, 1990; Luvall and Holbo, 1991; Luvall, 1989; Quattrochi and Luvall, 1999; Schneider and Kay, 1994b). Luvall and his co-workers have documented ecosystem energy budgets, including tropical forests, mid-latitude varied ecosystems, and semiarid ecosystems. Their data shows one unmistakable trend, that when other variables are constant, the more developed the ecosystem, the colder its surface temperature and the more degraded it's reradiated energy.

Table 1: Some expected changes in ecosystems as they develop. The underlying rational behind these expectations is that ecosystems will develop so as to more fully utilize the exergy in the energy available to them. (Exergy utilization results in degradation of the exergy content of the energy.)

1. More exergy capture:- because the more exergy that flows into a system the more there is to utilize.
2. More energy flow activity within the system:- again, the more energy that flows within and through a system, the greater the potential for the use of its exergy.
3. More cycling of energy and material:
   - Numbers of cycles:- more pathways for energy to be recycled in the system results in further utilization of the incoming exergy.
   - The length of cycles:- more mature systems will have cycles of greater length, i.e. more nodes in the cycle. Each chemical reaction at or within a node results in further exergy utilization; the longer the cycle, the more the reactions; the more complete the exergy utilization.
   - The amount of material flowing in cycles (as versus straight through flow) increases. The ecosystem becomes less leaky thus maintaining a supply of raw material for exergy utilization processes.
   - Turnover time of cycles or cycling rate decreases:- more nodes or cycles in a system will result in nutrients or energy being stored at nodes in the system resulting in longer residence time in the system.
4. Higher average trophic structure:
   - Longer trophic food chains:- exergy is utilized at each step of the trophic food chain, therefore longer chains will result in more thorough utilization.
   - Species will occupy higher average trophic levels:- This will result in more exergy utilization as energy at higher trophic levels has a higher exergy content.
   - Greater trophic efficiencies:- the exergy content of energy, that is passed higher up the food chain, will be more thoroughly utilized than that of energy that is shunted immediately into the detrital food chain.
5. Higher respiration and transpiration:- transpiration and respiration results in exergy utilization.
6. Larger ecosystem biomass:- more biomass means more pathways for exergy utilization.
7. More types of organisms (higher diversity):- more types of organisms will provide diverse and different pathways for utilizing exergy.

Work by Akbari, Murphy, Swanton and Kay (Akbari and others, 2000) on agricultural plots showed a similar trend. A lawn (single species of grass) had the warmest surface temperature, a undisturbed hay field was cooler, and a field which has been naturally regenerating for 20 years was coldest. These trends were confirmed over three years of observation. Also another field, which was regenerating for 20 years, was disturbed by mowing. Immediately its surface temperature rose significantly, but very quickly it returned to its cooler pre-disturbance value. Very recently Allen and

Norman have performed a set of experiments to explore the relationship between development and surface temperature in plant communities. So far their experimental results demonstrate that the surface temperature of plant communities tend to warm when they are removed from their normal conditions. That is plant communities are coldest (degrading the most exergy) when they are in the normal conditions which they are adapted to. All this is evidence that exergy degradation is the name of the game in ecosystem development.

Recently Luvall and his colleagues at NASA have used these observations about natural ecosystems to develop a "Green Cities" strategy (Lo and others, 1997). This has been applied in several urban centers in the United States. The green cities initiative begins by using the same surface temperature measurements described above to generate a thermodynamic description of the city. Two core tactics in this approach are to use the thermodynamic description to focus on roofing materials and the presence of flora, particularly trees. Both of these can dramatically alter the thermodynamic budget in a city. Using the analysis of surface temperature, areas of the city which could benefit from changes in roofing materials, more flora etc. are identified. This initiative is discussed further later in the chapter.

There is much to be gained from examining ecosystems through the lens of exergy degradation. A number of ecosystem phenomena can be explained and hypotheses concerning ecosystem development can be generated and tested. But there is more to the story. Most ecosystems will have many different options for exergy degradation available to them. Some will have different sources of exergy available. Different combinations of exergy sources and degradation possibilities may be equivalent from a exergy degradation perspective. So the number of possible variations on ecosystem organization, which are thermodynamically equivalent, may be significant. This quickly leads to a complicated set of possible organizational pathways. What is actually manifested may very well be a reflection of a collection of accidents of history.

The imperative of thermodynamics and exergy degradation is not the only one acting on living systems. Of equal importance is survival, an imperative which may not be consistent with maximum exergy degradation. Inevitably tradeoffs will have to be made and ecosystems, as they exist on the ground, will reflect these tradeoffs (Kay, 1984). There will not be single best solutions to the imperatives of exergy degradation and survival, just solutions that work longer than others. Furthermore, to add to the complexity and uncertainty, Dempster and Kay have shown that such systems must, by necessity, be recursively nested autopoietic (organizationally closed and self-duplicating, i.e. a cell) and synpoietic (organizationally open and evolving, i.e. a species) systems (Dempster, 1998).

Table 2: Properties of self-organizing hierarchical open systems to consider in mind when thinking about ecosystems. Bear in mind that SOHO systems are complex, adaptive, dissipative systems.

- **Open** to material and energy flows.
- **Nonequilibrium**: Exist in quasi-steady states some distance from equilibrium.
- **Thermodynamics:** Maintained by energy **gradients** (exergy) across their boundaries. The gradients are **irreversibly** degraded (the exergy is used) in order to build and maintain organization. These systems maintain their organized state by exporting entropy to other hierarchical levels.
- **Propensities**: As **dissipative** systems are moved away from equilibrium they become organized:
  - they use more exergy
  - they build more structure
  - this happens in spurts as new attractors become accessible.
  - it becomes harder to move them further away from equilibrium
- **Feedback loops**: Exhibit material or energy **cycling**: Cycling and especially autocatalytic cycling is intrinsic to the nature of dissipative systems. The very process of cycling leads to organization. **Autocatalysis** (positive feedback) is a powerful organizational and selective process.
- **Hierarchical:** Are **holarchically nested**. The system is nested within a system and is made up of systems. Such nestings cannot be understood by focusing on one hierarchical level (holon) alone. Understanding comes from the multiple perspectives of different **types** and **scale**.
- **Multiple Steady States:** There is **not** necessarily a unique preferred system state in a given situation. **Multiple attractors** can be possible in a given situation and the current system state may be as much a function of historical accidents as anything else.
- Exhibit **chaotic** and **catastrophic** behavior. Will undergo dramatic and sudden changes in **discontinuous** and **unpredictable** ways.
  - **Catastrophic Behaviour:** The norm
    Bifurcations: moments of unpredictable behaviour
    Flips: sudden discontinuities, rapid change
    Holling four box cycle Shifting steady state mosaic
  - **Chaotic Behaviour:** our ability to forecast and predict is always limited, for example to between five and ten days for weather forecasts, regardless of how sophisticated our computers are and how much information we have.
- **Dynamically Stable?:** There may not exist equilibrium points for the system.
- **Non-Linear:** Behave as a whole, a **system**. Cannot be understood by simply decomposing into pieces which are added or multiplied together.
- **Internal Causality:** non-Newtonian, not a mechanism, but rather is **self-organizing**. Characterized by: goals, positive and negative feedback, autocatalysis, emergent properties and surprise.
- **Window of Vitality:** Must have enough complexity but not too much. There is a range within which self-organization can occur. Complex systems strive for **optimum**, not minimum or maximum.

Table 2 summarizes the characteristics of ecosystems as self-organizing hierarchical open systems. These self-organizing characteristics require the consideration of very different issues, and the use of very different analytical tools than traditional ecological approaches would suggest are pertinent. In particular the issues of complexity and uncertainty must be confronted head on.

Sustainability and Complexity Theory: Some Lessons

Our partial understanding of ecosystems as complex systems suggest several lessons which need to be kept in mind when discussing sustainability (Kay and Regier, 1999; Kay and Schneider, 1994; Schneider and Kay, 1994b).

There is growing comprehension that sustainability issues cannot be discussed in isolation. They must always be examined within their broader context. Every system is a component of another system and is, itself, made up of systems. Thus, a wetland must be understood in the context of the subwatershed it is a part of, and in terms of the processes and species which make it up. The body of thinking which deals with these issues is called Hierarchy Theory (Allen and others, 1993; Allen and Hoekstra, 1992; Allen and Starr, 1982). Its central tenant is that sustainability issues can only be understood in terms of systems embedded in systems which are also embedded in systems or, in the vernacular of hierarchy theorists, as *nested holons* (Koestler, 1978; Koestler and Smythies, 1969).

The hierarchical nature of complex systems requires that they be studied from different types of perspectives and at different scales. There is no one correct perspective. Rather, a diversity of perspectives is required for understanding.

By their nature, complex systems are self-organizing. This means that their dynamics are largely a function of positive and negative feedback loops. Linear, causal mechanical explanations of their dynamics are precluded. In addition, emergence and surprise are normal phenomena in systems dominated by feedback loops. Inherent uncertainty and limited predictability are inescapable consequences of these system phenomena.

Complex systems organize about attractors. (See Figure 2) Complex systems have multiple possible operating states or attractors, and may shift or diverge suddenly from any one of them (Holling, 1986; Kay, 1991; Kay, 1997; Ludwig and others, 1997). Even when the environmental situation changes, the system's feedback loops tend to maintain its current state. However, when system change does occur, it tends to be very rapid and even catastrophic. When precisely the change will occur, and what state the system will change to, are generally not predictable. In a given situation, there are often several possible system states (attractors) that are equivalent. Which state is currently occupied is a function of its history. There is not a "correct" state for the system, although there may be a state which is preferred by humans.

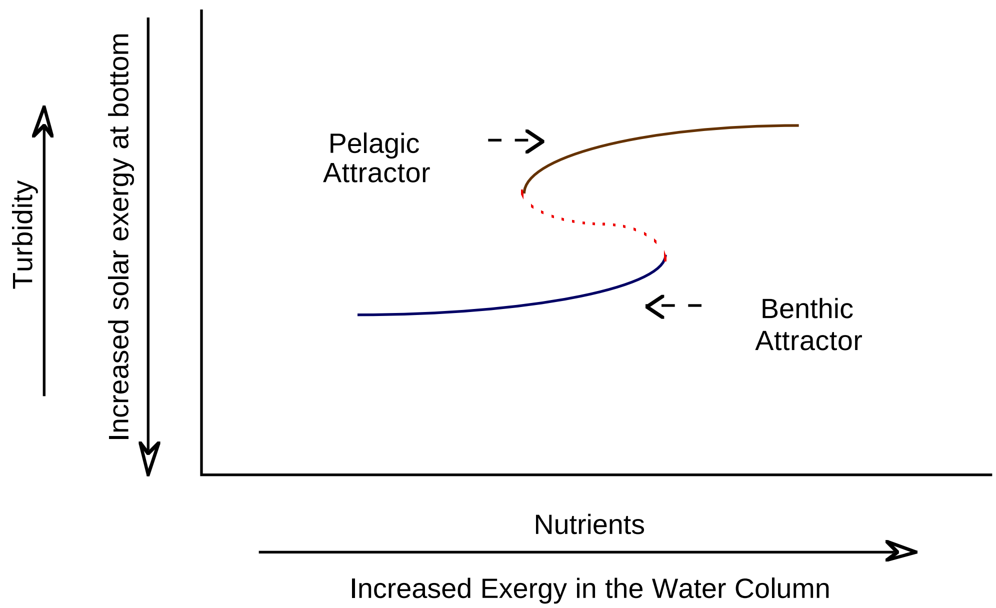
Thus categorical statements about the "correct" way to proceed, that is the correct ecosystem for a given circumstance, cannot be deduced from scientific arguments. Furthermore, which response comes to pass may be a function of history or just the moment. Thus there is an element of irreducible uncertainty about self-organizing behaviour, uncertainty about what may come to pass as well as uncertainty about what ought to come to pass. These properties of inherent uncertainty and emergence limit the capacity to predict how an ecological situation will unfold.

Figure 2: Benthic and Pelagic Attractors in shallow lakes

Two different attractors for shallow lakes have been identified. In the **benthic** state, a high water clarity bottom vegetation ecosystem exists. As nutrient loading increases the turbidity in the water, the ecosystem hits a catastrophe threshold and flips into a hypertrophic, turbid, phytoplankton **pelagic** ecosystem. The relationship of these two attractors, from a thermodynamic perspective, is as follows:

Let us assume that the benthic attractor is dominant and that the rate at which phosphorus is being added to the water is increasing. The benthic system has means of deactivating phosphorus. However the amount of active phosphorus will increase, albeit slowly, effectively increasing the exergy in the water column. As this exergy increases a critical threshold is passed which allows the pelagic system to self-organize to coherence. Once this occurs the exergy at bottom decreases rapidly due to shading (turbidity) thus catastrophically de-energizing the benthic system. This results in the eventual re-activation of the phosphorus in the bottom muds which the benthic system had previously deactivated, thus strengthening the pelagic attractor even more.

Assuming the pelagic attractor is dominant and if the level of active phosphorus in the water column decreases, a critical threshold is again reached below which it is no longer possible to capture enough solar energy to energize the pelagic system. In effect, the exergy in the water column decreases below the minimum level for the window of vitality of the pelagic system. As this occurs the exergy at the bottom increases thus re-energizing the benthic system. And so the aquatic system flips back and forth between the pelagic and the benthic regime depending on where in the water column the sunlight's exergy is available to energize the system.



Our premise is that resolving sustainability issues for ecological-economic systems entails understanding these systems as “self-organizing hierarchical open” (SOHO) systems. Such an understanding comes from thinking through the hierarchical nature of these systems by considering issues of type and scale, bounding and nesting of the system. This “hierarchical systems description” of the important processes and structures, and their relationships and context, is essential.

In addition, the self-organizing behaviours of the system need to be identified, described, and understood insofar as is possible. This involves identifying the attractors accessible to the system, the feedbacks which maintain the system at the attractors, the external influences which define the context for a specific attractor, and conditions under which flips between attractors are likely. The overall understanding of a system's behaviour, that comes from studying it as a SOHO system, is summarized in the form of a narrative of its dynamics. (A more detailed discussion of these notions can be found in (Kay and others, 1999; Kay, 1997).)

The understanding of ecological-economic systems as SOHO systems requires a major change in some of the ways in which science and decision making are conducted. Traditional reductionistic disciplinary science and expert predictions, the basis for much of the advice given to decision makers, have limited applicability. Narratives about possible futures for given SOHO systems are better able to capture the richness of possibilities. Other epistemological “mindsets” or causal metatypes must be brought to bear, notably explanations based on morphogenetic causal loops that involve both positive and negative feedback processes and autocatalysis (Caley and Sawada, 1994; Maruyama, 1980; Ulanowicz, 1997a). Expectations that decision makers can carefully control or manage changes in societal or ecological systems must be relinquished. Rather, adaptive learning and management, guided by a much wider range of human experience and understanding than disciplinary science, must form the basis for decision making in a sustainable society.

INDUSTRIAL ECOLOGY: THE DESIGN OF ECOLOGICAL-ECONOMIC SYSTEMS

The design principles, mentioned in the introduction, in combination with the insights of complex systems theory, especially with reference to ecosystems, provide a theoretical basis for an ecosystem approach to industrial ecology. *Industrial ecology is taken to be the activity of designing and managing human production-consumption systems, so that they interact with natural systems, to form an integrated (eco)system which has ecological integrity and provides humans with a sustainable livelihood.* In essence industrial ecology is about designing human ecological-economic systems which fit in with natural ecological systems.

The Normative Foundation

This definition of industrial ecology establishes the raison d'être for industrial ecology: ecological integrity and sustainable livelihoods. Together these two notions are the normative basis for the practice of industrial ecology. The first step in any industrial ecology enterprise must be to establish what constitutes a sustainable livelihood and ecological integrity in the given circumstances. Only when this has been done is there a basis for evaluating the outcome of an industrial ecology enterprise.

SUSTAINABLE LIVELIHOODS

According to the United Nations sustainable livelihoods (SL) programme:

> "A livelihood system is an aggregate yet dynamic environment of human activity that integrates both the opportunities and assets available to men and women as means for achieving their goals and aspirations as well as interactions with, and exposure to, a range of beneficial or harmful ecological, social, economic and political perturbations that change their capacity to make a living. …
>
> Sustainable livelihoods are derived from people's capacity to make a living by surviving shocks and stress and improve their material condition without jeopardizing the livelihood options of other peoples, either now or in the future. This requires reliance on both capabilities and assets (i.e., stores, resources, claims and accesses) for a means of living..
>
> The sustainability of livelihoods becomes a function of how men and women utilize asset portfolios on both a short and long-term basis. Sustainability should be defined in a broad manner and implies:
>
> - The ability to cope with and recover from shocks and stresses;
> - Economic efficiency, or the use of minimal inputs to generate a given amount of outputs;
> - Ecological integrity, ensuring that livelihood activities do not irreversibly degrade natural resources within a given ecosystem; and
> - Social equity which suggests that promotion of livelihood opportunities for one group should not foreclose options for other groups, either now or in the future.
>
> In other words, SL is the capability of people to make a living and improve their quality of life without jeopardizing the livelihood options of others, either now or in the future." (UNDP, 1998).

Sustainable livelihoods is the socio-economic impetus behind industrial ecology. The UNDP programme on sustainable livelihoods provides a set of tools for evaluating, designing and implementing sustainable livelihoods. It is left to the reader to investigate this further.

ECOLOGICAL INTEGRITY

Ecological integrity is the bio-physical purpose of industrial ecology.

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

The first of these is about the ecological health of the system; about its vigour, its well being and how well it is flourishing in the current circumstances. It concerns the current state of the ecosystem.

The second aspect of integrity is about the stress-response capability of the ecosystem, something which is often referred to as its resiliency. It is about what happens when the system's state is disturbed by outside influences, that is, its ability to re-organize in the face of change. Stress-response is about how the system deals with change that disturbs it from its current attractor and which possibly flips it into the domain of another attractor. This has been discussed in detail in (Kay, 1991).

The third aspect of integrity concerns the ecological system's potential to continue to self-organize. This pertains to the system's ability to develop, regenerate, and evolve in its normal environmental circumstances. This is about its capacity to:

a) continue to develop, that is, increase its organization relative to an attractor;
b) regenerate, to deal with birth-growth-death-renewal cycle (i.e. the Holling four box model (Holling, 1986; Holling, 1992)), that is to deal with the multiple nested dual attractor problem; and to
c) continue to evolve, that is switch attractors spontaneously (emergent complexity).

Put in the parlance of complex systems, ecological integrity is about maintaining the integrity of the process of self-organization. This has three facets,

a) the current organizational state of the system,
b) the ability of the system to reorganize in the face of environmental change
c) the system's capacity to continue to **self**-organize in its normal environment.

These three facets must be considered when evaluating the integrity of the ecological systems which emanate from the practice of industrial ecology.

We are only beginning to understand how to investigate and evaluate ecological integrity (Woodley and others, 1993). Much work on understanding ecosystems as complex self-organizing systems still remains to be done. In particular, the notion of attractors, and flips between attractors, has only been considered in the literature in the last fifteen years. Much remains to be learnt about these complex behaviours. In the meantime it seems prudent, given our ignorance, to adopt the precautionary principle.

Together the notions of ecological integrity and sustainable livelihoods form the normative basis for industrial ecology.

A conceptual model for industrial ecology

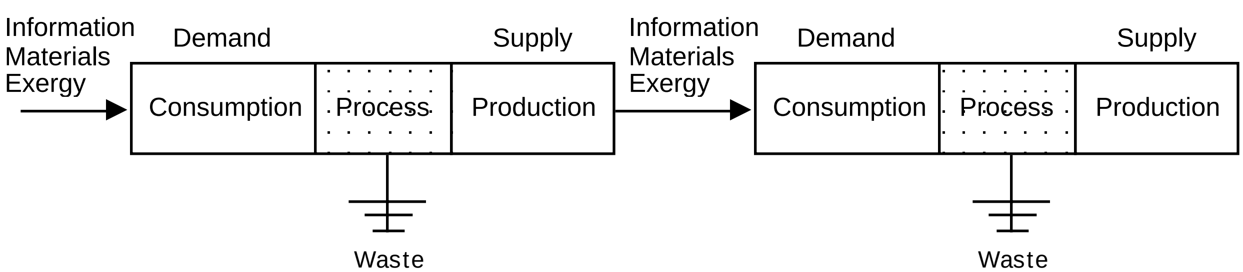
We have developed an integrated SOHO system model which portrays ecological-societal systems as dissipative complex systems (Boyle and others, 2000; Corning and Kline, 1998; Kay and Regier, 1999; Kay and others, 1999; Regier and Kay, 1996). This SOHO system model provides a conceptual basis for discussing ecological integrity and human sustainability (refer to Figures 3 through 5). It furnishes us with an integrated, nested ecosystem description of the relationship between natural and human systems. As such it can serve as a basis in industrial ecology for scrutinizing these relationships.

In this model, the elements of the landscape (e.g. woodlots, wetlands, farms, neighbourhoods) that make up the societal and ecological systems, are seen as self-organizing entities set in an environmental context. Self-organizing entities are understood through consideration of their constituent processes and structures, and the relationships between these. (For example, in a woodlot: processes would be evapotranspiration and growth of biomass; structure would be the species that make up the woodlot; and a description of the relationship between these processes and structure would be Holling's four box model.) The processes involve the flows of material, energy and information. The structures are the objects (i.e., trees) we see on the landscape. The processes allow for the emergence and support of structures, which in turn allow for the emergence of new processes, and so on. The recognition of this recursive relationship between process and structure separates this hierarchical conceptual model from more traditional ones.

Our conception of self-organization, as a dissipative system, was presented in Figure 1. It is a description of how a mass-energy transformation system emerges. This formulation is the kernel for the SOHO system model. Self-organizing dissipative processes emerge whenever sufficient exergy is available to support them. The details of the processes depend on the raw materials available to operate them, the information present to catalyze the processes, and the physical environment. The interplay of these factors defines the context for (i.e. constrains) the set of processes which may emerge. (Generally speaking, which specific processes emerge from the available set are uncertain.) Once a dissipative process emerges and becomes established it manifests itself as a structure.

This basic description characterizes mass-energy transformation systems in terms of the exergy, materials and information they consume and how these are used in dissipative processes. It focuses on the consumption side of the production-consumption duality of systems. However when more than one such element is connected to form a larger system, the production aspects of the system become clear. Each element not only consumes exergy, materials and information but also produces exergy, materials and information for the next element in the concatenation. Each element provides the context for another element. So horizontally each element

Figure 6: Each component of a SOHO system consumes exergy, materials and information. The dissipative process transforms these inputs into new forms of exergy, materials and information. These products or outputs of the dissipative process serve as inputs for another component in the SOHO system. Each element not only consumes exergy, materials and information but also produces exergy, materials and information for the next element in the concatenation. Each element provides the context for another element. So horizontally each element in the SOHO system model has a Janus two face, its consumption face and its production face. Therefore each component of a SOHO system must be thought through both as a producer and as a consumer.



in the SOHO system model has a Janus two face, its consumption face and its production face. (See Figure 6)

THE ECOLOGICAL-SOCIETAL SYSTEM INTERFACE

Ecological communities provide exergy, materials and information required for human societies to sustain themselves. This is depicted in Figure 3. The societal system depends on the flow of exergy, materials and information from the ecological system to support its processes and structures. These flows, along with the biophysical environment provided by the ecological systems, are the context for societal systems. The context constrains the possible societal processes and structures in a specific location. While Figure 3 illustrates a single ecological system providing the context for the societal system, the reality is that it is a suite of adjacent ecological systems (for example: woodlots, fields and wetlands adjacent to a farm) that provide this context. Alterations in these adjacent systems will alter the context and thus the possibilities for the system in question.

However, the societal system can also influence the ecological system in two ways. The first influence is through changes in the structure of the ecological system (for example: cutting trees down in a woodlot, filling in wetlands, and all the human activities which involve removing or dismantling ecological structures on the landscape). Such actions, of course, alter the flows from the ecological systems to the societal systems and thus create a feedback structure on the landscape. This is represented in Figure 3 by the lower arrow back from the societal system to the structure in the ecological system. The feedback to the societal system occurs because changes in the ecological structure change the context for the societal system.

The second influence occurs when the context of the ecological system is altered by the societal system. For example, the runoff into a wetland or stream may be altered by human activities on adjacent properties. It is depicted in Figure 3 by the upper arrow from the societal system back up to the context of the ecological system. This influence is qualitatively different than the structural influence just discussed.

The resulting feedback loop has more steps and accordingly is more indirect. By changing the context of the ecological system, the societal system affects the ecological processes and, in turn, the ecological structure and ultimately affects the societal system’s own context. For example, modifying the runoff into a waterway can dramatically alter the character of the waterway, and hence the type of fish found in it, and therefore the sport fishery and associated economic system.

To summarize this discussion, each self-organizing entity resides in an environment that provides: (a) the biophysical surroundings in which the entity exists; and, (b) flows of exergy, material and information that the entity depends upon for the continuation of the self-organizing processes which maintain its structure. The biophysical surroundings, in conjunction with the flows into the system, constitute the context for the self-organizing entity.

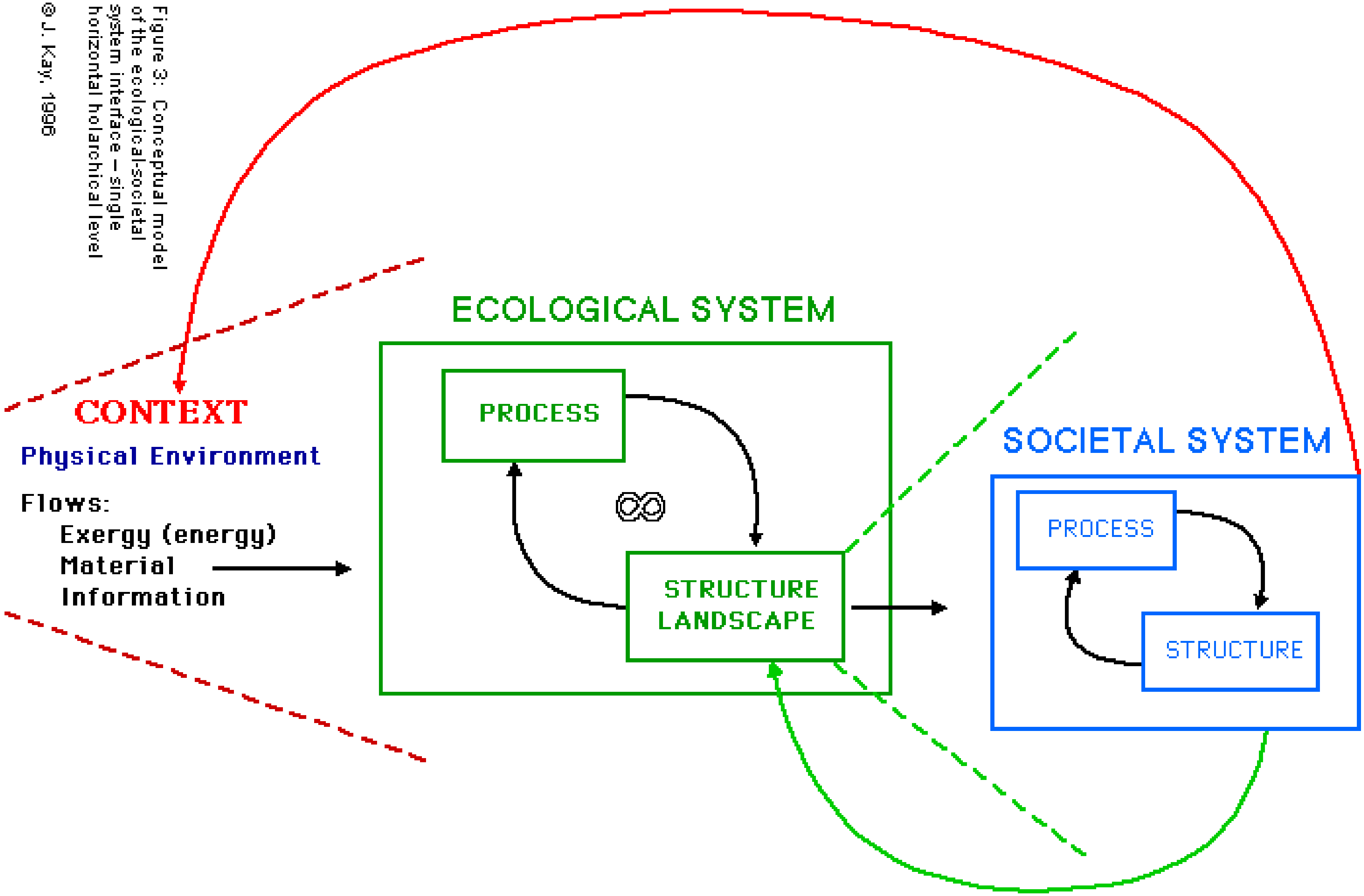


Figure 3: Conceptual model of the ecological-societal system interface – single horizontal holarchical level

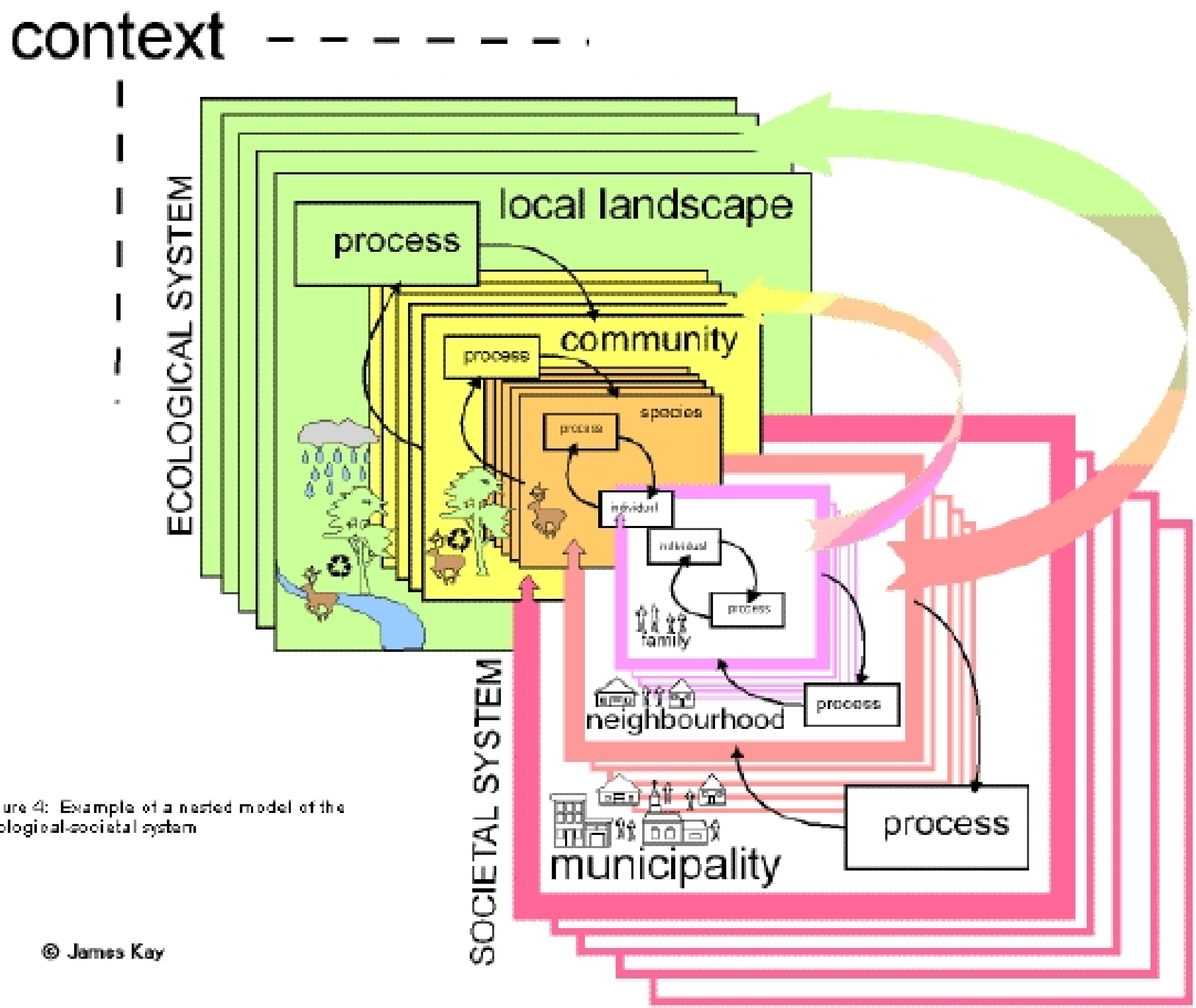


Figure 4: Example of a nested model of the ecological-societal system

© James Kay

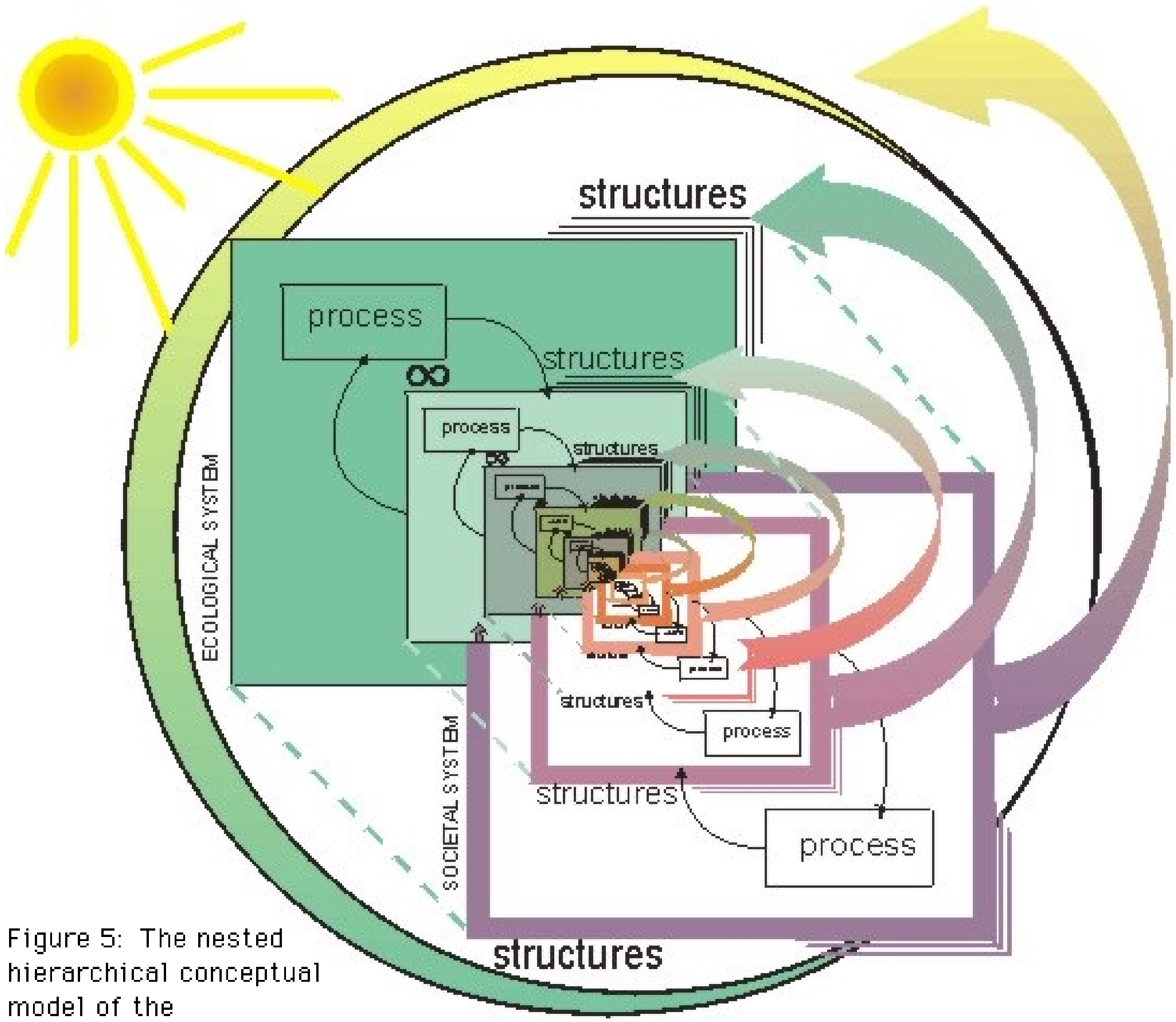


Figure 5: The nested hierarchical conceptual model of the ecological-societal system

Referring to Figure 3, the relationship between societal systems and ecological systems is three-fold:

- **Ecological systems provide the context for societal systems.** That is, they provide the biophysical surroundings and flows of exergy, material and information that are required by the self-organizing processes of the societal systems.
- **Societal systems can alter the structures in ecological systems.** (For example, cutting down a woodlot, removing beaver from a watershed.) Changes in the ecological structure can then, of course, alter the context for the societal systems themselves.
- **Societal systems can alter the context for the self-organizing processes of ecological systems.** (For example, a change in the drainage patterns into a wetland, a change in the local micro-climate, such as a heat island effect, for a woodlot.) Changes in ecological process can alter ecological structure and consequently the context for societal systems.

THE NESTED STRUCTURE OF THE MODEL

Figure 3 applies to one hierarchical level, but as observed earlier, sustainability and integrity issues can only be understood in terms of "nested holons". Figure 4 illustrates this idea of nesting. On the ecological side, "local landscape" can be thought of as a subwatershed, for example. The hydrological cycle is an example of a process in the subwatershed. The structures which make up the subwatershed are the ecological communities (e.g. woodlots, wetlands, open fields, etc.). The communities are in turn made up of species. On the societal side, municipalities rest on the local landscape. These in turn are made up of neighbourhoods, which are made up of families and businesses.

In many cases, the local subwatershed defines the context for the local municipality. However, the municipality can, and does, directly modify the ecological communities in the subwatershed and thus its own context. Similarly, the context for local neighbourhoods is determined by the adjacent ecological communities. Nonetheless, the local neighbourhood is quite capable of influencing ecological communities, through direct structural change (such as harvesting wood from a woodlot), or changing the context of an ecological community (for example, changing drainage patterns into a wetland).

Figure 4 and the examples are meant to be illustrative and not exhaustive, although they do demonstrate that such changes can cascade through the nested holons to ultimately effect individual families and businesses. Figure 5 shows the full conceptual model which would be used as a template to develop a situation specific conceptual model in which the important levels, processes, structures, contextual, and influence/feedback considerations are specifically identified.

THE CHALLENGE OF CONSTRUCTING A SOHO SYSTEM DESCRIPTION

Sustainability is about maintaining the integrity of the combined ecological - societal system. This means maintaining their self-organizing processes and structures. *This will happen naturally if we maintain the context for self-organization in* *ecological systems, which in turn will maintain the context for the continued well-being of the societal systems. It is this relationship which must be thought through if the promise of industrial ecology is to come to fruition.*

This will require building production-consumption models of each element in the combined ecological-societal system. These models will need to tell us about the relationship between the organizational state (attractor) of the element and its context. This in turn requires a description of the context. The contextual description has four aspects, a description of the flow of energy, material and information and the physical environment. Given this description, then one needs to link specific contextual states to organizational attractors. This turns out to be the fundamental challenge to successfully developing a programme for industrial ecology. We are only beginning to explore the relationship between context and self-organization.

The most progress has been made in discussing energy flow. If one considers only the energy aspect of the flows in a SOHO system description, then Network Thermodynamics, using graph theoretic techniques allows a complete system description. At the core of this description are measures of the quantity and quality of the flow. (Most readers will know that energy is measured in calories or joules. However the problem is that all joules are not equivalent. I can do less with a joule of crude oil than I can with a joule of household heating oil, and I can do less with a joule of both of these than I can with a joule of electricity. The quality of each of these joules is different and is measured by exergy.) Each component is described by the change in quality and quantity of flow between its inputs and outputs. This effectively involves measuring the gradient drop across the component and the associated flow through the component. Overall the components together, that is the system, must conform to two rules, know variously as Kirchkoff's laws; the cutset and circuit equation; or the first and second law of thermodynamics. In electrical systems, the measure of quantity is current and the measure of quality is voltage. In hydrodynamic systems, the measure of quantity is volume flow and the measure of quality is pressure. In general it has been shown that for any energy flow system, the quantity measure is flow of energy and the quality measure is exergy density (exergy per unit energy) (Ahern, 1980; Brodyansky and others, 1994; Edgerton, 1982; Ford and others, 1975; Gaggioli, 1980; Gaggioli, 1983; Hevert and Hevert, 1980; Moran, 1982; Szargut and others, 1988; Wall, 1986; Wong, 1979).

The details of how to measure these and how to do the analysis are not important here and are left for the reader. What is important is that this body of work has demonstrated unequivocally that any description of a real physical flow system must be in terms of BOTH a quality and quantity measure, if meaningful results are to arise from the analysis. Only with both types of measures can the full effect of the first and second law of thermodynamics be taken into account. Most energy analysis has traditionally looked only at energy flow and it has been demonstrated in a number of works that this has lead to poor decisions, both at the micro (plant or building) level and at the macro (describing the economy) level. In spite of the power of this form of analysis, it has only begun to work its way into the engineering curriculum and textbooks in the past decade.

Unfortunately such a body of knowledge does not exist for the other aspects of the contextual descriptions necessary for a self-organizing hierarchical open systems description of ecological-societal systems. We can guess that similar measures of the quality and quantity of material flow are needed. While quantity measures of material flow are self-evident, quality measures elude us. Yet these are critical if we are to evaluate the implications of such strategies as material recycling. Even more unclear is the calculus of information. The central role of information in directing the emergence of self-organizing processes and structures has only recently been put forward and how to describe this role remains quite unclear.

This gap in our knowledge presents a major challenge to the development of industrial ecology. There are profound and fundamental theoretical issues related to complexity and self-organization which we must resolve before we will have a robust theoretical basis for discussing sustainability, ecological integrity and industrial ecology. These issues revolve around the question of system description and quality. Even with this profound gap in our knowledge, there is still much that complex systems thinking can say about design and industrial ecology. We explore this in the next section.

Design Principles

Design principles and tools for industrial ecology have been proposed elsewhere (Allenby, 1999; Ehrenfeld, 1997; van Berkel and Lafeur, 1997; van Berkel and others, 1997). There is much overlap between these principles and the four introduced in the beginning of this chapter. (See Table 3) These four are somewhat different in that they are explicitly derived from a systematic application of system's theory. They explicitly deal with the implications of the second law of thermodynamics, hierarchy and attractors and finally, although this is a curiosity more than anything, they were first published in 1977.

Table 3: Some Design Principles for Industrial Ecology.

The design of production consumption systems should be such that:

- the interface between societal systems and natural ecosystems reflects the limited ability of natural ecosystems to provide energy and absorb waste before their survival potential is significantly altered, and that the survival potential of natural ecosystems must be maintained. This is referred to as the problem of interfacing.
- the behavior and structure of large scale societal systems should be as similar as possible to those exhibited by natural ecosystems. This is referred to, after Papanek, as the principle of bionics. (In the IE literature it is often referred to as mimicry)
- whenever feasible the function of a component of a societal system should be carried out by a subsystem of the natural biosphere. This is referred to as *using* appropriate biotechnology.
- non-renewable resources are used only as capital expenditures to bring renewable resources on line.

INTERFACING HUMAN NATURAL (ECO)SYSTEMS

The first of the design principles is: *the interface between man-made systems and natural ecosystems must reflect the limited ability of natural ecosystems to provide energy and absorb waste before their survival potential is significantly altered, and that the survival potential of natural ecosystems must be maintained.* This is referred to as the problem of *interfacing*.

In an ideal situation, efforts to address the interfacing problem, would be based on an analysis of the situation using the SOHO system description discussed above. This description would deal with each component as a self-organizing production-consumption system. All the relevant flows of exergy, materials and information and the effect of changes in these on self-organization would be accounted for. The nested nature of the system requires that design implications be considered at different spatial and temporal scales. In particular, the effects of the two different forms of feedback (from the societal to the natural system) would need to be thought through in detail.

The criteria for evaluating the implications of the design are the normative principles of sustainable livelihoods and ecological integrity. The nature of self-organizing systems requires that these criteria be applied in quite a different way than we are used to. Our normal way of applying such criteria is based on an assumption that an incremental change in the context (that is the influence of the design on the natural system) will result in an incremental change in the natural system. But self-organizing systems do not work this way. There can be substantial changes in context, which the system can buffer itself from and hence there will be no change in the system's state. However once this buffering capacity is used up, a very small change in context can cause dramatic change in the system's state. For example, as documented elsewhere, (see Figure 2) the incremental addition of phosphorous to a shallow lake will have little effect until a threshold is reached. After the threshold, a small change in phosphorous loading will trigger a massive and dramatic re-organization in the lake, a flip between attractors (Kay and Regier, 1999; Scheffer, 1998; Scheffer and others, 1993). Once a flip is precipitated it requires a massive change in context to return the system to its original state. In the case of Lake Erie, billions of dollars and decades of phosphorous remediation programmes were necessary to "clean up the lake", that is trigger a flip back to its earlier "clean" state.

The point is that when thinking through how a particular design is going to affect ecological integrity and sustainable livelihoods, it cannot be done using a linear incremental approach to the relationship between cause (the design) and effect (the ecosystem's re-organization). Rather a non-linear hierarchical mindset, which takes into account thresholds, cumulative effects, buffering, flips between attractors and cross-scale dynamics, must be used. Put another way, an industrial plant could increase it's discharge by 50% (an arbitrary choice of %) with little noticeable change in the surrounding natural ecosystems but an increase of 55% could trigger a dramatic and irreversible change in the surrounding natural ecosystems. A linear incremental change approach to evaluating the implications of a design would not suggest such a possibility.

If there is one lesson from the past thirty years of dealing with environmental issues, it is this: the complexity of the relationship between societal and natural ecosystems requires a significantly more sophisticated approach than that of normal scientific methods of analysis and evaluation.

Unfortunately our current state of knowledge is not up to the task. The type of information needed to build up a SOHO system description is generally not collected. (For details on a monitoring programme to accomplish this see (Boyle and others, 1996; Boyle and others, 2000).) In addition the study of ecological attractors and flips between them is in its infancy. Our understanding of these phenomena is at best qualitative and ambiguous. Thus, we do not have an understanding of the relationship between context and self-organization of a system. This ignorance is a major stumbling block to discussing ecological integrity. We certainly do not know what the thresholds for flips are.

In terms of dealing with the interfacing of societal and natural ecosystems we are left in a quandary. While we understand how to frame the discussion of the implications of a particular design, we are not, at this time, in a position to make specific statements about the implications of a specific design that are sufficiently robust to allow us to proceed with confidence. We know the questions to ask, but not how to answer them. We do not have sufficient understanding of cause and effect relationships in these situations. This is a fundamental challenge for the practice of industrial ecology. How do we proceed in the face of such profound uncertainty? These are two strategies: adaptive management and the precautionary principle.

Adaptive management involves assuming that one's design is at best a temporary transient solution to a situation. Then one must build into one's design the ability to change and adapt to changing circumstances. This requires that a design be inherently flexible. It also requires that comprehensive monitoring be carried out so that change in the environment can be detected sufficiently early to allow for appropriate change in the design. In effect, our design process must change so that the resulting systems have the capacity to re-organize. They should be constructed as self-organizing systems. This involves a profound shift in paradigm. We can no longer treat our designs as mechanical clock work edifices designed to withstand the test of time.

Given our ignorance about how our interactions with natural systems will affect them, it behooves us to minimize these interactions. This is the precautionary principle. Whenever possible we should limit the effluent from societal systems (both waste materials and energy) flowing across the interface into natural systems. We should minimize the displacement on the landscape of natural systems by societal systems. Given that human society is appropriating more than half the photosynthetic capacity of the biosphere, human systems must decrease their use of energy. In short, adoption of the precautionary principle mandates that our designs minimize their ecological footprint.

This is not inconsistent with some of the core design principles espoused in the industrial ecology literature. Closing the material flow loops, dematerialization and lifecycle efficiency are all strategies to decrease the ecological footprint of a design. However, curiously enough, the rationale for these strategies is very different in the industrial ecology literature, from the one presented herein. The normal justification in the literature is based on these being properties of natural ecological systems that our designs should mimic. This line of logic is incorrect as we shall see in the next section. But this does not negate the validity of these efficiency related design principles. However some words of caution from systems theory concerning efficiency are in order.

About efficiency

As mentioned earlier, physical flows must be analyzed in terms of quantity and quality. Efficiency is about how well the quantity of flow is used. Effectiveness is how well the quality of the flow is used. When the flow is energy, quality is measured by exergy density. Effectiveness measures how much exergy is used in the system relative to a theoretical best case scenario. (The theoretical best case, according to the second law of thermodynamics, is when all processes are performed reversibly and all the available work (exergy) is extracted from the energy).

Second law analysis is the activity of studying how effectively the quality of a flow is utilized in a system. Only a handful of authors have suggested that quality and effectiveness (i.e. exergy analysis) are important considerations for design in industrial ecology (Ayres and others, 1998; Brodyansky and others, 1994; Connelly and Koshland, 1997; O'Rourke and others, 1996). Yet it has been well-demonstrated that focusing on efficiency alone will lead to poor decisions. Take for example electric radiant heat versus natural gas forced air furnace. While the efficiency (First Law) of an electric heater is essentially 100% (all of the electricity is converted to heat), its second law effectiveness is much lower than that of natural gas furnace. This is because the quality of the electricity is wasted. The electricity could have been used to run a heat pump or other devices which in turn would have generated heat while doing other tasks as well. The point here is that only focusing on efficiency, as much industrial ecology work does, will lead to designs which use more exergy and produce more waste than they need to. Focusing only on efficiency leads to a design with a larger ecological footprint than necessary.

Another problem with the focus on efficiency is suboptimization. There is an underlying assumption that if individual processes and subsystems are made efficient, then the overall system will be efficient. This assumption is only valid when the interconnections between elements of the system are strictly linear. This is rarely true in real physical systems. For example, we undertook to change a student residence cafeteria, so that less waste would be produced. Observation of the food which remained on plates after students had finished their meals revealed a large amount of untouched food, and unopened packages which ended up in the garbage. Surveys of students revealed that this was because food was served on a fixed price, "all you can eat" basis. A redesign of the cafeteria was undertaken so that students paid for what they put on their plates. This reduced the waste from plates after meals by 72%. The redesign seemed to be a big success. However we monitored all the waste generated, from the time the food entered the university, through all the processing steps, until it was disposed of or consumed. The changes in the overall food system required by the redesign actually increased the waste generated in some subsystems. When all the waste generated is taken into account, a 45% decrease was obtained.

The point is that anytime one part of a system is optimized in isolation, another part will be moved further from its optimum in order to accommodate the change. Generally when a system is optimal, its components are themselves run in a suboptimal way. One cannot assume that imposing an efficiency criteria on every component in a system will lead to the most efficient system overall. Generally it will not. Instead a nested approach must be taken when dealing with efficiency.

Allenby takes this observation one step further. He notes that one cannot talk about a sustainable process or plant, but only about a sustainable biosphere (Allenby, 1999). Sustainability, like efficiency, must be a property of the overall nested system, not of each of the subsystems and components.

The exploration of the issue of interfacing natural and societal systems illustrates our profound ignorance of how the natural biosphere works. Dealing with this ignorance is the single most important scientific challenge facing our species. In lieu of the knowledge necessary to evaluate the implications of our designs for natural systems, the only currently viable way of dealing with interfacing, other than ignoring it in the design process, is to design for adaptability and to minimize the ecological footprint of our designs.

MIMICRY OF NATURAL ECOSYSTEMS

The second design principle is *the behavior and structure of large scale man-made systems should be as similar as possible to those exhibited by natural ecosystems.*

This seems to be the cornerstone of industrial ecology and has been proposed by many authors. (p. 72, (Kay, 1977); P.144 (Frosch and Gallopoulos, 1989); p.85 (Boons and Bass, 1997); p.6, (Tibbs, 1992); p.90, (O'Rourke and others, 1996); (Erkman, 1997)) The rationale for this principle is typically in the form:

> "The purpose of having man-made production-consumption systems mimic natural ones is to benefit from the "learning" that is embedded in the structure and behaviour of natural systems. As long as man ultimately depends on the sun for energy and the earth for material resources he would be foolish to ignore the teachings of several billion years of evolution." (p.84,(Kay, 1977))

or

> Nature is the undisputed master of complex systems, and in our design of a global industrial system we could learn much from the way the natural global ecosystem functions. In doing so, we could not only improve the efficiency of industry but also find more acceptable ways of interfacing it with nature. Indeed, the most effective way of doing this is probably to model the systemic design of industry on the systemic design of the natural system. This insight is at the heart of the closely related concepts of industrial ecology, industrial ecosystems, industrial metabolism, and industrial symbiosis, all of which have been emerging in recent years." (p.5, (Tibbs, 1992))

Unfortunately the application and discussion of this principle is often flawed by a romantic turn of the last century Clementsian, Odumesque (E.P. not H.T.) view of ecosystems as superefficient, closed loop, highly tuned systems. As Boons and Bass point out, this is simply not the case (p.79, (Boons and Bass, 1997)). (Nor are ecosystems random accidents of history, as suggested by the Gleasonian school of ecology.) Rather, as I have summarized briefly in the beginning of this chapter and have written about at length elsewhere, ecosystems are complex, adaptive, self-organizing hierarchical systems. There are two broad themes to self-organizations of ecosystems:

- Coping with a changing environment
- Making good use of available resources.

At any time the state of development of an ecosystem reflects a historical balancing act between these sometimes contradictory themes. An ecosystem which is superefficient, and has a highly articulated mass-energy flow network is usually quite brittle, that is unable to cope with change. So to successfully apply this principle we need to significantly alter our notion of how ecosystems develop. Ecosystems are not necessarily about "closing the loop" but rather about making effective (in a second law sense) use of the resources available while maintaining adaptability. Striking this balance is what maintaining ecological integrity is about.

In some instances, with respect to some resources, ecosystems are very leaky. For example, a shallow lake in a benthic regime will extract incoming phosphorous from the water column and burying it in the bottom muck where it is deactivated. In effect all the phosphorous is removed from the system. Ironically when the ecosystem can no longer accomplish this, a flip to a different regime (the pelagic) is precipitated, and, in the process, the phosphorous in the bottom muck is re-released into the water column where it fuels the new regime. (I cannot help but think of our practice of landfilling our garbage and how this buried waste may become a valuable resource when our "ecosystem" flips.)

From an efficiency point of view, terrestrial ecosystems are not. Less than 2% of the incoming solar energy is converted to green stuff. Over 80% of the incoming solar energy is turned into heat or is used to pump water. This is not to an example of efficiency. However from a second law effectiveness point of view, ecosystems have effectiveness ratios which exceed 80%. They are very effective at using their resources.

There are three ways to cope with a changing environment.

1) Take control of the environment,
2) Isolate the system from the environment,
3) Adapt the system to the changed environment by:
    a) Changing the behaviour and role of elements of the system.
    b) Change the elements of the system.
    c) Change the interconnections between elements.

Natural ecosystems do make use of the first and second of these strategies. (Beavers build dams, tropical rainforests throw up a cloud cover daily thus limiting solar energy hitting the canopy, streams are isolated from changes in ion concentration in precipitation by the filtering action of adjacent forests.) However, the primary means of coping is the last strategy, adapting. In particular, the loss of elements of an ecosystem (death of individuals and loss of species through displacement) are common. (Survival of the fittest, Holling four box model).

On the other hand, humans tend to focus on the first and second strategy as versus the third. This is well-illustrated by our tendency to bulldoze the natural landscape and replace it with concrete and gardens. The act of building a house or office is about isolating the system (humans) from the environment (nature). Humans do not tend to focus on adaptability insofar as it means abandoning or radically changing elements of the system. We value human life and try to minimize the "hardships" felt by members of our species. Natural ecosystems have no such concerns.

So while it would behoove us to take advantage of the collective learning and wisdom that is reflected in the system characteristics of natural ecosystems, mimicry of natural ecosystems must be tempered by an appreciation that humans have a set of priorities which will cause them to find a different balance, between the need to make good use of resources while coping with a changing environment.

APPROPRIATE BIOTECHNOLOGY

The third design principle is *whenever feasible, the function of a component of a man-made system should be carried out by a subsystem of the natural biosphere*. This is referred to as using *appropriate biotechnology.* Over the past two decades, in the Region of Waterloo, Ontario, a number of experiments using "appropriate biotechnology" have been tried. For example it is now standard practice to use natural landscapes for storm water management, in place of concrete channels. These natural landscapes include holding ponds and creeks with natural vegetation on the slopes. Our experience is that the capital costs for "natural" storm water management is about 10% that of concrete and operating costs are similarly less. Furthermore, these waterways double as aesthetically attractive recreational amenities in the community. Another example is the replacement of turfgrass with natural communities that are self-maintaining. This significantly reduces the cost (both dollars and environmental damage due to chemicals etc.) of maintaining landscapes. Composting has been actively promoted by Regional government with tens of thousands of composters being distributed, thus diverting solid waste from local landfills. Wetlands (both existing and man-made) have been used for sewage treatment plants and for remediation of mine tailing ponds. Luvall's work on greening U.S. cities has demonstrated how judicious use of trees and other flora can significantly reduce the heat load on a city. The experience with "appropriate biotechnology" has been that it saves much money, both in capital and operating costs.

RENEWABLE RESOURCES

The final design principle is *non-renewable resources should be used only as capital expenditures to bring renewable resources on-line*. This principle is a corollary to the axiom that we must live within our carrying capacity. Resources are not inherently renewable. It is how we use them that makes them renewable. When a resource is used at a rate which is less than the rate at which the resource can be replenished by natural systems, then the use of the resource is renewable. Be clear that term replenished is not a synonym for produced. Replenished means the natural system is producing stock of the resource at a rate such that the stock of the resource in the natural system does not decrease. Recycled materials are a renewable resource in so far as the cost of recycling is born by renewable resource consumption. In the final analysis, unless humans move off the planet, the human population must be such that it can be supported by renewable resources.

CONSTRUCTION ECOLOGY

So far this chapter has sketched out the relationship between industrial ecology and complex systems and ecosystem thinking. The challenge posed by these considerations is how to design an adaptive, resilient, evolving, self-organizing hierarchical human production-consumption system, which provides for a sustainable livelihood, whose ecological footprint is minimal, and which interfaces with natural systems in a way which promotes ecological integrity. In this section this challenge is explored in the context of construction ecology. The issues that this poses for construction ecology is not so much how to construct efficiently, but rather how to construct a building system which is resilient and can adapt and evolve while fitting into the natural environment. Currently, construction ecology seems to focus on buildings that deal with a changing environment by being robust enough to be impervious to change. Thus our only means of adapting or evolving our structures seems to be by tearing them down and starting over. Surely we can come up with a better process for our structures to evolve than blowing them up in a spectacular fashion. Perhaps the notion of mimicry is a place to start thinking about how to do this.

Currently buildings are essentially static structures. If they are to mimic natural ecosystems then they must have the capacity to self-organize, that is to reshape the internal configuration of the building and to change the buildings connection to the outside world, in response to a changing situation. This would need to be thought

Table 4: Ecological integrity is the bio-physical purpose of industrial ecology. Ecological integrity is about three facets of the self-organization of ecological systems: a) current well being, b) resiliency, c) capacity to develop, regenerate and evolve (Kay & Regier 2000). An evaluation of ecological integrity must consider:

- the current organizational state of the system,
- the ability of the system to reorganize in the face of environmental change
- the system's capacity to continue to self-organize in its normal environment, that is to:
    1. continue to develop, that is increase its organization relative to an attractor;
    2. regenerate, to deal with birth-growth-death-renewal cycle (i.e. the Holling four box model {Holling 1986, 1992), that is to deal with the multiple nested dual attractor problem; and to
    3. continue to evolve, that is switch attractors spontaneously (emergent complexity).

through from different types of perspectives at different scales. For example some of the types of perspectives would be in the context of the different energy flows and material flows through a building and the ability to incorporate different flows as they come on and off line.

For example at our university the need to accommodate different forms of recyclable material has been a major challenge. Over the past fifteen years, there have been significant changes in the market for recyclables with paper being desirable in one year, cardboard the next and aluminum the year after. This has necessitated frequently putting in place and taking out collection systems for the specific recyclables at some economic and aesthetic cost. We are thinking hard about how new buildings could be built so that they can accommodate the oscillation in the demand for different elements of the solid waste stream. Another type of perspective would be that of the users of the building. Is there a way of reconfiguring the internal layout of the building as user needs change? A number of other perspectives (maintenance, deconstruction, HVAC, etc.) can be thought through in terms of the integrity (See Table 4) and adaptability (See Table 5) of the building.

These issues will also need to be thought through at different scales. There are the obvious scales of the basic units of the building (rooms, offices, etc.) and the building itself, but also the scale of the group of buildings and natural ecosystems which the building is connected to. How does the building fit into the bigger man-made and natural system? What is the hierarchical nesting of holons which it is a part of? What are the feedback loops between the building and the bigger world. Can the connections between the building and the outside world be changed?

For example at our university we investigated the possibility of recycling all the water on campus. This turned out to be feasible only because all the buildings on campus are connected to an internal campus waterworks. This waterworks is only connected to the city works in two places. So closing the loop for the campus could be done. If each building had been individually connected to the city waterworks, closing the water loop would have been physically impossible without reconnecting all the buildings on campus. The physical infrastructure at the scale of the campus allowed for an evolutionary strategy that otherwise would not have been practical.

So thinking of a building in terms of a SOHO system model opens up a whole set of design questions related to adaptability and integrity that are not normally considered. This recasts buildings as evolving dynamic structures which can be reshaped as the situation changes. And if one accepts Holling's four box phase

Table 5: There are three ways a system can cope with a changing environment. It can adapt by:

- Taking control of the environment,
- Isolating itself from the environment,
- Changing its internal organization by:
  1. Changing the behaviour and role of elements of the system.
  2. Changing the elements of the system.
  3. Changing the interconnections between elements.

model for ecosystems, it begs the question: what is the birth-growth-deconstruction-renewal process for a building, at all scales? This short section only scratches the surface of what I think is a very exciting challenge for the design of buildings. It goes far beyond the issues of efficiency and industrial parks which are usually associated with mimicry of natural ecosystem in industrial ecology.

The next step is to undertake some projects which demonstrate what an adaptable self-organizing building might look like. (The only example of this that I am aware of is the FLEX housing project of CMHC (Canada Mortgage and Housing Corporation (Gov't of Canada), 1997).) The key question to be explored is how the tradeoff between capital costs and efficiency plays off against the overhead of flexibility, redundancy, renewability and monitoring associated with adaptability. Nature is constantly revisiting this balance and I suspect this will also be the case with construction ecology.

In addition to the self-organization issue that ecosystem mimicry brings up, there is also the issue of mimicry of specific strategies of ecosystems. For example, terrestrial ecosystems will capture all the precipitation they need and store it for times of drought. Recently a set of apartment buildings was built locally which attempted to

Table 6: A sampling of green design standards for buildings. (prepared by James Wu.)

1. ASHRAE	energy consumption benchmark
2. BREEM	approximately 18 criteria (organized as global, local and indoor)
3. BEPAC	approximately 30 criteria, with subsets (organized as ozone layer protection, environmental impact of energy use, indoor environmental quality, resource conservation and site and transportation)
4. C-2000	170 criteria targeting commercial construction (energy efficiency, environmental impact, health/comfort/productivity, functional performance, longevity, adaptability, ease of operation and maintenance, economic viability)
5 Eco-Profile	criteria are structured in four main areas energy, indoor environment, pollution and exterior environment
6. Embodied Energy Profile	
7. Global Env. Impact	criteria categorized under 7 major headings: reduction in greenhouse gas emissions, conservation of tropical rain forest, reduction in gases that reduce acid rain, conservation of water resources, solid waste, reduction in ozone depleting substances, ecological considerations
8. Green Builder Program	approximately 16 criteria (water, energy, building materials, solid waste)
9. Green Building Program (City of Austin '96)	81 criteria targeting commercial construction (pre-design, programming, schematic design, design development, construction management, commissioning, post occupancy)
10. LEED (US Green Building Council, Green Building Rating System)	
11. Life cycle Assessment	

minimize their ecological footprint. One strategy incorporated in these building was to mimic nature by collecting all the precipitation on all surfaces on the site. The collected water is stored in a large reservoir that could provide for all non-potable water needs for 3 months (the longest time without significant precipitation in our area.)

Another example is the work of Luvall in greening cities (Lo and others, 1997). He has studied the radiation properties (absorption, reflection, emmisivity, etc.) of forest canopies and applied the lessons learned to desirable characteristics of roofing materials. Forest canopies tend to have large thermal inertia, it is hard to heat them up or cool them down. This means that the canopy temperature has a much smaller swing from day to night than the air temperature. By using roofing materials which have similar radiative characteristic as forest canopies, it is quite easy to drastically reduce the HVAC load on a building.

It would be interesting to compile a catalogue of such properties of natural ecosystems and their application to building design. Such a document could act as guide for architects and engineers.

The next logical step, beyond mimicking natural systems, is to actually incorporate the natural systems in buildings. This brings us to the subject of appropriate biotechnology for buildings. John Todd's Living Machines are an example of this (Todd and Todd, 1994). He constructs, in buildings, natural ecosystems which transform waste water into drinking water. At a larger scale this could be used for neighborhood sewage treatment plants. Another example is the use of rooftop gardens to insulate and cool buildings. By picking species with significant transpiration capacity, such gardens can actively cool buildings in the daytime. This can also be accomplished by planting mini-woodlots next to buildings, an idea pioneered by R. S. Dorney of University of Waterloo (UW). Composting is a means of dealing with organic waste. UW is experimenting with in-building composting using worms and other fauna in soil pots distributed throughout a building. (And no, we have never had a worm escape!) A final example of appropriate biotechnology is the effort to develop assemblage of vegetation which can act as air purifiers in buildings. A compilation of "appropriate biotechnologies" and a focused research program on the use of these technologies would further their use in construction.

So far in the discussion of construction ecology, the second and third design principles have been discussed. The first and the fourth have been left for the end of the discussion as much has been written about design for efficiency, using renewable resources, and minimizing ecological footprint in construction (Papanek, 1995; Todd and Todd, 1994; Vale and Vale, 1991; Yeang, 1995). One of my students, James Wu, has written a hundred page summary of these ideas, and I will not attempt to condense this here. In Table 6 are eleven different green design standards for buildings which he identified. However this literature does not deal with the problem of interfacing in an integrated systems way (the SOHO system model) as discussed earlier. As discussed earlier there are fundamental theoretical and practical obstacles to be overcome before this can be done in a satisfactory way.

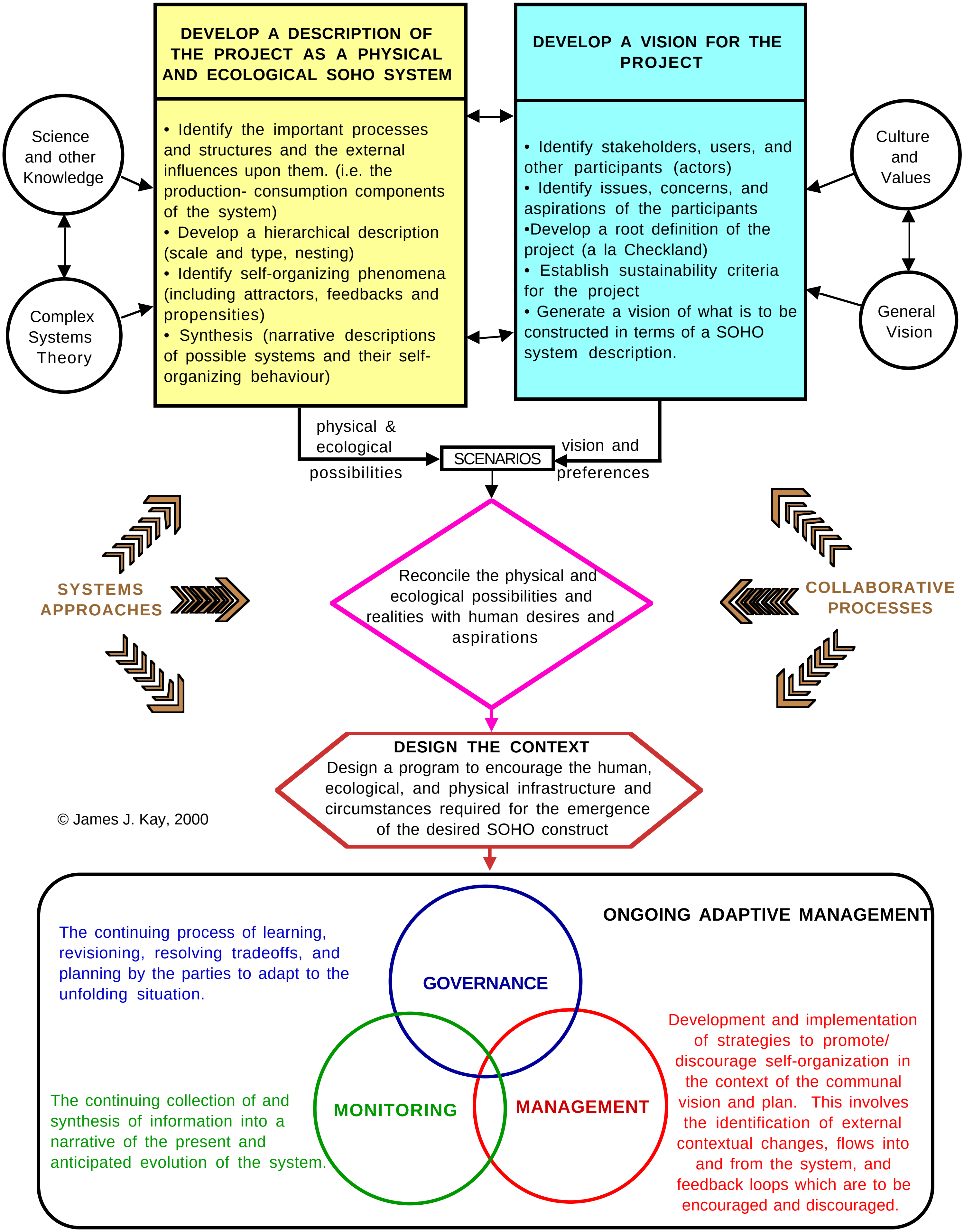


Figure 7: An adaptive ecosystem approach to construction ecology. Fundamental to this approach is a different mindset about design. Design can no longer be seen as finding a solution to a problem, in effect the right answer. Rather, it must be seen as setting in process the evolution of a built environment which evolves to meet the evolving needs of users and which can adapt so as to fit into changing environmental conditions.

One issue I wish to flag again is that of quality vs. quantity, of effectiveness vs. efficiency. The difference between these is rarely acknowledged in the literature. As pointed out earlier there are many situations where a design is efficient but not effective, and hence opportunities to decrease ecological footprint are missed.

For example if one is using natural gas turbines to generate electricity (as is done in the new "green" city hall in Kitchener, Ontario) and is using the waste heat from the generators to heat the building, or through an adsorption cycle, to cool the building in summer, the gain from using the waste heat will not show up in an efficiency calculation but will show up in an effectiveness calculation. Similarly buildings (such as the Ontario Hydro headquarters in Toronto, Ontario) which capture heat generated during the day by workers and machines etc. and store it for use to heat the building at night, do not have any advantage from an efficiency point of view, but do from an effectiveness perspective. Effectiveness must become as important a criteria as efficiency as a more effective solution can actually be less efficient, while having a smaller ecological footprint (for example natural gas vs. electrical domestic hot water systems).

An Ecosystem Approach

Central to the design process is the activity of making tradeoffs. Choosing between alternatives usually comes down to people's values. This is inescapable, especially when dealing with complex systems (Funtowicz and Ravetz, 1993; Funtowicz and Ravetz, 1994; Kay and Schneider, 1994). So ethics and values must be incorporated into any discussion of industrial ecology, if for no other reason than trade-offs between sustainable livelihoods and ecological integrity will have to be made. This leads me to reject the position of Allenby and IEEE.

> "This elucidation makes the important point that industrial ecology strives to be objective, not normative. Thus, where cultural, political, or psychological issues arise in an industrial ecology study, they are evaluated as objective dimensions of the problem. ... Whether this is good or bad—whether it "should" be the case—is not properly an issue for industrial ecology." (p.41, (Allenby, 1999))

It is a waste of time to try and build industrial ecology in the mode of traditional normal science. The inherent complexity of the subject it deals with means that a "post-normal" science epistemology will be much more fruitful. (I leave it to the reader to explore the literature and debate in this regard).

I have proposed, with others, an ecosystem approach for planning and decision making for sustainability (Kay and others, 1999). In Figure 7, I have adapted this approach for construction ecology.

There are two steps done in parallel at the beginning, identifying the players (stake holders, actors, users, etc.) and the issues they have surrounding the project and the building of systems description of the situation, preferably cast in the mode of SOHO system model. These two steps generate a set of descriptions (narratives) of how the building project might proceed. These scenarios represent different integrations of science and best practice with people's preferences. They reflect different combinations of tradeoffs. A decision making process must be developed that resolves these tradeoffs in a way that is acceptable to all actors. (Which begs the question, who gets to decide, which in turn leads to having to deal with issues of power and politics).

Once a resolution is reached, it is necessary to develop an ongoing adaptive management strategy. This involves monitoring and managing the internal organization of the building and its relationship to the outside so that if any re-organization is needed, it can be identified. However such re-organization can only occur if an appropriate governance structure is in place to make decisions about re-organization. Without a governance structure, no adaptation is possible.

Fundamental to this approach is a different mindset about design. Design can no longer be seen as finding a solution to a problem, in effect the right answer. Rather, it must be seen as setting in process the evolution of a built environment which evolves to meet the evolving needs of users and which can adapt so as to fit into changing environmental conditions. In an ecosystem approach, design must become about developing dynamic processes rather than static structures. Only in this way can our construction fit into an evolving, dynamic biosphere.

SUMMATION

> "Man is facing a resource crisis which his present world model, economics, seems to be unable to cope with. It appears that man's alternatives are as follows:
>
> 1) Continue our present behaviour and hope that we continuously evolve make-shift solutions (i.e. find sufficient new energy and material resources, technical fixes and places to dump our wastes so that we can continue to grow.) All evidence suggests that this would end in disaster.
>
> 2) Continue our present behaviour but the pressures of environmental factors force us to expand outward into space (via development of interstellar flight capabilities). This would be the classical solution, since throughout history whenever man did not have enough resources he expanded into new territory. This solution would gamble our remaining nonrenewable resources on an attempt to develop the technology necessary and then find the new resources.
>
> 3)Maintain the present system but assign dollar costs to the usage of resources and to the dumping of wastes in the environment. The problem then becomes one of management.
>
> 4) Man recognizes he is part of the natural environment and not external to it. He must integrate himself into this environment. His behaviour must take into account the limitations of the natural environment.
>
> The last alternative seems to offer the best chance for man's survival." (p.91, (Kay, 1977))

In this regard, this chapter argues that industrial ecology is the activity of designing and managing human production-consumption systems, so that they interact with natural systems, to form an integrated (eco)system which has ecological integrity and provides humans with a sustainable livelihood. To accomplish this end requires an ecosystem approach, the application of systems thinking to the analysis and design of biophysical mass and energy transformation systems. In essence industrial ecology is about designing human ecological-economic systems which fit in with natural ecological systems. Construction Ecology is about constructing built environments which have integrity and the ability to adapt.

The practice of industrial ecology and construction ecology must be carried out against the backdrop of the new understanding of complex systems, and in particular ecosystems, which is emerging. The hierarchical nature of these systems requires that they be studied from different types of perspectives and at different scales of examination. There is no one correct perspective. Rather a diversity of perspectives is required for understanding. Ecosystems are self-organizing. This means that their dynamics are largely a function of positive and negative feedback loops. This precludes linear causal mechanical explanations of ecosystem dynamics. In addition emergence and surprise are normal phenomena in systems dominated by feedback loops. Inherent uncertainty and limited predictability are inescapable consequences of these system phenomena. Such systems organize about attractors. Even when the environmental situation changes, the system's feedback loops tend to maintain its current state. However, when ecosystem change does occur, it tends to be very rapid and even catastrophic. When precisely the change will occur, and what state the system will change to, are often not predictable. Often, in a given situation, there are several possible ecological states (attractors), that are equivalent. Which state the ecosystem currently occupies is a function of its history. There is not a "correct" preferred state for the ecosystem.

This new understanding requires that the practice of industrial ecology and construction ecology must address the issues of complexity, self-organization and inherent uncertainty. As suggested in this chapter, this requires a very different framing of design. Design becomes about developing dynamic processes rather than static structures, about setting in motion an evolutionary process. An (eco)system based approach for doing this, which has its underpinnings a Self-organizing Hierarchical Open Systems analysis of the situation is sketched out in this chapter. As suggested herein, much work remains to be done to flesh out this approach.

In the end, human socio-economic systems are utterly dependant on natural systems for their context. As McHarg put it so eloquently thirty years ago, human society must fit in with nature (McHarg, 1998). Humans must understand that the integrity of human societal ecosystems are inextricably linked to the integrity of natural ecosystems. Maintaining the integrity of the biosphere is necessary for the continuation of our society. These means that we must design our physical systems so as to maintain the context for the integrity of the self-organizing processes of natural ecosystems that are necessary for the continued existence, on this planet, of self-organizing human ecosystems. This is the task that industrial ecology must accomplish, to design the intertwined ecological-societal system which is emerging on this planet.

ACKNOWLEDGEMENTS:

I would like to acknowledge the work of two undergraduate students who researched this topic for me, James Wu and Craig Hawthorne. I would like to thank

Charles Kibert for drawing me back into this topic after a long absence. Finally I would like to acknowledge the tremendous foresight exhibited by my graduate supervisor, M. Chandrashekar, in championing research in this area from the mid-70s on. I would have welcomed his co-authorship of this piece but alas he passed away at the untimely age of fifty, last year.

Reference List

Ahern, J. E. The Exergy Method of Energy Systems Analysis. New York: J. Wiley & Sons; 1980.

Akbari, M.; Murphy, S.; Kay, J. J., and Swanton, C. Energy-Bases Indicators of (Agro)Ecosystem Health. Quattrochi, D. and Luvall, J., ed. Thermal Remote Sensing in Land Surface Processes. Ann, Arbor, Michigan: Ann Arbor Press.; 2000.

Allen, T. F. H.; Bandurski, B. L., and King, A. W. The Ecosystem Approach: Theory and Ecosystem Integrity. International Joint Commission; 199364(Report to the Great Lakes Science Advisory Board).

Allen, T. F. H. and Hoekstra, T. W. Toward a Unified Ecology. New York: Columbia University Press; 1992.

Allen, T. F. H. and Starr, T. B. Hierarchy: Perspectives for Ecological Complexity. Chicago: University of Chicago Press; 1982.

Allenby, B. R. Industrial Ecology: Policy Framework and Implementation. New Jersey: Prentice-Hall; 1999.

Ayres, R.; Ayres, L., and Martin, K. Exergy, Waste Accounting, and Life Cycle Analysis. Energy. 1998; 23(5):355-363.

Boons, F. and Bass, L. Types of industrial ecology: the problem of coordination. J. Cleaner Prod. 1997; 5(1/2):79-86.

Boyle, M.; Kay, J. J., and Pond, B. State Of The Landscape Reporting: The Development of Indicators for the Provincial Policy Statement Under the Land Use Planning and Protection Act. Ontario Ministry of Natural Resources; 1996.

---. Monitoring and Assessment as Part of an Adaptive Ecosystem Approach to Sustainability and Health. Munn, T. E., ed. Encyclopaedia of Global Environmental Change. New York: John Wiley & Sons; 2000.

Brodyansky, V.; Sorin, M., and LeGoff, P. The Effeciency of Industrial Processes: Exergy Analysis and Optimization. Amsterdam: Elsevier; 1994.

Caley, M. T. and Sawada, D. Mindscapes: the Epistemology of Magoroh Maruyama. Langhorne, Pennsylvania: Gordon and Breach Science Publishers; 1994.

Canada Mortgage and Housing Corporation (Gov't of Canada). FLEX Housing - Homes That Adapt [Web Page]. 1997. Available at: http://www.cmhc-schl.gc.ca/rd-dr/en/flex/.

Casti, J. L. Complexification: Explaining a Paradoxical World Through the Science of Surprise. New York: Harper Collins; 1994.

Chinneck, J. Systems Theoretic Overview Models of Industrial Plant Energy Systems Incorporating Exergy [Ph.D. Thesis]. Waterloo, Ontario: Systems Design Engineering, University of Waterloo; 1983.

Chinneck, J. and Chandrashekar, M. Models of Large-Scale Industrial Energy Systems- 1. Simulation. Energy, The International Journal. 1984; 9(1):21-34.

Connelly, L. and Koshland, C. P. Two Aspects of Consumption: Using an Exergy-based Measure of Degradation to Advance the Theory and Implementation of Industrial Ecology. Resources, Conservation and Recycling . 1997; 19:199-217.

Corning, Peter and Kline, Stephen. Thermodynamics, Information and Life Revisited, Part 1: "To Be or Entropy". Systems Research and Behavioural Science. 1998; 15:273-295.

Dempster, B. A Self-Organizing Systems Perspective on Planning For Sustainability [Master's Thesis]. Waterloo, On.: School of Planning, University of Waterloo; 1998; c1998.

di Castri, F. The Evolution of Terrestrial Ecosystems. Ravera, O., Ed. Ecological Assessment of Environmental Degradation, Pollution and Recovery. Amsterdam: Elsevier Science; 1987; pp. 1-30.

Edgerton, Robert H. Available Energy and Environmental Economics. Lexington, Massachusetts: D.C. Heath; 1982; ISBN: 0-669-04699-x.

Ehrenfeld, J. Industrial Ecology: a framework for product and process design. J. Cleaner Prod. 1997; 5(1/2):87-85.

Erkman, S. Industrial Ecology: An historical overview. Journal of Clean Technology. 1997; 5:1-10.

Ford, K. W.; Rochlin, G. I., and Socolow, R. H. Effecient Use of Energy. New York: American Institute for Physics; 1975.

Fraser, R. and Kay, J. Exergy, Solar Radiation and Terrestrial Ecosystems. Quattrochi, D. and Luvall, J., ed. Thermal Remote sensing in Land Surface Processes. Ann Arbor, Michigan: Ann Arbor Press.; 2000.

Frosch, R. and Gallopoulos, N. Strategies for Manufacturing. Scientific American. 1989; 261(3):144-154.

Funtowicz, S. and Ravetz, J. Science for the post-normal age. Futures. 1993; 25(7):739-755.

---. Emergent Complex Systems. Futures. 1994; 26(6):568-582.

Gaggioli, Richard A., Ed. Thermodynamics: Second Law Analysis. Washington, D.C.: American Chemical Society; 1980. ISBN: 0-8412-0541-8.

---, Ed. Efficiency and Costing; Second Law Analysis of Processes. Washington, D.C.: American Chemical Society; 1983.

Graedel, T. E. and Allenby, B. R. Industrial Ecology. New Jersey: Prentice-Hall; 1995.

Hevert, H. and Hevert, S. Second Law analysis: An alternative indicator of system efficiency. Energy-The International Journal. 1980; 5(8-9):865-873.

Holling, C. S. The Resilience of Terrestrial Ecosystems: Local Surprise and Global Change. Clark, W. M. and Munn, R. E., Eds. Sustainable Development in the Biosphere. Cambridge: Cambridge University Press; 1986; pp. 292-320.

---. Cross-scale Morphology, Geometry, and Dynamics of Ecosystems. Ecological Monographs. 1992; 62(4):447-502.

IEEE electronics and the environment committee . White Paper On Sustainable Development and Industrial Ecology [Web Page]. 1995; Accessed 2000. Available at: computer.org/tab/ehsc/ehswp.htm.

Jantsch, E. The Self-Organizing Universe: Scientific and Human Implications of the Emerging Paradigm of Evolution. Toronto: Pergamon Press; 1980.

Kay, J. and Regier, H. An Ecosystem Approach to Erie’s Ecology. Munawar, M.; Edsall, T., and Munawar, I. F. The State of Lake Erie (SOLE) - Past, Present and Future. A tribute to Drs. Joe Leach & Henry Regier. Netherlands: Backhuys Academic Publishers; 1999; pp. 511-533.

Kay, J.; Regier, H.; Boyle, M., and Francis, G. An Ecosystem Approach for Sustainability: Addressing the Challenge of Complexity. Futures. 1999; 31(7):721-742.

Kay, J. J. A Non-equilibrium Thermodynamic Framework for Discussing Ecosystem Integrity. Environmental Management. 1991; 15(4):483-495.

Kay, J. J and Regier, H. Uncertainty, Complexity, And Ecological Integrity: Insights from an Ecosystem Approach. Crabbé, P.; Holland, A.; Ryszkowski, L, and Westra, L., eds. Implementing Ecological Integrity:Restoring Regional and Global Environmental and Human Health. The Netherlands: Kluwer; 2000; pp. 121-156.

Kay, J. J. and Schneider, E. D. Thermodynamics and Measures of Ecosystem IntegrityMcKenzie, D. H.; Hyatt, D. E., and Mc Donald, V. J., eds. Ecological Indicators, Proceedings of the International Symposium on Ecological Indicators; Fort Lauderdale, Florida. Amsterdam: Elsevier; 1992: 159-182.

---. Embracing Complexity, The Challenge of the Ecosystem Approach. Alternatives. 1994; 20(3):32-38.

Kay, James. An Investigation into Engineering Design Principles for a Conserver Society [Master's Thesis]. Waterloo, Ontario, Canada: Systems Design Engineering, University of Waterloo; 1977.

---. Self-Organization in Living Systems [Ph.D. Thesis]. Waterloo, Ontario, Canada: Systems Design Engineering, University of Waterloo; 1984.

---. Some notes on: The Ecosystem Approach, Ecosystems as Complex SystemsMurray, Tamsyn and Gallopin, Gilberto, eds. Integrated Conceptual Framework for Tropical Agroecosystem Research Based on Complex Systems Theories; CIAT, Cali, Colombia. Cali, Colombia: Centro Internacional de Agricultura Tropical, 1997; c1997: 69-98.

Koenig, B. and Tummala, R. Enterprise Model for the Design and Management of Maufacturing Systems. Proceedings Joint U.S./ German Conference on New Directions for Operations Research in Manufacturing; Gaithersburg, MD. 1991.

Koenig, H. E. and Cantlon, J. E. Quantitative Industrial Ecology. IEEE SMC. 1998; 28(1):16-28.

---. Sustainable Ecological Economies. Ecological Economics. 1999; 31(1):107.

Koenig, H. E.; Cooper, W., and Falvey, J. Engineering for Ecological, Sociological and Economic Compatibility. IEEE SMC. 1972; 2(3):319-331.

Koenig, H. E.; Edens, T., and Cooper, W. Ecology, Engineering and Economics . Proceedings of the IEEE. 1975; 63(3):501-511.

Koenig, H. E. and Tummala, R. L. Principles of Ecosystem Design and Management. IEEE SMC. 1972; 2(4):449-459.

Koestler, A. Janus: A Summing Up. London: Hutchinson; 1978.

Koestler, A. and Smythies, J. R., eds. Beyond Reductionism. London: Hutchinson; 1969.

Lo, C. P.; Quattrochi, D., and Luvall, J. C. Applications of High-Resolution Thermal Infrared Remote Sensing and GIS to Assess the Urban Heat Island Effect. International Journal of Remote Sensing. 1997; 18(2):287-304.

Ludwig, D.; B. Walker, B., and Holling, C. S. Sustainability, stability, and resilience. Conservation Ecology. 1997; 1(1):Article 7.

Luvall, J. C. and others. Estimation of tropical forest canopy temperatures, thermal response numbers, and evapotranspiration using an aircraft-based thermal sensor. Photogrammetric Engineering and Remote Sensing. 1990; 56(10):1393-1401.

Luvall, J. C. and Holbo, H. R. Thermal Remote Sensing Methods in Landscape Ecology. Turner, M. and Gardner, R. H., ed. Quantitative Methods in Landscape Ecology. Berlin: Springer-Verlag.; 1991; p. Chapter 6.

Luvall, J. C. and H. R. Holbo. Measurements of Short Term Thermal Responses of Coniferous Forest Canopies Using Thermal Scanner Data. Remote Sens. Environ. 1989; 27.:1-10.

Maruyama, M. Mindscapes and science theories. Current Anthropology. 1980; 21:589-599.

McHarg, I. Architecture in an Ecological View of the World (1970). McHarg, I. and Steiner, F. R., eds. *To Heal the Earth: Selected Writings of Ian L. McHarg* . Washington, DC: Island Press; 1998; pp. 175-185.

Moran, Michael J. Availability Analysis: A Guide to Efficient Energy Use. New Jersey: Prentice-Hall; 1982; ISBN: 0-13-054874-x.

Nicolis, G. and Prigogine, I. Self-Organization in Non-equilibrium Systems. New York: J. Wiley & Sons; 1977; ISBN: 0-471-02401-5.

---. Exploring Complexity. New York: W.H. Freeman; 1989; ISBN: 0-7167-1860-6.

O'Callaghan, P. W. Design and Management for Energy Conservation. Toronto: Pergamon Press; 1981; ISBN: 0-08-027287-8.

O'Rourke, D.; Connelly, L., and Koshland, C. Industrial Ecology: a critical review. Int. J. Environment and Pollution. 1996; 6(2/3):89-112.

Odum, E. P. The Strategy of Ecosystem Development. Science. 1969; 164:262-270.

Papanek, V. Design for the Real World. London: Thames & Hudson; 1970.

---. The Green Imperative: Ecology and ethics in design and architecture. London: Thames & Hudson; 1995.

Peacocke, A. R. The Physical Chemistry of Biological Processes. Oxford: Oxford University Press; 1983; ISBN: 0-19-855359-5.

Peusner, L. Studies in Network Thermodynamics. Amsterdam: Elsevier Science Publishers; 1986.

Quattrochi, D. and Luvall, J. C. Thermal Infrared Remote Sensing for Analysis of Landscape Ecological Processes: Methods and Applications. Landscape Ecology.

1999; 14:577-598.

Regier, H. A. and Kay, J. J. An Heuristic Model of Transformations of the Aquatic Ecosystems of the Great Lakes-St. Lawrence River Basin. Journal of Aquatic Ecosystem Health. 1996; 5:3-21.

Saama, P. J.; Koenig, B. E., and Koenig, H. E. Analytical Tools for Material and Energy Balance, Cash Flow, and Environmental Loads in a Dairy Cattle Enterprise. Journal of Dairy Science. 1994; 77(4):94.

Scheffer, M. Ecology of Shallow Lakes. London: Chapman and Hall; 1998; ISBN: 0 412 74920 3.

Scheffer, M. S.; Hosper, H.; Meijer, M-L; Moss, B., and Jeppesen, E. Alternative equilibria in shallow lakes. Trends in Ecology and Evolution. 1993; 8(8):275-279.

Schneider, E. and Kay, J. J. Exergy Degradation, Thermodynamics, and the Development of EcosystemsTsatsaronis G.; Szargut, J.; Kolenda, Z., and Ziebik, A., eds. *Energy, Systems, and Ecology*, *Volume 1*, Proceedings of ENSEC' 93; Cracow, Poland. 1993: 33-42.

---. Life as a Manifestation of the Second Law of Thermodynamics. Mathematical and Computer Modelling. 1994a; 19(6-8):25-48.

Schneider, E. D and Kay, J. J. Complexity and Thermodynamics: Towards a New Ecology. Futures. 1994b; 24(6):626-647.

Schneider, E. S. Thermodynamics, Information, and Evolution: New Perspectives on Physical and Biological Evolution. Weber, B. H.; Depew, D. J., and Smith, J. D., Eds. Entropy, Information, and Evolution: New Perspectives on Physical and Biological Evolution. Cambridge: MIT Press; 1988; pp. 108-138.

Szargut, J.; Morris, D. R., and Steward, F. R. Exergy Analysis of Thermal, Chemical, and Metallurgical Processes. New York: Hemisphere Publishing Corp.; 1988; ISBN: 0-89116-574-6.

Tibbs, B. C. Industrial Ecology: An Environmental Agenda for Industry. Whole Earth Review. 1992(Winter):4-19.

Todd, John and Todd, Nancy. From Ecocities to living machines: designing for sustainability. Berkeley, California: North Atlantic Books, 1994.

Tummala, R. and Koenig, B. Process Network Theory and Implementation for Technology Assessment in Maufacturing. Proceedings Joint U.S./ German Conference ; Hagen, Germany. Berlin: Springer-Verlag; 1993.

Ulanowicz, R. E. Ecology, the Ascendent Perspective. New York: Columbia University Press; 1997a; ISBN: 0-231-10828-1.

Ulanowicz, R. E. Limitations on the Connectivity of Ecosystem Flow Networks.Rinaldo, A. and A. Marani, A., eds. Biological Models: Proceedings of the 1992 Summer School on Environmental Dynamics.; Venice. Venice: Istituto Veneto di Scienze, Lettere ed Arti; 1997b: 125-143.

Ulanowicz, R. E. and Hannon, B. M. Life and the Production of Entropy. Proc. R. Soc. London B. 1987; 232:181-192.

UNDP. Sustainable Livelihoods Concept Paper [Web Page]. 1998. Available at: http://www.undp.org/sl/Documents/Strategy_papers/Concept_paper/Concept_of_SL.htm.

Vale, Brenda and Vale, Robert. Green Architecture: Energy-Conscious Future. Boston, Massachusetts: Little Brown; 1991.

van Berkel, R. and Lafeur, M. Application of an industrial ecology toolbox for the introduction of industrial ecology in enterprises-II. J. Cleaner Prod. 1997; 5(1-2):27-37.

van Berkel, R.; Williams, E., and Lafeur, M. Development of an industrial ecology toolbox for the introduction of industrial ecology in enterprises-I. J. Cleaner Prod. 1997; 5(1-2):11-25.

von Bertalanffy, L. General Systems Theory. New York: George Brazillier; 1968.

---. Perspectives on General Systems Theory. New York: Goerge Brazillier; 1975.

Wall, G. Exergy- A Useful Concept. Goteborg, Sweden: Physical Resource Theory Group, Chalmers University of Technology; 1986; ISBN: 91-7032-269-4.

Wicken, J. S. Evolution, Thermodynamics, and Information: Extending the Dawinian Program. Oxford: Oxford University Press; 1987.

Wong, F. C. System-Theoretic Models for the Analysis of Thermodynamic Systems [Ph.D. Thesis]. Waterloo, Ontario: Systems Design Engineering, University of Waterloo; 1979.

Wong, F. C. and Chandrashekar, M. Thermodynamic Systems Analysis. Energy: The International Journal. 1982; 7(6):539-566.

Woodley, S.; Kay, J., and Francis, G. Ecological Integrity and the Management of Ecosystems. Florida: St. Lucie Press; 1993.

Yeang, Ken. Designing with Nature. New York: McGraw-Hill Inc.; 1995.