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Revisiting and Reorienting Ecological Design

Charles J. Kibert, Powell Center for Construction & Environment, University of Florida
+1 (352) 273 1189 ckibert@ufl.edu http://www.cce.ufl.edu

Introduction

As is generally the case with other economic sectors, construction industry is expending significant effort to *green* its products, namely buildings and infrastructure. This is not an easy task because the process of greening is an ill-defined and not well understood concept. In the construction sector, green building has several definitions, one being "the design and operation of a healthy based environment based on resource efficiency and ecological principles (Kibert 1994)." Generally the concepts of healthy buildings and resource efficiency are well-understood, with the possible exception of resource efficiency as it applies to materials. Ecological principles, and by extension, ecological design, are the sine qua non of the definition, but in practice are not well understood. At least three distinct approaches to ecological design, each of which employs different key philosophies and each of which would have distinctly different outcomes, can be enumerated. These approaches are referred to in this paper as *strong ecological design*, *intermediate ecological design*, and *weak ecological design*. Several different approaches that meant to articulate ecological design have been proposed, for example, *biomimicry*, *cradle-to-cradle*, *The Natural Step*, *natural capitalism* and the *Hannover Principles*. Several researchers and thinkers have articulated approaches to ecological design as applied to materials, varying from practical to purely philosophical. This paper will generally address the issue of materials cycles which appears to be the most difficult problem facing the movement to green the built environment. It will start by reviewing the various approaches to ecological design that have been articulated and that may affect the materials cycle of the built environment. This is a crucial problem because construction industry is by far the biggest consumer of extracted materials. In the U.S. in a typical year, on the order of 2.5 billion metric tons (MT) materials are used to produce the built environment, compared to 70 million tons for machinery and equipment (producer durables) and 20-30 million of consumer durables. Although it represents about 8% to 9% of GDP, resource extraction for construction exceeds 95% of the U.S. domestic total. Construction industry is also responsible for inordinate quantities of waste materials, on the order of 150 million MT of construction and demolition waste, compared to a municipal solid waste stream of about 300 million MT. The gap between current practice (cradle-to-grave) and the optimistic best practice (biomimicry and cradle-to-cradle) is enormous and the dramatic shift that would be required to virtually eliminate waste would require an enormous transformation in material production, chemistry, product design, building design and construction, and the post-use materials system. Limits imposed by physics in the form of thermodynamics as well as differences in the very nature of ecosystems compared to human systems, not to mention the lack of any real incentives, make the prospects for fundamental changes such as these virtually nil in the short term. Consequently it would be useful to revise the goals of movements seeking to green the built environment as well as other sectors to provide more realistic and achievable ends. Altruism needs to be applauded but reality also needs to be checked.

This paper argues that the strong version of ecological design, most ardently represented by proponents of biomimicry and cradle-to-cradle approaches, is not only not achievable, but there is also no evidence that pursuing it would lead to a superior outcome. In its intermediate and weak forms, where integration with nature and minimization of environmental impacts are the goals, there is hope for wider application. At the core of this argument to reduce the emphasis on strong ecological design is the fact that that humans, the only forward-thinking and acting species, behave differently than any other of the myriad backward looking species in the global ecosystem whose existence is based solely on ecological history. As a consequence human beings have created enormous varieties of materials and products that have no precedent in nature. In the built environment these include plastics, pure metals and metal alloys, concrete, and glass, to name but a few. Adding more complexity is the human exploitation of physical phenomena to achieve many effects not seen in nature, to include refrigeration, lighting systems, elevators and escalators, spectrally selective glass, building automation, and a host of others. If we were to glance sideways at other sectors we would find even more radical departures such as antibiotics, computer chips, photovoltaics, fission reactors, nanotechnology, genetically modified organisms, and innumerable other examples. Humans will continue to create even more exotic materials, processes, and products and the only true constraints will be: risk acceptance/avoidance, ethics, and economics. Society will decide what risks are acceptable, what behavior is acceptable, and what costs are acceptable when it comes to nuclear power, genetic engineering, nanotechnology, and air-conditioning, to name but a few.

Ecological Design

Green building has been repeatedly described as based on so-called *ecological design*, alternatively referred to as *green design* or *sustainable design*. In the context of construction, ecological design is generally described either as designing buildings that are modeled on natural systems functioning or as mitigating the impacts of the built environment on the nature (van der Ryn 1998). We can refer to the former as *strong* or *active* ecological design and the latter as *weak* or *passive* ecological design. This parallels the notion of strong sustainability (no substitution for natural systems) to weak sustainability (some degree of substitution allowed for natural systems). Weak ecological design can be readily achieved in the design and construction of buildings by minimizing the life cycle impacts of products, building operation, and building and building product disposal. Strong ecological design, in contrast, is extremely difficult to achieve because it requires the actors creating the built environment to have a deep understanding of ecology and ecological systems dynamics and, if biomimicry is fostered, to be able to develop only those materials for which there is a precedent in nature or that mimic nature. Ecologists themselves admit that ecosystem functioning can never be completely understood, that at best we can create incomplete models of complex, chaotic systems. Consequently modeling human designed products and systems based on nature is difficult to impossible. At best the mimicking of nature in human designs is one-dimensional, non-complex, and border on being trivial.

In addition to strong and weak ecological design, an *intermediate* version of ecological design which can contribute to an improved, greener built environment, is the integration of built environment systems with ecosystems. Examples include constructed wetlands for processing waste, eco-roofs, use of landscape to assist heating and cooling, employment of trees to uptake and store stormwater, ground coupling (employing an abiotic ecosystem component), calorie production in the form of food, and the use of landscape as art. Intermediate ecological design could also be employed from individual building level all the way up to bioregional level where the integration is at city level. In addition to the benefits of reducing the need for costly infrastructure, intermediate ecological design could result in the restoration and protection of significant areas of critical ecological systems that are integrated with human activities.

Principles and Approaches for Ecological Design

Over the past 15 years, a number of thinkers have proposed approaches, principles, and even philosophies for ecological design. Among these are the following:

1. General Management Rules for Sustainability (Barbier 1989, Daly 1990)
2. Design Principles for Industrial Ecology (Kay 2002)
3. The Golden Rules for EcoDesign (Bringezu 2002)
4. Adaptive Management (Petterson 2002)
5. Biomimicry (Benyus 1998)
6. Factor 4 and Factor 10 (von Weiszacker, A. Lovins, and H. Lovins 1998) (not described in this draft)
7. Cradle to Cradle (McDonough and Braungart 2002)
8. The Hannover Principles (McDonough 1992)
9. The Natural Step (Robèrt 1989)
10. Natural Capitalism (Hawken and Lovins 2000)
11. Cardinal Rules for Closing the Materials Cycle (Kibert 2005)
12. The USGBC LEED Approach (Materials & Resources (2000-present)

The following paragraphs describe these points of view and their relationship to ecological design, with special emphasis on the materials cycle of the built environment.

General Management Rules for Sustainability

Proponents of ecological economics have formulated several pragmatic rules for “managing” sustainability (Barbier 1989, Daly 1990).According to the first rule, the use of renewable resources should not exceed the regeneration rate. In order to operationalize this demand, one has to consider that the use of either naturally or technically renewable materials always requires some inputs of non-renewables (e.g. mineral fertilizer for the loss of nutrients due to leaching in agriculture, and the requirements for materials and energy for recycling processes). As a consequence, the total life cycle of products has to be checked for the use of renewables and non-renewables. The former will have to be distinguished according to criteria on sustainable modes of production in agriculture, forestry and fishery. In the construction sector the origin of timber products from sustainable cultivation would be an example.

The second rule states that non-renewable resources may only be used if physical or functional substitutes are provided, for example, investments in solar energy systems from gains from fossil fuels. Here the basic assumption is that man-made capital may be substituted for natural capital (“weak sustainability“). The central requirement from an economic perspective is that the sum of natural and man-made capital is not reduced (Pearce and Turner 1990). However, from a natural systems perspective it may be argued that there are minimum requirements of nature which may not be depleted without risk for life-support functions. Therefore, man-made capital should not be substituted (permanently) for natural capital (“strong sustainability“). Under this assumption the second rule would require a minimization of the use of non-renewables.

The third rule states that the release of waste matter should not exceed the absorption capacity of nature. This can be operationalized by comparing “critical loads“ of water, soil, and air compartments with actual levels of emission rates. After measures have been successfully applied to reduce pollution problems, the “after-end-of-pipe“ approach to limit critical loads is also important. The implementation of the third rule is usually based on substance specific analyses. This approach has some limitations. Generally we must acknowledge that we are aware of only the tip of the iceberg with respect to the potential future impacts of all materials and substances released to the environment. Many natural functions react in a non-linear manner. The complex interactions of natural substances like carbon dioxide, not to mention thousands of synthetic chemicals, cannot be foreseen in total.

From experience we know that the effects of certain emissions become obvious after release and the change of the environment takes place. There is a huge time lag between the scientific finding, public perception and political reaction. Thus the chances for comprehensive and precautionary materials management are extremely limited. A long-term effective implementation of the third rule should begin before the end-of-pipe and should aim to minimize the environmental impact potential of anthropogenic material flows. This impact potential is generally determined by the volume of the flow times the specific impacts per unit of flow. The second term is unknown for most materials released to the environment. The first term, the volume or weight used or released in a certain time period, can be made available for nearly every material handled. It may be used to indicate a generic environmental impact potential. As long as detailed information on specific impacts is lacking, it may be assumed that the impact potential is growing with the volume of the material flow. The overall volume of outputs from the anthroposphere can only be reduced when the inputs to this system are diminished. This is especially important for construction material flows with large scale and significant retention time within the anthroposphere. Starting from a situation when the assimilation capacity of nature is overloaded for a variety of known substances, the long-term implementation of the third rule requires a reduction of the resource inputs of the anthroposphere in order to lower the throughput and ultimate output to the environment.

Another rule which has not yet attracted sufficient attention may be derived from the relation of inputs and outputs of the anthroposphere. Currently the input of resources exceeds the output of wastes and emissions in industrialized as well as developing countries. As a consequence, the economies of these countries are growing physically (in terms of new buildings and infrastructure). The stock of materials in the anthroposphere is therefore increasing. In Germany, for example, the rate of net addition to stock has been about 10 t per capita annually in the middle of nineties. Associated with this accumulation of stock is an increase in built-up land area and a consequent reduction in reproductive and ecologically buffering land. Keeping in mind the limited space on our globe, this development cannot continue infinitely. Thus a flow equilibrium between input and output must be expected. However, a question naturally arises: When will the economy stop growing physically and to what physical level?

Design Principles for Industrial Ecology (James J. Kay)

James Kay (2002), the late ecologist from the University of Waterloo, proposed a set of principles that would govern the production-consumption system. They are based on the premise that all man-made systems should contribute to the survival of natural systems.

1. *Interfacing*: 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 the fact that the survival potential of natural ecosystems must be maintained.

2. *Bionics*: The behavior of large-scale societal systems should be as similar as possible to those exhibited by natural systems.

3. *Appropriate biotechnology*: Whenever feasible, the function of a societal system should be carried out by a subsystem of a natural biosphere.

4. N*on-renewable resources*: Non-renewable resources are used only as capital expenditures to bring renewable resources on line.

The Interfacing and Appropriate Biotechnology principles are related to intermediate ecological design in that they call for natural systems to interface with human systems in a synergistic manner to the benefit of both systems. Natural systems could provide services that would otherwise be performed by expensive engineered systems, for example, stormwater control and waste processing. The Bionics Principle is closely related to strong ecological design but notably for large scale functions. The Non-Renewable Resource principle has its roots in ecological economics where investing limited non-renewables in transitioning to renewable resources is a key tenet. In effect, Kay's Design Principles are a mix of various levels of several types of ecological design and he does not come down on one version as the most preferable.

The Golden Rules for Ecodesign (Stefan Bringezu)

To assist engineers, architects and planners in the production of an environmentally benign built environment, Stefan Bringezu of the Wuppertal Institute suggested five "golden rules of ecological design (Bringezu 2002)."

1. Potential impacts to the environment should be considered on a life cycle-wide basis (from "cradle to cradle")

2. Intensity of use of processes, products, and services should be maximized.

3. Intensity of resource use (material, energy, and land) should be minimized.

4. Hazardous materials should be eliminated.

5. Resource input should be shifted toward renewables.

The first Golden Rule aims to avoid shifting problems between different processes and actors. For instance, if the energy requirements for heating or cooling during the use phase of buildings were not to be considered in the planning phase, the options with the highest potential for energy efficiency would be neglected. And if one considers only the direct material inputs for construction, the environmental burden associated with the upstream flows will become hidden.

The second Golden Rule reflects the fact that most buildings products are not used much of the time. For a considerable part of each day and of each week, homes, offices, and public buildings are not essentially unoccupied. Nevertheless, economic, and environmental and probably also social costs have to be paid for maintenance. Multifunctionality and more flexible models of use may reduce the demand for additional construction and contribute to lower costs for the users. The model of car sharing may also be applied for construction. Part time employees already share the same office. And there is even potential for more efficient building use beyond normal working hours.

The third Golden Rule may be specified with the factor 4 to 10 target for material requirements including energy carriers, and should be applied to the average of products and services. In order to reach these goals it seems essential to invest more intellectual power into the search for alternative options to provide the services and functions demanded by the users.

Golden Rule number 4 calls for the elimination of hazardous substance, at face value a very sensible rule, but very difficult to implement from the perspective of today’s economy. The use of nuclear energy violates this rule and self-replicating nanomachines or genetically modified organisms may also be considered hazardous according to some criteria.

The final Golden Rule is a restatement of a key concept of ecological economics, namely that supplies of non-renewables will clearly diminish over time as finite resources of this variety are consumed. For example, recent studies of copper consumption in the U.S. indicate the only 1/3rd of the original dowry of copper ore exists today. The logic is that as these resources disappear a shift to renewable resources must occur, and that in fact the consumption of non-renewables should support the development of renewable resources. In the case of copper, a substitute renewable material will perhaps be not so easy to develop.

Adaptive Management (C.S. Holling, Lance Gunderson, and Gary Petterson)

Ecology, like other fields, has several distinct schools, one of which is *Adaptive Management* as articulated by C.S. Holling. Gary Petterson, one of Holling's doctoral students and now a faculty at the University of Wisconsin, described adaptive management as an approach to ecosystem management which argues that ecosystem functioning can never be totally understood. As Petterson (2002) notes, ecosystems are continual changing due to internal and external forces. Internally, ecosystems change due to the growth and death of individual organisms, as well as fluctuations in population size, local extinction, and the evolution of species traits. Ecosystems are also changed by external events such as the immigration of species, alterations in disturbance frequency and shifts in the diversity and amount of nutrients entering the ecosystems. To cope with these changes, management must continually adapt. Management becomes adaptive when it persistently identifies uncertainties in human-ecological understanding, and then uses management intervention as a tool to strategically test the alternative hypotheses implicit within these uncertainties. Consequently, basing the design of human systems on ecosystem function means creating materials, products, and processes using models that are not very well understood. Clearly this means that it is probably impossible to implement strong ecological design in other than one-dimensional, virtually trivial applications.

Adherents to this line of thinking are also responsible for posing the fundamental and crucial question: "Why are systems of people and nature not just ecosystems?" (Westley et al., 2002). Gary Petterson (2002) addresses this issue clearly as follows:

> Humans, individually or in groups, can anticipate and prepare for the future to a much greater degree than ecological systems. People use mental models of varying complexity and completeness to construct views of the future. People have developed elaborate ways of exchanging, influencing, and updating these models. This creates complicated dynamics based upon access to information, ability to organize, and power. In contrast, the organization of ecological systems is a product of the mutual reinforcement of many interacting structures and processes that have emerged over long periods or time. Similarly, the behavior of plants and animals is the product of successful evolutionary experimentation that has occurred in the paste. Consequently, the arrangement and behavior of natural systems is based upon what has happened in the past, rather than looking in anticipation toward the future. The difference between forward-thinking human systems and backwards-looking natural systems is fundamental. It means that understanding the role of people in ecological systems requires not only understanding how people have acted in the past, but also how they think about the future.

Following this chain of thinking, humans are certainly going to create materials that have not evolved in a natural sense. The question then becomes: what constraints should society place on the development of new materials, products and processes? The ongoing debates about genetically modified organisms (GMO) and cloning are indicative of the uncertainty about the outcomes of human tinkering with the blueprints of life, not to mention the creation of materials that have uncertain long term impacts.

Biomimicry (Benyus)

Janine Benyus (1997) describes biomimicry as the conscious emulations of life's genius. In her popular book on the subject, she state that " 'Doing it nature's way' has the potential to change the way we grow food, make materials, harness energy, heal ourselves, store information, and conduct business." She goes on to say "In a biomimetic world, we would manufacture the way animals and plants do, using sun and simple compounds to produce totally biodegradable fibers, ceramics, plastics, and chemicals." Farms would be modeled on prairies, new drugs would be based on plant and animal chemistry, and even computers would be based on carbon rather than silicon based structures. Proponents of biomimicry point to the 3.8 billion years of research and development that nature has invested in evolving a wide range of materials and processes that could benefit humans. She also laid out a series of ten lessons for corporations that are based on the emulation of nature as the model for human designed systems:

1. Use waste as a resource
2. Diversify and cooperate to fully use the habitat
3. Gather and use energy efficiently
4. Optimize rather than maximize
5. Use materials sparingly
6. Don't foul the nest
7. Don't draw down resources
8. Remain in balance with the biosphere
9. Run on information
10. Shop locally

She also suggests 'four steps to a biomimetic future':

1. Quieting: immerse ourselves in nature
2. Listening: interview the flora and fauna of our own planet
3. Echoing: encourage biologists and engineers to collaborate, using nature as model and measure
4. Stewarding: preserve life's diversity and genius

With respect to Step 3. , Echoing, she provides a list of ten questions for testing innovation or technology for its acceptability and all ten, according to Benyus, should be answered affirmatively.

1. Does it run on sunlight?
2. Does it use only the energy it needs?
3. Does it fit form to function?
4. Does it recycle everything?
5. Does it reward cooperation?
6. Does it bank on diversity?
7. Does it utilize local expertise?
8. Does it curb excess from within?
9. Does it tap the power of limits?

10. Is it beautiful?

In the arena of materials she states that nature has four approaches:

1. Life friendly manufacturing processes
2. An ordered hierarchy of structures
3. Self-assembly
4. Templating of crystals with proteins

As she points out, nature does produce a wide range of complex and functional materials. Abalone (twice as tough as high tech ceramics), silk (five times stronger than steel), mussel adhesive (works underwater), and many other natural materials are remarkable in their performance. Each is created out of the local environment and biodegrades back to the environment in a harmless manner at the end of their useful lives.

In spite of its attraction, biomimicy has any number of drawbacks. The pace at which nature manufactures its products is not generally a critical issue and is a function of information and local resources. In contrast, humans have learned to make products at an astounding pace and over time, to dematerialize and deenegize their production systems. Humans can and do observe nature and natural phenomena and apply their observations to create all manner of products, not all of them beneficial. Perhaps she had it wrong, that humans will redesign what we call nature and the future may evolve in the direction set by humans or be destroyed because of it. The interplay of humans and nature has been long underway, with biological organisms mutating as humans attempt to control or destroy them. Biomimicry provides a number of interesting insights but as a key component of ecological design, its contributions are somewhat limited.

Cradle-to-Cradle (McDonough and Braungart)

The concept of cradle-to-cradle design is meant to describe approaches that contrast to designs that employ a cradle-to-grave approach or mentality. More recently this concept has been popularized in a book by McDonough and Braungart (2002). In laying the foundation for the cradle to cradle concept, they suggest that people and industry should set out to create the following:

- Buildings that, like trees, produce more energy than they consume and purify their own wastewater
- Factories that produce effluents that are drinking water
- Products that, when their useful life is over, do not become useless waste but can be tossed on the ground to decompose and become food for plants and animals and nutrients for soil; or, alternatively, that can return to industrial cycle s to supply high quality raw materials for new products.
- Billions, even trillions of dollars’ worth of materials accrued for human and natural purposes each year
- A world of abundance, not one of limits, pollution, and waste

Clearly these are fanciful ideas, many of which were described in the Hannover Principles developed by McDonough as part of the preparations for the 1992 Hannover Worlds Fair. They deserve repeating below because in the context of the built environment McDonough has a large following who are influenced by his thinking.

McDonough Braungart suggest the solution is to follow nature's model of *eco-effectiveness*. This entails separating the materials we use in human activity into *biological* substances (which can be sent back into the natural ecosystem, where they can actually benefit other creatures as nutrients) and *technical* substances (which can, with proper design, be 100% recollected and recycled or even upcycled (producing, in second use, products of greater value than their original use, with zero waste). Carpets and shoes, for example, could be made of two layers -- a biological "outside" one that abrades over time, whose fibers could serve as nutrients in the soil or compost, and a much more durable technical "inside" layer that would be 100% recyclable, after its long life, into another identical product. A biological nutrient is a material or product that is designed to return to the biological cycle. They state that packaging, for example, can be designed as biological nutrients whereby at the end of its use it can be, as they put it, thrown on the ground or compost heap. A technical nutrient is a material or product that is designed to go back into the technical cycle, into the industrial metabolism from which it comes. They also define a class of materials they refer to as the unmarketables, that are neither technical nor biological nutrients. There are many significant problems with this approach. Biological nutrients, for example, are not so easily defined. Is a biopolymer, produced from corn or cellulose, and which is biodegradable, a biological nutrient? Is a biodegradable synthetic material a biological nutrient or a technical nutrient? The fact is that biomaterials such as biopolymers use natural materials as feedstock but alterations to the basic feedstock produce materials which have no precedent in nature. Furthermore the consequences of their biodegradation is not well known. Whether or not biodegradation results in nutrients or waste has not been firmly established.

McDonough and Braungart suggest implementing changes to products and systems based on Five Steps to Eco-Effectiveness:

Step 1. Get rid of know culprits
X substances: materials that are bioaccumulative; mercury, cadmium, lead, PVC

Step 2. Follow informed personal preferences
Prefer ecological intelligence, being sure that a product or substance does not contain or support substances or practices that are blatantly harmful to human and environmental health
Also includes: Prefer respect and Prefer delight, celebration and fun.

Step 3. Creating a "passive positive" list, harm in manufacture or in use.
The X list: same as X substance in Step 1. Includes substances that are carcinogens or problematic as defined by the International Agency for Research on Cancer (IARC) and Germany's Maximum Workplace Concentration (MAK) list. They define to lists of substances,

the gray list and the P list. The gray list: problematic substances not so urgently in need of phaseout. The P list is the positive list

Step 4. Activate the positive list.
Redesign products focusing on the P list substances.

Step 5. Reinvent
Totally reinvent products such as the automobile to be ‘nutri-vehicles.’

Dave Pollard describes this process more elegantly in his blog
http://blogs.salon.com/0002007/2006/02/12.html (12 February 2006):

1. Free ourselves from the need to use harmful substances (e.g. PVC, lead, cadmium and mercury).
2. Begin making informed design choices (materials and processes that are ecologically intelligent, respectful of all stakeholders, and which provide pleasure or delight).
3. Introduce substance triage: (a) phase out known & suspected toxins, (b) search for alternatives to problematic substances, and (c) substitute for them 'known positive' substances.
4. Begin comprehensive redesigns: to use only 'known positives', separate materials into biological and technical, and ensure zero waste in all processes and products.
5. Reinvent entire processes and industries to produce 'net positives' -- activities and products that actually *improve* the environment.

The Hannover Principles (McDonough)
The Hannover principles were developed by William McDonough at the request of the Mayor of Hannover prior to the Hannover World’s Fair in 1992. These principles are as follows:

- Insist on rights of humanity and nature to co-exist in a healthy, supportive, diverse and sustainable condition.
- Recognize interdependence. The elements of human design interact with and depend upon the natural world, with broad and diverse implications at every scale. Expand design considerations to recognizing even distant effects.
- Respect relationships between spirit and matter. Consider all aspects of human settlement including community, dwelling, industry and trade in terms of existing and evolving connections between spiritual and material consciousness.
- Accept responsibility for the consequences of design decisions upon human well-being, the viability of natural systems and their right to co-exist.
- Create safe objects of long-term value. Do not burden future generations with requirements for maintenance or vigilant administration of potential danger due to the careless creation of products, processes or standards.
- Eliminate the concept of waste. Evaluate and optimize the full life-cycle of products and processes, to approach the state of natural systems, in which there is no waste.

- Rely on natural energy flows. Human designs should, like the living world, derive their creative forces from perpetual solar income. Incorporate this energy efficiently and safely for responsible use.
- Understand the limitations of design. No human creation lasts forever and design does not solve all problems. Those who create and plan should practice humility in the face of nature. Treat nature as a model and mentor, not as an inconvenience to be evaded or controlled.
- Seek constant improvement by the sharing of knowledge. Encourage direct and open communication between colleagues, patrons, manufacturers and users to link long term sustainable considerations with ethical responsibility, and re-establish the integral relationship between natural processes and human activity.

As is the case with several other proposed approaches to sustainability, the Hannover Principles provide inspiration but little more. Advice to "Consider all aspects of human settlement including community, dwelling, industry and trade in terms of existing and evolving connections between spiritual and material consciousness" is impossible to interpret in utilize in any effective way.

Thermodynamics: Limits on Recycling and the Dissipation of Materials

http://www.ihdp.uni-bonn.de/html/publications/reports/report12/AppIV.htm

One of the notions repeatedly suggested by McDonough is his assertion that human designs should behave like natural systems. One of his oft-stated principles is "There is no waste in nature," with the implication that human systems should be designed to eliminate the concept of waste. In fact, zero waste systems are not possible due to the laws of physics, more specifically the laws of thermodynamics. Georgescu-Roegen (1971) dealt with the implications of the entropy law and the second law of thermodynamics for economic analysis. Georgescu-Roegen described the important difference between primary factors of production (energy and materials) and the agents (capital and labor) that transform those materials into goods and services. The agents are produced and sustained by a flow of energy and materials which enter the production process as high quality, low entropy inputs and ultimately exit as low quality, high entropy wastes. This restricts the degree to which the agents of production (capital and labor) can substitute for depleted or lower quality stocks and flows of energy and material inputs from the environment (Cleveland *et al*., 1984; Ayres and Nair, 1984; Costanza and Daly, 1992).

Thermodynamics can inform us about ultimate limits. There are irreducible thermodynamic minimum amounts of energy and materials required to produce a unit of output that technical change cannot alter. In sectors that are largely concerned with processing and/or fabricating materials, technical change is subject to diminishing returns as it approaches these thermodynamic minimums (Ayres, 1978). Ruth (1995) uses equilibrium and non-equilibrium thermodynamics to describe the materials-energy-information relationship in the biosphere and in economic systems. In addition to illuminating the boundaries for material and energy conversions in economic systems, thermodynamic assessments of material and energy flows, particularly in the case of effluents, can provide information about depletion and degradation that are not reflected in market price.

What are the implications of thermodynamics and the entropy law for materials recycling? Georgescu-Roegen (1981) argued that materials are dissipated in use just as energy is, so complete recycling is impossible. He elevated this observation to a Fourth Law of Thermodynamics - or Law of Matter Entropy - describing the degradation of the organizational state of matter. The bottom line for Georgescu-Roegen is that due to material dissipation and the generally declining quality of resource utilization, materials in the end may become more crucial than energy. However, Georgescu's Fourth Law has been criticized by a number of analysts in both economics and the physical sciences (see Cleveland and Ruth, 1997, for a review).

A recent paper by Reuter et al (2005) addresses the dissipation of materials in recycling by examining the technical feasibility of a EU mandate for 95% end of vehicle life (ELV) recycling by 2015 with an intermediate goal of 85% by 2006. One of the conclusions is that while the 85% target is achievable, the basic constraints of thermodynamics make it virtually impossible to reach the 95% goal. Consequently at least 5% of the automobile mass dissipates into the biosphere. This is true of all recycling activities, that the materials being recycled are dissipating to background concentrations as dictated by the Second and perhaps the Fourth (according to Georgescu) laws of thermodynamics. Indeed the dissipation of materials in the recycling process begs a number of questions, among them what are the health and ecological impacts of recycling as practiced and as envisioned for a sustainable future?

A 1998 U.S. Geological report by Michael Fenton indicated some of the practical problems with so-called cradle-to-cradle strategies. Steel and iron scrap, for which there is high demand, is not recycled at a very impressive rate. In this report he stated that in 1998, an estimated 75 MMT of steel and iron scrap was generated and that the recycling efficiency was 52% and the recycling rate was 41%.

In short, materials will be lost in recycling processes and due to entropy, will naturally seek to return to background concentration for naturally occurring substances and to very low concentrations for synthetic materials. Cradle to cradle and other approaches do not address this potentially difficult issue when suggesting that recycling of technical nutrients is desirable. Again, recycling, like most other issues facing improving materials cycles, is a matter of ethics, risk, and economics.

The Natural Step

One philosophical approach to designing the built environment is to use the well-known Natural Step, a tool developed to assess sustainability, as guidance for materials, product, and building design. The Natural Step, which is based on four scientifically based System Conditions, was developed in the 1980’s by Dr. Karl Henrik Robèrt, a Swedish oncologist. The Four System Conditions of the Natural Step are described in the following paragraphs.

1. **In order for a society to be sustainable, nature’s functions and diversity are not systematically subject to increasing concentrations of substances extracted from the earth's crust.**

In a sustainable society, human activities such as the burning of fossil fuels and the mining of metals and minerals will not occur at a rate that causes them to systematically increase in the ecosphere. There are thresholds beyond which living organisms and ecosystems are adversely affected by increases in substances from the earth's crust. Problems may include an increase in greenhouse gases leading to global climate change, contamination of surface and ground water, and metal toxicity which can cause functional disturbances in animals. In practical terms, the first condition requires society to implement comprehensive metal and mineral recycling programs and decrease economic dependence on fossil fuels.

2. **In order for a society to be sustainable, nature's functions and diversity are no systematically subject to increasing concentrations of substances produced by society**

In a sustainable society, humans will avoid generating systematic increases in persistent substances such as DDT, PCBs, and freon. Synthetic organic compounds such as DDT and PCBs can remain in the environment for many years, bioaccumulating in the tissue of organisms, causing profound deleterious effects on predators in the upper levels of the food chain. Freon, and other ozone depleting compounds, may increase risk of cancer due to added ultraviolet radiation in the troposphere. Society needs to find ways to reduce economic dependence on persistent human-made substances.

3. In order for a society to be sustainable, nature's functions and diversity are not systematically impoverished by over-harvesting or other forms of ecosystem manipulation.

In a sustainable society, humans will avoid taking more from the biosphere than can be replenished by natural systems. In addition, people will avoid systematically encroaching upon nature by destroying the habitat of other species. Biodiversity, which includes the great variety of animals and plants found in nature, provides the foundation for ecosystem services which are necessary to sustain life on this planet. Society's health and prosperity depends on the enduring capacity of nature to renew itself and rebuild waste into resources.

4. In a sustainable society resources are used fairly and efficiently in order to meet basic human needs globally.

Meeting the fourth system condition is a way to avoid violating the first three system conditions for sustainability. Considering the human enterprise as a whole, we need to be efficient with regard to resource use and waste generation in order to be sustainable. If one billion people lack adequate nutrition while another billion have more than they need, there is a lack of fairness with regard to meeting basic human needs. Achieving greater fairness is essential for social stability and the cooperation needed for making large-scale changes within the framework laid out by the first three conditions. To achieve this fourth condition, humanity must strive to improve technical and organizational efficiency around the world, and to live using fewer resources, especially in affluent areas. System condition number four implies an improved means of addressing human population growth. If the total resource throughput of the global human population continues to increase, it will be increasingly difficult to meet basic human needs as human-driven processes intended to fulfill human needs and wants are systematically degrading the collective capacity of the earth's ecosystems to meet these demands.

Applying the System Conditions to new building construction, with a particular focus on building materials, produces a matrix as shown in Table 1. The matrix indicates the relationship between the System Condition and the various major types of materials used or generated in construction: durables, consumables, and solid waste. It also shows which System Conditions are violated when contemporary practices are used.

TABLE 1 – Violation of Natural Step System Conditions in the application of construction materials

System Condition					
Item	**Violation examples**	**1**	**2**	**3**	**4**
DURABLES	Use less abundant, mined metals & minerals (copper, chromium, titanium)	**X**		**X**	
	Use of heavy metals (mercury, lead, cadmium)	**X**			
	Use of persistent, synthetic materials (PVC, HCFC, formaldehyde)		**X**		
	Wood from rainforests and old growth timber that is harvested unsustainably			**X**	
CONSUM-ABLES	Use of petroleum based products (solvents, oils, plastic film)	**X**	**X**	**X**	**X**
	Excessive packaging and other disposables		**X**	**X**	**X**
SOLID WASTE	Landfill disposal of construction and demolition waste including toxic components such as lead and asbestos	**X**	**X**	**X**	**X**

In practical terms, applying the Natural Step to the employment of building materials would result in the following materials practices:

1. All materials will be non-persistent, non-toxic and procured either from reused, recycled, renewable, or abundant (in nature) sources.
    a) Reused means reused or remanufactured in the same form, such as remilled lumber, in a sustainable way.
    b) Recycled means the product is 100% recycled and can be recycled again in a closed loop in a sustainable way.
    c) Renewable means able to regenerate in the same form at a rate greater than the rate of consumption.
    d) Abundant means human flows are small compared to natural flows, i.e., aluminum, silica, iron, etc.
    e) In addition, the extraction of renewable or abundant materials has been accomplished in a sustainable way, efficiently using renewable energy and protecting the productivity of nature and the diversity of species.

2. Design and use of materials in the building will meet the following in order of priority:

a) Material selection and design favor deconstruction, reuse, and durability appropriate to the service life of the structure.
b) Solid waste is eliminated by being as efficient as possible, or
c) Where waste does occur, reuses are found for it on-site, or
d) For what is left, reuses are found off-site.
e) Any solid waste that can not be reused is recycled or composted.

On a system-wide, in this case planetary scale, the Natural Step indicates that, unless we are willing to severely compromise human health, we need to ultimately eliminate the extraction of ores and fossil fuels mined and extracted to produce energy and materials. Additionally it calls for the ultimate elimination of synthetic materials whose concentration in the biosphere is compromising not only human health, but also the very health of the biosphere in which we reside. The Natural Step also cautions against the degradation of the biosphere by human activities because it is the very source of the resources needed to sustain life. And finally it addresses the social aspects of sustainability by noting that human needs in all parts of the world need to be met. Upon examining the Natural Step approach in more detail, the message is to reduce resource extraction, increase reuse and recycling, and minimize emissions that affect both ecosystems and human systems.

Natural Capitalism

The concept of natural capitalism was articulated in its most recent form in the book of the same name (Hawken, Lovins, and Lovins 1999)Implementing Natural Capitalism entails four basic shifts in business practice.

Shift #1 Radical Resource Productivity – Dramatically increase the productivity of natural resources

Shift #2 Ecological Re-Design – Shift to biologically inspired models

Shift #3 Service and Flow Economy – Move to solutions-based business models

Shift #4 Investment in Natural Capital – Reinvest in natural capitalism

Each of these shifts is echoed in the other previously mentioned sets of principles and approaches. Relative to shift number one, the productivity of natural resources can certainly be increased. However natural renewable resources have little play in the creation of building, the vast bulk of which are made of human designed materials. The authors claim that the industrial manufacturing system converts 94% of extracted materials into waste with just 6% becoming product. It is unclear how accurate these numbers are or if they reflect the actual situation. The ultimate goal is to reduce resource extraction which can be accomplished in several ways:

(1) dematerialization of products
(2) increasing the recycling rate of products at the end of their life cycle
(3) increasing the durability of products.

If the industrial system were to double each of these factors, a Factor 8 increase in resource productivity would occur. And each of these is achievable over the short term.

The second shift, to biologically inspired models, is also echoed time and again, and focuses on developing systems with closed loop behavior. However as pointed out in the paper on End of Life Vehicle recycling, the laws of thermodynamics and the separation efficiency dictate that closed loops are indeed not closed loops at all and that some fraction of materials being recycled will dissipate into the environment and that ultimately, after many recycling loops, they will be for all practical purposes totally dissipated.

The shift to a service and flow economy, is a proposal that has been made numerous times over the past decade and which has received little serious attention. Having manufacturers retain ownership of building components and maintaining responsibility for reusing or recycling them makes good sense on paper. However the practicalities of maintaining the link between manufacturer and product, even after decades of use, would be extremely difficult and the logistics system that would be required to dismantle buildings and return materials to their originators would be enormously complicated.

Shift four, re-investing in natural capital is certainly an important point and its implementation in the built environment context can be strongly reinforced. It is indeed possible to restore damaged sites and to insure the net ecological value of many sites is greater than it was prior to the alterations caused by building.

Cardinal Rules for a Closed Loop Building Materials Strategy

A truly green building product should ideally be comprised of materials that are also green. At present many green building products are not themselves inherently green, for example, low-emissivity windows, T-8 lighting fixtures, and energy recovery ventilators, to name but a few, all of which have significant materials components that could hardly be considered to be green or that may hamper the reuse and recycling of the product.. Although there are many arguments about what constitutes a green building product perhaps the primary question relates to the ultimate fate of the product and its constituent materials. Presuming that ecology is the ideal model for human systems, and in nature there is no waste, it follows that the building materials cycle should be closed as possible and as waste-free as the laws of thermodynamics permit. A closed loop building product and materials strategy must address several levels of materials use in its implementation: the building, the building products, and the materials used in building products and in construction. Ideally the building materials system should follow the Cardinal Rules for an Ideal Closed Loop Building Materials Strategy listed in Table 2 (Kibert 2005).

TABLE 2 – Cardinal Rules for a Closed Loop Building Materials Strategy

1. Buildings must be deconstructable
2. Products must be disassemblable
3. Materials must be recyclable
4. Products/materials must be harmless in production and in use
5. Materials dissipated from recycling must be harmless

The Cardinal Rules provide for the complete dismantling of the building and all of its components in order that materials that are input at the front end of the building's construction can be recovered and put back into productive use at the tail end of the building's useful life. The Cardinal rules provide the ideal conditions for materials and products used in building. It should be noted that very few materials and products are able to adhere to these five rules and consequently the behavior of materials is far from its ideal state. Consequently the path to actually creating a system of materials, products, and buildings that support closed loop behavior is in the distant future. Nonetheless this thought process can be used as a touchstone for making decisions about the development of new products, materials, and technologies that support the high performance green building movement.

The USGBC LEED-NC Approach

The U.S. Green Building Council (USGBC) has developed a suite of building assessment systems know as Leadership in Energy and Environmental Design (LEED), most prominent of which is LEED for New Construction or LEED-NC. The latest version of LEED gives points for the Materials and Resource (MR) category as indicated below.

MR Prerequisite 1	Storage and Collection of Recyclables
MR Credit 1.1	Building Reuse: Reuse 75% of Existing Walls, Floors & Roof
MR Credit 1.2	Building Reuse: Reuse 90% of Existing Walls, Floors & Roofs
MR Credit 1.3	Building Reuse: Maintain 50% of Interior Non-Structural Elements
MR Credit 2.1	Construction Waste Management: Divert 50% from Disposal
MR Credit 2.2	Construction Waste Management: Divert 75% from Disposal
MR Credit 3.1	Materials Reuse: 5%
MR Credit 3.2	Materials Reuse: 10%
MR Credit 4.1	Recycled Content: 10% (post-consumer + ½ post-industrial)
MR Credit 4.2	Recycled Content: 20% (post-consumer + ½ post-industrial)
MR Credit 5.1	Regional Materials: 10% Extracted, Processed, Manufactured Regionally
MR Credit 5.1	Regional Materials: 20% Extracted, Processed, Manufactured Regionally
MR Credit 6	Rapidly Renewable Materials
MR Credit 7	Certified Wood

One point is available for each credit for a maximum of 13 points for the MR Category. For comparison the other categories of LEED has maximum points as follows:

Sustainable Sites:	14 points
Water Efficiency:	5 points
Energy and Atmosphere:	17 points
Indoor Environmental Quality:	15 points
Innovation and Supervision:	5 points

A maximum of 69 points is possible and building are rated as platinum (52-69 points), gold (39-51 points), silver (33-38 points), or certified (26-32 points).

LEED is simply a first step in a long process of setting up systems that can adequately measure good from poor building design. In the Materials & Resources category of LEED, it does address many of the measures that will undoubtedly lower the enormous impacts of the built environment. MR Credits 1.1, 1.2, 1.3, 3.1 and 3.2 cover the reuse of buildings and building components, which saves considerable materials and energy as well as upstream impacts. This approach is closely related to weak ecological design or the mitigation of environmental impacts. MR Credits 2.1 and 2.2, which address reducing and recycling construction waste, and Credits 5.1 and 5.2 which focus on regional materials are also mitigation measures. This is also largely true of MR Credits 4.1 and 4.2 which address recycled content. MR Credit 6 suggests that plantation harvesting of some organic materials is preferable to other extraction means, an unproven approach as it motivates the replacement of natural ecosystems with human agriculture. MR Credit 7 which calls for sustainable forestry products does focus on the sensible exploitation of natural systems and also fits into the category of mitigation or weak ecological design. At this point in time significant important measures are not addressed in LEED, among them deconstructability of buildings, decoupling of building systems, disassemblable products, and Extended Producer Responsibility. It would appear that LEED employs the weak approach to ecological design. The integration of natural systems with buildings would be an implementation of intermediate ecological design and is an area for future exploration that would lead to better buildings and probably more protection for now badly needed ecosystems.

Biological materials, Biomaterials and Other Nature-Based Materials

Clearly one of the shifts advocated by many of the approaches described above is a shift from non-renewable resources to renewable resources. Natural Capitalism, the Natural Step, Cradle-to-Cradle, to name a few, suggest that this shift is fundamental for sustainability in general. A shift to renewable resources implies a shift in the materials sector to biological materials, biomaterials, and other natural or nature-based materials. Biological materials and biomaterials are two distinct classes of materials. Biological materials are natural systems products such as wood, hemp, and bamboo while biomaterials are materials with novel chemical, physical, mechanical, or "intelligent" properties, produced through processes that employ or mimic biological phenomena (www.nal.usda.gov/bic/bio21/gloss.html). Biomaterials include several emerging classes of biopolymers such as polylactic acid (PLA) and olyhydroxyalkanoate (PHA). Long chain molecules synthesised by living organisms, for example, proteins, cellulose and starch are natural biopolymers. Synthetic biopolymers are generated from renewable natural sources, are often biodegradable, and not toxic to produce. Synthetic biopolymers can be produced by biological systems (i.e. micro-organisms, plants and animals), or chemically synthesized from biological starting materials (e.g. sugars, starch, natural fats or oils, etc.). Biopolymers are an alternative to petroleum-based polymers (traditional plastics). (Bio)polyesters have properties similar to traditional polyesters. Starch-based polymers are often a blend of starch and other plastics (for example, PE), which allows for enhanced environmental properties.

Biological materials, such as wood pulp and cotton, can pose environmental problems. Unsound agricultural or silvicultural practices can quickly turn a fertile tract into a disaster area. Because biological resources are renewable, there is a popular tendency to think of them as unlimited. Nothing could be further from the truth. If cultivated carefully, crops can be planted in perpetuity. But if the land is pushed past its carrying capacity or otherwise abused, permanent damage can be done (Hayes 1978).

A widespread shift to biological materials for both energy and materials has other implications because large quantities of land may be required to provide ethanol, biological materials, and the feedstock for biomaterials such as biopolymers. An ethical debate is shaping up over taking excess land from food production and shifting it to these other applications, causing increases in food prices and impacting the poor and hungry of the world.

The fact that these materials are biodegradable and compostable means they are recyclable via a biological route. However there is a great deal of uncertainty about the quality and utility of the degraded materials and the logistics for effectively using these nutrients of unknown quality in agriculture or the support of natural systems.

Finally, there is little evidence that biologically based materials can replace the synthetic materials that have become common in construction, especially structural materials such as steel and concrete, not to mention copper and aluminum wiring, glass, and the wide variety of polymers used in myriad applications.

Synthesis

After examining the range of principles and approaches that describe how to create an environmentally sound and sustainable built environment, and taking into account the orientation of the human species toward the future, the development and deployment of new materials and products will likely be based on ethics, risk, and economics. Clearly there have been ample lessons learned about the introduction of toxics and estrogen mimickers into the environment, the impacts of emissions on human and natural systems, the effects of extraction on the environment and human communities, the impacts of waste, and all the other well-known negatives of the production system. Changing the decision system, screening all substances for a broad range of impacts is badly needed to insure the risks to nature and humans is minimized. Certainly nature's materials and processes provide inspiration for human designed materials and products and the behavior of natural systems can inform human systems. But many novel materials and products will continue to be produced and a systematic approach to examining the extraction, production, use, recycling, and disposal of these resources. This would include life cycle assessment but with application of toxicology and other screens to produce a fuller understanding or the risks associated with the entire life cycle of materials. Beyond the question of materials is responsibility for products and insuring their potential for disassembly. In the context of the built environment, one other level of disassembly, that of the whole building, must be considered for closing materials loops. Economics, underpinned by policy in the form of taxes that penalize negative behavior in the production and consumption system, will also help dictate the future. In the final analysis ethics will have to govern the decision system. This sustainability ethics will include the Precautionary Principle, the Reversibility Principle, the Chain of Custody Principle, Animal Rights, the Rights of the Non-Living World. They must also address how humans use knowledge of potential negative impacts and ideally require detailed screening of all new chemicals and processes to insure their effects are well understood. Knowing this would allow risk assessment and the ultimate decision as to whether the benefits outweigh the costs.

Conclusions

Ecological design, a vague concept, is the underpinning of greening the built environment. Three levels of ecological design can be identified, from weak ecological design which seeks to mitigate environmental design, to intermediate ecological design which calls for integration of human and natural system in a synergistic manner, to strong ecological design which calls for the emulation of nature. At the crux of deciding which version(s) of ecological design should be the focus of implementation is the fundamental difference between the human species and other species, the former being forward looking and the latter being a function of their past. It is a logical and necessary outcome that humans will produce new materials and processes that are indeed independent of the evolution of nature and constrained only by nature's laws. The exact nature of what is produced is constrained only by imagination, risk, ethics, and economics. Society is likely to decide what risks are appropriate and it is clear that we need to learn from the past and include screens and standards for the materials and processes we create to insure they will not cause unacceptable problems. In spite of the best efforts to understand, assess, and limit risk, there will be inevitable problems, debate, and struggles for understanding. The current debate over genetically modified organisms is instructive because the effects of introducing new species of plants into the biosphere are unknown. There are enormous potential benefits including feeding a growing world population and potentially reducing the need for water, fertilizers, and pesticides. The risks include the displacement of species that are part of the natural web of life, thus compromising the entire system; domination of the business of agriculture by a limited number of corporation, making the economic system more brittle and less resilient to shocks; and unintended consequences caused by a lack of a fuller understanding of the consequences of introducing new species into the biosphere. This latter point is important because history is rife with society having to reverse technological course when a lack of knowledge led to the introduction of asbestos, DDT, and PCB, to name but a handful, and then their later costly abandonment and attendant, expensive cleanup. Problems with biomimicking and bioaccumulating materials, substances that contribute to global warming and ozone depletion, persistent organic pollutants (POP), heavy metals, cancer causing substance, and many other technologies with negative impact are motivating society to create more effective standards and screens. The broader application of ethical principles, such as the Precautionary Principle and Reversibility Principle must provide the basis for these standards and screens for determining acceptable technologies. In the final analysis, the only force preventing human behavior from compromising both biological and human health is a strong system of ethics that provides rules and constraints for human activities in general.

References

Barbier, E.B. 1989. *Economics, Natural Resource Scarcity and Development. Conventional and Alternative Views.* London: Earthscan.

Benyus, J. 1978. *Biomimicry: Innovation Inspired by Nature*. New York: William Morrow & Company.

Bringezu, Stefan. 2002. Construction ecology and metabolism. in *Construction Ecology: Nature as the Basis for Green Building,* C.J. Kibert, J. Sendzimir, and G.B. Guy, Eds., London: Spon Press.

Daly, H. E. 1990. Towards some operational principles of sustainable development. *Ecological Economics* 2: 1-6

Fenton, M.D. 1998. *Iron and Steel Recycling tin the United States in 1998*. U.S. Geological Survey Open File Report 01-224.

Georgescu-Roegen, N. 1971. *The Entropy Law and the Economic Process*, Cam-bridge/MA: Harvard University Press.

Georgescu-Roegen, N. 1979,Energy analysis and economic valuation', *Southern Economic Journal*, **45**, 1023-1058.

Hawken, P., Lovins, A., and Lovins, H. 1999. Natural Capitalism, New York: Little Brown.

Hayes, D. 1978. *Repair, Reuse, Recycling: First Steps Toward a Sustainable Society*. Worldwatch Paper 23, Washington, DC: The Worldwatch Institute

Kay, James. 2002. Complexity theory, exergy, and industrial ecology. in *Construction Ecology: Nature as the Basis for Green Building,* C.J. Kibert, J. Sendzimir, and G.B. Guy, Eds., London: Spon Press.

Kibert, Charles J. 1994. Principles and a model for sustainable construction, *Proceedings of the First International Conference on Sustainable Construction*, Tampa Florida, 6-9 November 1994, 1-9.

Kibert, Charles J. 2005. Sustainable Construction: Green Building Design and Delivery, New York: John Wiley & Sons.

McDonough, William and Braungart, Michael, 2002. *Cradle to Cradle: Remaking the Way We Make Things*. New York: North Point Press.

Pearce, D.W.; Turner, R.K. 1990. *Economics of Natural Resources and the Environment*. Baltimore: Johns Hopkins University Press.

Reuter, M.A., van Schaik, A., Ignatenko, O., and de Haan, G.J. Fundamental limits for the recycling of end of life vehicles, Minerals Engineering, draft at http://www.assurre.org/downloads/archive/fcae9820-3e67-4e5a-882a-3c8cc94d001b.pdf

Petterson, Gary. 2002. Using ecological dynamics to move toward an adaptive architecture. in *Construction Ecology: Nature as the Basis for Green Building*, C.J. Kibert, J. Sendzimir, and G.B. Guy, Eds., London: Spon Press.

Ruth, M. 1995. Thermodynamic implications for natural resource extraction and technical change in U.S. copper mining, *Environmental and Resource Economics*, **6**, 187-206.

Westley, F., Carpenter, S., Brock, W., Holling C.S.and Gunderson, L.H. 2002. Why systems of people and nature are not just social and ecological systems. in *Panarchy*, L.H. Gunderson and C.S. Holling Eds., Covelo, CA: Island Press.