Construction Ecology

Nature as the basis for green buildings

Edited by
Charles J. Kibert, Jan Sendzimir,
and G. Bradley Guy

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Contents

strategy for achieving this is to place buildings underground, where ground contact and beneficial interaction with natural systems is maximized.

The final chapter, Conclusions, provides an overview of the outcomes of this initial collaboration of ecologists, Industrial Ecologists, and architects. This overview is organized into three major sections: (1) recommendations and agreements; (2) critical issues requiring further investigation; and (3) additional observations.

Summary and conclusions

Developing an ecology of construction is an important step in the evolution of green building movements around the world. In almost every case, national and international movements indicate ecological design and the adoption of ecological principles as key elements of green building or sustainable construction. However, theory and practice developed in ecology have had little or no actual connection to green building and, as a consequence, the green building movement, although highly successful, stands a fair chance of ultimate failure because of the lack coherent underpinnings. This book suggests that for the green building movement to emerge successfully as standard practice, it must rely on ecology and industrial ecology to provide the coherent structure and science needed to serve as the basis for developing new theory, practices, and experiments; for decision making; and to serve as its general compass.

In addition to providing a badly needed basis for green building, construction ecology will require built environment professionals to dramatically increase their understanding of ecology. Because it could be said that the *raison d'être* for green building is the protection of natural systems, the re-education of planners, architects, builders, and policy-makers in ecological theory can only result in more sharply focused attention on the important issues of green building. The introduction of ecological education as a requirement for a professional design or construction license to impact natural systems in the dramatic fashion characteristic of the built environment would seem to be a highly beneficial and worthwhile outcome for society.

1 Defining an ecology of construction

Charles J. Kibert, Jan Sendzimir, and G. Bradley Guy

The construction and operation of the built environment has disproportionate impacts on the natural environment relative to its role in the economy. Although it represents about 8% of gross domestic product (GDP) in the USA, the construction sector consumes 40% of all extracted materials, produces one-third of the total landfill waste stream, and accounts for 30% of national energy consumption for its operation. The sustainability of this industrial sector is dependent on a fundamental shift in the way in which resources are used, from non-renewables to renewables, from high levels of waste to high levels of reuse and recycling, and from products based on lowest first cost to those based on life cycle costs and full cost accounting, especially as applied to waste and emissions from the industrial processes that support construction activity. Construction, like other industries, would benefit from observing the metabolic behavior of natural systems, in which sustainability is a property of a complex web of niche elements. The emerging field of industrial ecology, which is examining Nature for its lessons for industry, provides some insights into sustainability in the built environment or sustainable construction. This book proposes and outlines the concept of construction ecology, a view of construction industry based on natural ecology and industrial ecology for the purpose of shifting construction industry and the materials and manufacturing industries supporting it onto a path much closer to the ideals of sustainability. Additionally, construction ecology would embrace a wide range of symbiotic, synergistic, built environment–natural environment relationships to include large-scale, bioregional, "green infrastructure" in which natural systems provide energy and materials flows for cities and towns and the human occupants provide nutrients for the supporting ecological systems.

Introduction

Ecosystems are the source of important lessons and models for transitioning human activities onto a sustainable path. Natural processes are predominantly cyclic rather than linear; operate off solar energy flux and organic storages; promote resilience within each range of scales by diversifying the execution of functions into arrays of narrow niches; maintain resilience across all scales by operating functions redundantly over different ranges of scale; promote efficient use of materials by developing cooperative webs of interactions between members of complex communities; and sustain sufficient diversity of information and function to adapt and evolve in response to changes in their external environment. A variety of approaches to considering the application of natural system design principles to the industrial subsystem of human activities is emerging to help redesign the conduct of a linear economy based largely on the consumption of non-renewable resources.

Industrial ecology is an emerging discipline that is laying the groundwork for adapting ecosystem models to the design of industrial systems. In more recent thinking, industrial ecology is being redefined and extended to include industrial symbiosis, design for the environment (DFE), industrial metabolism, cleaner production, eco-efficiency, and a host of other emerging terms describing properties of a so-called "eco-industrial system." Industrial symbiosis refers to the use of lessons learned from the observation of ecosystem behavior to make better use of resources by using existing industrial waste streams as resources for other industrial processes. An emerging discipline, DFE is altering the design process of human artifacts to enhance the reuse and recycling of material components of products. Industrial metabolism examines the inputs, processes, and outputs of industry to gain insights into resource utilization and waste production of industry, with an eye toward improving resource efficiency. Cleaner production is the systematic reduction in material use and the control and prevention of pollution throughout the chain of industrial processes from raw material use through product end of life (Business and the Environment 1998). Eco-efficiency calls on companies to reduce the material and energy output of goods and services, reduce toxic waste, make materials recyclable, maximize sustainable use of resources, increase product durability, and increase the service intensity of goods and services (Fiksel 1994).

Construction and operation of the built environment in the countries in the Organization for Economic Cooperation and Development (OECD), i.e. the major industrial countries, accounts for the greatest consumption of material and energy resources of all economic sectors and could benefit the most from employing natural systems models. Within the framework being defined by industrial ecology, construction industry would be well served by the definition of a subset, construction ecology, that spells out how this industry could achieve sustainability, both in the segment that manufactures the products that constitute the bulk of modern buildings and in the segment that demolishes existing buildings and assembles manufactured products into new or renovated buildings. As is the case with other industrial systems, construction would be aided in this effort by an examination of its throughput of resource, i.e. its "metabolism."

This chapter examines the potential for construction industry to incorporate the lessons learned from both natural systems and the emerging field of industrial ecology, primarily in its materials cycles, but also at larger scale for regional energy and materials flows. It also explores the issue of dematerialization and its relevance to the built environment. In many respects, the construction industry is no different from other industrial sectors. However, there are enough differences, especially the long lifetime and enormous diversity of products and components constituting the built environment, that it requires special attention and treatment. Consequently, attempts to apply ecology to this industry and to understand its metabolism present some unique problems not encountered in other industrial sectors.

Construction industry compared with other industrial sectors

Buildings, the most significant components of the built environment, are complex systems that are perhaps the most significant embodiment of human culture, often lasting over time measured in centuries. Architecture can be a form of high art, and great buildings receive much the same attention and adoration as sculpture and painting. Their designers are revered and criticized in much the same manner as artists. This character of buildings as more than mere industrial products differentiates them from most other artifacts. Their ecology and metabolism is marked by a long lifetime, with large quantities of resources expended in their creation and significant resources consumed over their operational lives.

The main purpose of the built environment is to separate humans from natural systems by providing space for human functions protected from the elements and from physical danger. Modern buildings have increased the sense of separation from the natural climatic processes and have made the underlying biological and chemical processes of Nature irrelevant for their occupants. Until humans achieved space travel, the extraction and conversion of materials for building construction was the most powerful expression of humankind's dominance over bioclimatic and material constraints. This has. in turn. created an ecological illiteracy and had profound psychological and human health impacts (Orr 1994). Concentrations of buildings affect microclimate (heat islands), hydrology (run-off), soils and plants (suffocation and compression), and create false natural habitats (nests on buildings). This increasing separation of ecological feedback loops inherent in the design, construction, and use of buildings since the Industrial Revolution has influenced many architects to reconsider this de-evolutionary and unsustainable path. The construction industry is extremely conservative and subject to slow rates of change because of regulatory and liability concerns as well as limited technology transfer from other sectors of society. The extended chain of responsibility and the separation of responsibilities for manufacturing materials, design and construction, operations and maintenance, and eventual adaptation or disposal have resulted in a breakdown of feedback loops among the parties involved in creating and operating the built environment.

Modern buildings, although products of industrial societies, are perhaps unique among modern technologies in terms of the diversity of components, unlimited forms and content, waste during the production process, land requirements, and long-term environmental impacts. In the USA, the construction industry, although representing only 8% of GDP, uses in excess of 40% of all extracted materials resources in creating buildings (Wernick and Ausubel 1995), which consume 30% of total US energy production in their operation. It is estimated that as much as 90% of the extracted stock of materials in the USA is contained in the built environment, making it a potential great resource or a future source of enormous waste.

The built environment interacts with the natural environment at a variety of levels. Individual structures may affect only their local environment, but cities can have an impact on the regional environment, by affecting the weather through changes in the Earth's albedo (Wernick and Ausubel 1995) and other surface characteristics, altering natural hydrologic cycles, and degrading air, water, and land via the emissions of their energy systems, as well as through the behavior of their inhabitants.

Buildings can be distinguished from other artifacts by their individuality and the wide variety of constituent parts. Buildings are assembled from a wide array of components that can be generally divided into five general categories:

1 manufactured, site-installed commodity products, systems, and components with little or no site processing (boilers, valves, electrical transformers, doors, windows, lighting, bricks);
2 engineered, off-site fabricated, site-assembled components (structural steel, precast concrete elements, glulam beams, engineered wood products, wood or metal trusses);
3 off-site processed, site-finished products (cast-in-place concrete, asphalt, aggregates, soil);

4 manufactured, site-processed products (dimensional lumber, drywall, plywood, electrical wiring, insulation, metal and plastic piping, ductwork);
5 manufactured, site-installed, low mass products (paints, sealers, varnishes, glues, mastics).

Each of these categories of building components has an influence on the potential for reuse or recycling at the end of the building's useful life and the quantity of waste generated during site assembly. Category 1 components, because they are manufactured as complete systems, can be more easily designed for remanufacturing, reuse, and disassembly, and thus have a excellent potential for being placed into a closed materials loop. Category 2 products also have this potential although engineered wood products, a relatively new technology, have not been scrutinized as to their fate. Concrete products fit into the first three categories, and the extraction of aggregates for further use is technically and, in many cases, economically feasible (Figure 1.1). Category 4 products are in some cases more difficult to reuse or recycle, although metals in general are recycled at a very high rate in most countries. Category 5 products are virtually impossible to recycle, and in many cases are sources of contamination for other categories of products, making their recycling more difficult.

Buildings as artifacts of human society are also distinguished to a large extent by their relatively large land requirements and the environmental effects of the co-option of this valuable ecological resource. The built environment significantly modifies natural hydrologic cycles, contributes enormously to global environmental change, has tremendous effects on biodiversity, contributes to soil erosion, has major negative effects on water and air quality, and is the source of major quantities of solid waste. In the USA, construction and demolition waste accounts for the majority of industrial waste, amounting to perhaps 500 kg per capita or of the order of 136 million metric tons (MMT) annually. In the USA, the proportion of this waste that is reused or recycled is not known, but it is probably under 20% of the total mass and perhaps closer to 10%. Only concrete, recycled for its aggregates, and metals are recycled at high rates because of their relatively high economic value.

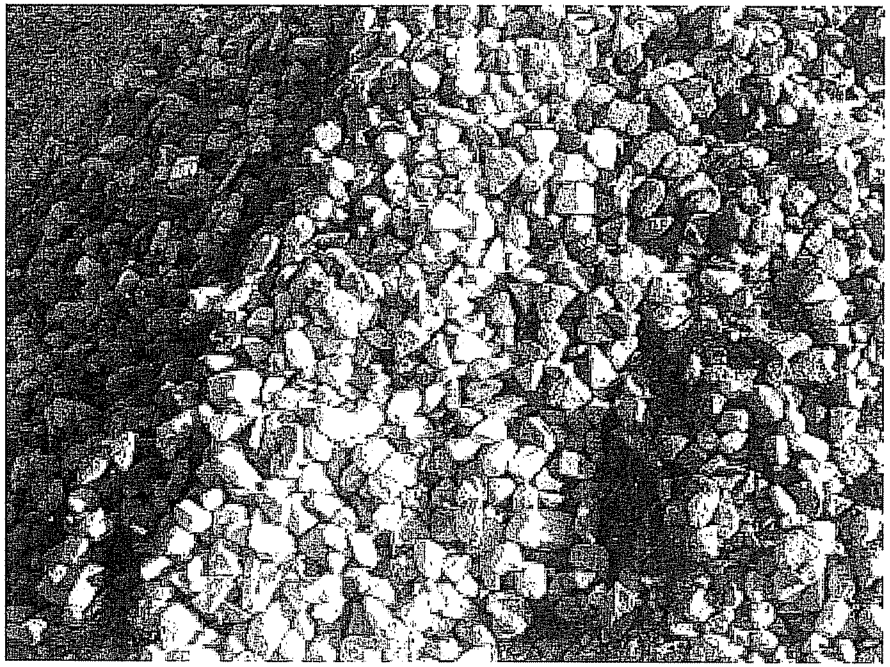

Figure 1.1 Mixed rubble including concrete aggregate, brick, masonry, and ceramic tile has substantial economic value when it can be reused in concrete mix design, as is the case with this material in The Netherlands.

The construction industry also differs from other industrial sectors in that the end products, buildings, are not factory produced with high tolerances, but are generally one-off products designed to relatively low tolerances by widely varying teams of architects and engineers, and assembled at the site using significant quantities of labor from a wide array of subcontractors and craftspeople. The end products or buildings are generally not subject to extensive quality checks and testing and they are not generally identified with their producers, unlike, for example, automobiles or refrigerators. Unlike the implementation of extended producer responsibility (EPR) in the German automobile industry, which is resulting in near closed-loop behavior for that industry, buildings are far less likely to have their components returned to their original producers for take-back at the end of their life cycle. Arguably, EPR could be applied to components that are routinely replaced during the building life cycle and that are readily able to be decoupled from the building structure (chillers, plumbing fixtures, elevators). The bulk of a building's mass is not easily disassembled, and at present little thought is given in the design process to the fate of building materials at the end of the structure's useful life (Figures 1.2 and 1.3).

Most industrial products have an associated lifetime that is a function of their design, the materials constituting them, and the character of their service life. The design life of buildings in the developed world is typically specified in the range of 50–100 years. However, the service lives of buildings are unpredictable because the major component parts of the built environment wear out at different rates, complicating replacement and repair schedules. Brand (1994) describes these variable decay rates as "shearing layers of change," which create a constant temporal tension in buildings (Figure 1.4). Brand adapted O'Neill *et al.*'s (1986) hierarchical model of ecosystems to illustrate the issue of temporal hierarchy in buildings that can be related to the spatial decoupling of components. Faster cycling components such as space plan elements are in conflict with slower materials such as structure and site. Management of a building's temporal tension might be achieved with more efficient use of materials through spatial decoupling of slow and fast components. Components with faster replacement cycles would be more readily accessible. This hierarchy is also a hierarchy of control, i.e. the slower components will control the faster components. However, when the physical or technical degradation of faster components surpasses critical thresholds, the faster components begin to drive changes to the slower components such that dynamic structural change can occur. For example, in a typical office building electrical and electronic components wear out or become obsolete at a fairly high rate compared with the long-lived building structure. At some critical threshold the motivation to maintain the overall building ebbs and the building rapidly falls into disuse and disrepair simply because of the degradation of the faster, more technology-dependent components. Odum (1983) developed the concept of

Figure 1.2 A 1960s era student residence hall at the University of Florida in the process of demolition. Although 12,000 bricks were recovered for reuse in new construction, in excess of 90% of the brick was unrecoverable because of the high-strength Portland cement mortar used to bind the bricks together and the lack of provision for disassembly of multistorey brick structures.

"emergy," the energy embodied in the creation and maintenance of a factor or process, as a means to quantify the relative contributions of different components to the operation of a hierarchy (see Chapter 2). Odum's theory predicts that the control of faster components by slower components is reflected in the latter's higher emergy transformity values. Transformity values are efficiency ratios of total emergy to actual energy, normalized in solar equivalent joules, that enumerate a process's relative capacity to influence system behavior. Using emergy to distinguish more carefully between slower and faster components and processes would allow designers to couple buildings to external processes of manufacture, reuse, and recycling more rationally. As such, this theory provides a quantitative framework for relating building design to its material components based on their relative contributions to the functions of an "ecosystem" that includes the built environment and the materials and processes that sustain it.

There are many similarities between construction industry and other industrial sectors when it comes to materials utilization. First, construction is in fact closely tied to industries that produce many of the products that ultimately constitute the built environment. Consequently, segments of these industries providing built environment products could be said, in a larger sense, to be a part of the construction industry. Thus, the environmental and resource impacts of their production systems are an integral part of the overall impacts of the built environment. Closing the loop for the manufactured systems that constitute much of the cost of construction is dependent on the originating industries applying DFE principles to allow disassembly and recycling or reuse of components as well as the establishment of reverse distribution systems in tandem with EPR legislation.

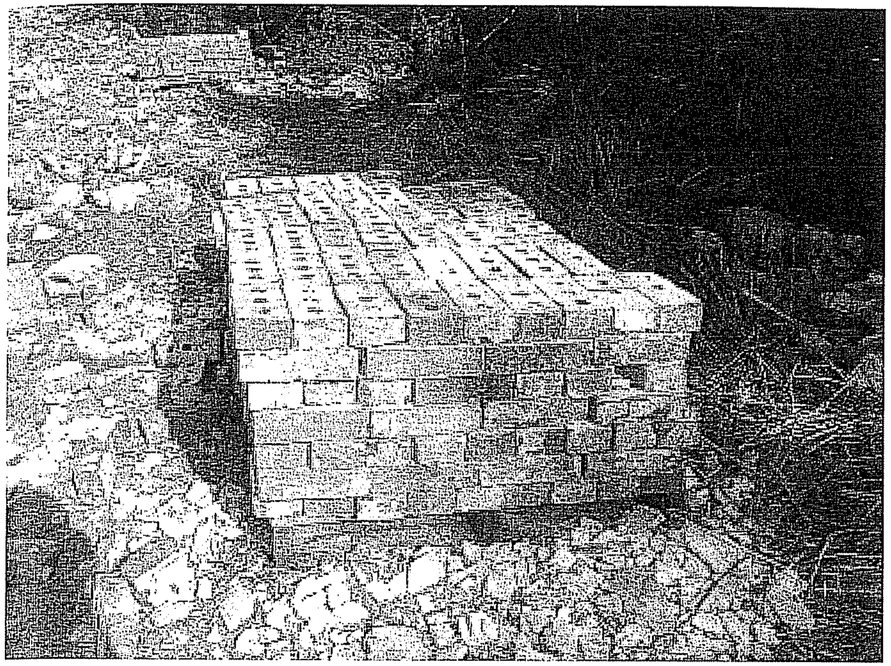

Figure 1.3 Pallet of bricks recovered from the student residence hall at the University of Florida.

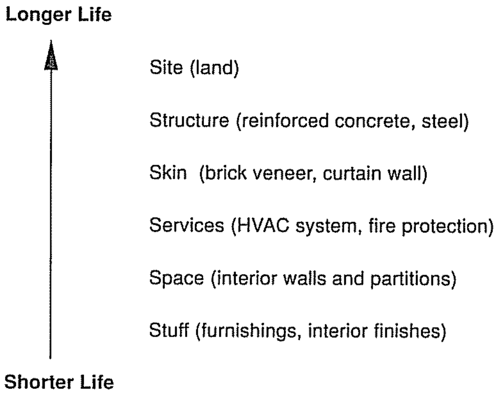

Figure 1.4 Temporal hierarchy of building components (after Brand 1994).

Placing construction materials into a closed-loop system is hampered by many of the same problems hampering other industrial sectors, such as the automotive and electronic industries. Components are often made of materials that are difficult if not impossible to recycle. They are, for the most part, not designed for disassembly to facilitate recycling. There are no requirements for manufacturers or suppliers to take back assembly waste or the worn-out products. The situation with regard to closing the materials loops varies from country to country, with, for example, US industry at one extreme and German industry at the other. American industry functions in an economy marked by a strong culture of almost pure market response, low levels of government intervention, and a history of cheap resources and low waste disposal costs. Consequently, recycled content or remanufactured products must compete with virgin resource-based products that are subject to only minor environmental cost internalization at best. The US federal government and other public sector organizations have a recent history of requiring the procurement of recycled content products, and consumer surveys have shown a favorable response to environmentally sensitive products. Several federal agencies, such as the National Park Service, the US Post Office, and several branches of the Department of Defense, are requiring "green" building design. This is having an impact on the building products industries, on the building design professions, and on the buying public. However, the purchasing cost of building products reflects little or no shifting of responsibility for environmental impacts addressing, for example, poor forestry practices, production emissions, and, in the case of construction, relatively large demolition and building assembly waste. German industry functions within a strong regulatory framework that constrains industry to a higher standard of materials use than is present in the USA. The Duales Deutschland System, EPR, and other regulatory systems are forcing German manufacturers to create products that are taken back by their producers to become raw materials for new products.

Materials and sustainability

Sustainability is affected by anthropogenic materials use as a result of (1) environmental effects of mass materials movement during extraction, (2) depletion of high-quality mineral stocks for industrial use, and (3) dissipation of concentrated materials resulting from wear and emissions. Mass materials movements and their negative environmental impacts are a recently identified phenomenon. As humans deplete the relatively accessible and valuable stocks of minerals, there are fewer of these resources available for future generations, and the energy needed to extract more dilute stocks and the distances to them will both undoubtedly increase. The dissipation of artifacts is the thermodynamic equivalent of increasing entropy or conversion from useful to useless (Georgescu-Roegen 1971; Ayres 1993).

The Earth, along with its biosphere, is essentially a closed system with respect to materials and materials flux. Organizations studying materials cycles are producing convincing arguments that the environmental damage caused by extraction of primary materials is exceeding the capacity of natural systems to cope with the damage being caused by the mass material movements accompanying their extraction. The Wuppertal Institute estimates that the materials flux of human processes is twice the flux caused by all natural forces and systems combined, including hurricanes, earthquakes, tornadoes, and volcanoes, excluding sea floor spreading and continental subduction. Almost thirty years ago, Brown (1970) suggested that humankind had already become a major geologic force. He noted the need for increased recycling efficiency and a lowered demand on extraction as the source for metals to both protect the environment and address the worldwide disparity in resource availability between rich and poor nations. Accompanying the Wuppertal Institute scenario is the hypothesis that sustainability requires that the human-induced materials flux should be no greater than the natural flux. Parallel to the enormous quantities of matter being moved by humankind is the co-option of the order of 40% of all terrestrial and aquatic biomass by humans for their own use at the expense of all other species (Vitousek *et al.* 1986). Additionally, humans are also co-opting over 50% of all accessible water run-off worldwide, which is expected to increase to 70% in the next three decades (Postel *et al.* 1996). One-third to one-half of the Earth's surface has been transformed by human activities, and more nitrogen is fixed by humans than by all natural sources combined (Vitousek *et al.* 1997). The introduction of tens of thousands of synthetic chemicals, many of them hazardous, into the global environment is another factor that is causing documented illnesses and disturbances to the reproductive systems of animals, including humans, throughout the world. The net effect of all these human disturbances is not clearly understood, but the result can only be catastrophic if these trends continue, especially if synergism and positive feedback loops amplify these negative effects.

With regard to materials, the Wuppertal Institute suggests that the materials input per service unit (MIPS) must be reduced by a factor of 10 to move into a regime that could be considered sustainable (von Weizsäcker *et al.* 1997). Alternatively, it could be said that resource efficiency must be increased by a factor of 10 to achieve the same end. The Factor 10 Club is laying the groundwork for an international effort that originated with the Cournoules Statement in 1994, calling on industry and governments to transform their policies to effectively dematerialize their countries' economies. Dematerialization is the reduction of the quantities of materials needed to serve economic functions or the decline over time in the weight of materials used in industrial end products (Wernick *et al.* 1996). It should be noted that this proposal for dematerialization does not distinguish between virgin and recycled or reused resources. Closing materials loops could produce, in effect, a factor 10 reduction in human-induced materials flux from the Earth, with a far smaller reduction in aggregate materials throughput.

In addressing dematerialization, Bunker (1996) notes that, instead of being an environmental or sustainable development response, dematerialization is not much more than an attempt to increase profitability, that it is not a new idea because industry always strives to lower the unit costs of production. The intensity of use (IOU) index measures materials mass per unit of GDP, and for all industrialized countries IOU indices have been generally falling for many decades, indicating, by this metric, a steady dematerialization of their economies. In fact, industries compete to offer ever more lines of products, increase labor productivity, and in effect, increase demand and the consumption of materials. In housing, for example, over the past thirty years the average American home has steadily increased in size from 170 to 220 square meters while the average number of occupants has fallen from 3.5 to 2.5. Aggregate materials use or throughput, in contrast to IOU indices, is steadily increasing, and environmental damage is climbing proportionately. Also neglected in discussions of dematerialization are the toxic by-products associated with extraction and processing of, for example, metals such as copper, zinc, platinum, and titanium. Part of the problem with clearly assessing dematerialization is the substitution of lighter weight materials for heavier ones. In what is a classic scenario in materials use, high-technology polymers and carbon composites are rapidly replacing metals in many applications (Williams *et al.* 1989). Although dematerialization in an IOU sense is occurring by shifting to these alternatives, the environmental damage caused by the production of these materials and their general non-recyclability can make the benefits of dematerialization questionable.

True dematerialization must focus on virgin resource extraction rather than just dematerialization in the IOU sense, and the environmental impacts of the technologies and substitutions creating dematerialization need to be carefully scrutinized. Dematerialization must also focus on a shift to reuse, recycling, and remanufacturing, all important aspects of closing materials loops. Additionally, de-energization, decarbonization, and detoxification of the industrial system should accompany dematerialization if significant resource and ecological benefits are to be achieved. It must also be kept in mind that, although human ingenuity can perhaps effectively dematerialize the global economy, Ayres (1993) notes:

> There are no plausible technological substitutes for soil fertility, clean fresh water, unspoiled landscapes, climatic stability, biological diversity, biological nutrient recycling and environmental waste assimilative capacity. The irreversible loss of species and ecosystems, and the buildup of greenhouse gases in the atmosphere, and of toxic metals and chemicals in the topsoil, groundwater and in the silt of lake-bottoms and estuaries, are not reversible by any plausible technology that could appear in the next few decades. Finally, the great nutrient cycles of the natural world – carbon, oxygen, nitrogen, sulfur, and phosphorous – require constant stocks in each environmental compartment and balanced inflows and outflows. These conditions have already been violated by large-scale and unsustainable human intervention.

Finally, Hayes (1978) suggested that a sustainable world would be one in which "Material well-being would almost certainly be indexed by the quality of the existing inventory of goods, rather than by the rate of physical turnover. Planned obsolescence would be eliminated. Excessive consumption and waste would become causes of embarrassment, rather than symbols of prestige."

Lessons from natural systems

Many authors have suggested that human industrial systems can and must use the metaphor of biological systems as guidance for their design. The field of ecological engineering emerged from Odum's (1983) pioneering work, which explored how functions and services could be optimized at much greater efficiencies by integrating human and natural systems through adept redesign. These lessons can be explored at a large or systems scale as well as at the small or microscopic scale in terms of the metabolism of natural systems versus industrial systems. At large scale this might mean that industry should recast itself as an industrial ecosystem comprising an interrelated network of producers and consumers that would function much as a natural ecosystem (Frosch and Gallopoulos 1989, 1992; Frosch 1997). Industrial processes would function much as biological organisms in that excess energy and waste from some systems would serve as inputs for industries requiring energy and which can use the waste in their production systems (Ausubel 1992). After their "birth, life, and death" at one scale, the products of industry would ultimately be metabolized and reutilized at another scale, mimicking the closed, waste-free cycles of natural systems. This proposition has profound implications for designers and builders, given the scale of energy and materials use in the built environment.

There are many questions to be answered in attempting to redesign industry to behave like Nature. Do natural systems in fact use resources optimally or can technology actually improve on the energy and matter utilization of Nature, perhaps through observing Nature itself? Are there limits to using the natural system metaphor for industrial systems, and, if there are, what are they? Can humankind really live off current solar income, as has been suggested, or is this impossible if quality of life for present and future populations is to be maintained? What is the human-carrying capacity of the Earth if adequate natural systems functions are to be maintained? Can natural systems perform many critical functions required by humankind and, in effect, substitute for the work of industry in some cases? This last question was at least partly answered recently by a team that estimated the mean value of a range of natural systems to be about $33 trillion or almost twice the total world economic output (Costanza *et al.* 1997). However, this estimate is at best controversial in the sense it depends to a great extent on people's "willingness to pay" for ecological services.

Ayres (1989) described some of the analogies between natural and economic systems by noting that natural systems themselves might not have always been sustainable. Alternatively, it can be said that no natural system is sustainable over long time scales. Changes in natural systems reflect experiments that shift the composition of processes, functions, and species, both independently and in response to novelty of system composition or of context (changing conditions). Evolutionary history is studded with unprecedented leaps of novelty that rendered unsustainable many systems that had endured for eons. Stage 1 of life on Earth consisted of fermentation-based life forms functioning and replicating by anabolism, generating carbon dioxide waste that accumulated in the atmosphere. This "waste" proved to be the resource for the next leap of evolution. The anerobic stage 1 organisms were followed in stage 2 by organisms employing photosynthesis to utilize the carbon and discharge oxygen as waste, thus killing most extant biota, for which oxygen was a toxic gas. Oxygen, initially a "toxic waste," created the conditions for novel stage 3 organisms that utilized oxygen to metabolize a larger range of molecules and allowed them to function with far greater energy, stamina, and diversity of shapes and sizes in an enormous variety of new environments. The emergence of oxygen was a radical shift in context that permitted an explosive increase in opportunities for biota that would have been unimaginable beforehand. In this manner, novelty periodically resets the standard for what is sustainable (Holling *et al.* 1995). Ayres (1989) suggests that the present industrial system, so dependent on fossil fuel-based energy systems, is analogous to the stage 1 fermentation cells that essentially convert stocks of carbon fuels to waste carbon dioxide. A similar catabolism–anabolism metabolic behavior is characteristic of industrial systems except that industrial systems, unlike ecosystems, metabolize their energy-matter throughput into largely useless waste.

Another related view is that the current industrial systems are the equivalent of type I or pioneer species, also known as r-strategists, which rapidly colonize areas laid bare by fire or other natural catastrophes. Their strategy of maximum mobility and reproduction involves investing all their energy in seeds and rapid growth and minimizes investments in structure. r-strategists are mobile, surviving by being the first at the scene of a disturbance and securing resources before they are eroded away (Begon *et al.* 1990; Holling *et al.* 1995). However, when the resource base has been expended, their populations will diminish to very low levels. They are not competitive in the long run, and only excel at outcompeting each other in a loose "scramble competition," eventually losing out to the K-strategists. In natural succession, type II species supplant type I species because they spend less energy on generating seeds and more on systems such as roots that will enable their survival during periods of lower available resources. Type III or K-strategists live in synergy with surrounding species and are far more complex than the other types. K-strategists, unlike r-strategists, are not mobile but survive longer at higher density by developing highly efficient resource and energy feedback loops. Both K- and r-strategists are present everywhere, with r-strategists surviving in subdued populations in "older" sites and exploding in population in "younger," disturbed sites. K-strategists invest more in structure than in mobility, and this is the template around which their complex interrelationships efficiently conserve the flow of energy and resources. In a similar manner, it could be said that industrial systems behave in a similar fashion (Graedel and Allenby 1995; Karamanos 1995). Type I industrial ecosystems are the typical industrial processes of today, linear systems with little or no recovery of materials from the waste stream. Type II are emerging industrial ecosystems that include reuse and recycling in their processes but also require significant primary material inputs for their functioning. Closed-loop type III industrial ecosystems with full materials recovery do not exist at present, partly because of a lack of technology and partly because of poor product design. Perhaps industrial ecology is simply another stage in a process of never-ending change in which human-designed systems "naturally" evolve in a manner similar to natural ecosystems (Erkman 1997). The question for humankind that may emerge from this observation of nature is how to move as rapidly as possible from our current type I global economy to a type III economy or from a r-strategy to a K-strategy (Benyus 1997; Shireman *et al.* 1997).

Both natural and industrial systems require energy to reproduce and maintain their functions. Natural systems, for the most part, use solar flux or stored solar energy in the form of biomass for their functioning whereas industrial systems use a wide variety of energy sources. The intensity of industrial operations requires energy sources that are refined to the highest quality by geological forces operating over millions or years. Natural systems are characterized by their use of renewable energy sources. In the present era, industrial systems operate largely by using stored solar energy in the form of fossil fuels, but these are being consumed at a pace on the order of 10,000 times their regeneration rate.

Natural systems are sustained by the emergence of surprise (Holling 1986) and novelty (Kauffman 1993) and by the diversity of information found in genetic codes, which instruct the fabrication and operation of organisms. This diversity is present at several levels: within each population of a species, across all populations of a species, and across all species in communities (Begon *et al.* 1990). Ecosystems are also sustained by a diversity of ecological functions that process energy, matter, and information in a shifting balance of competitive and cooperative relations. Functional diversity is maintained at several levels. Within each range of scales, different functions are partitioned among species that occupy separate, narrow niches. For example, at the scale of a stand of trees, a variety of different bird and mammal species occupy individual niches, each of which focuses on a different resource (insects, fruits, and seeds). Functional diversity is maintained across all scales in a system when specific functions are performed at different scales. For example, tiny birds may eat individuals of a species of insect found on tree branches, but flocks of birds will appear to eat the same insect when that insect's population explodes and it is evident as a swarm across an entire stand of trees (Peterson *et al.* 1998). Industrial systems tend to function similarly, with technological information being the equivalent of genetic codes (Rothschild 1990). They cooperate through strategic alliances and absorb one another through acquisitions. They struggle to occupy niches and fiercely compete to dominate their environment, their markets. It would be interesting to determine the degree to which industrial systems are more resilient because of the redundancy of function within scales and across scales. For example, corporate buy-outs or bankruptcies can reduce the diversity of companies performing the same function at the same scale. Cross-scale resilience, the performance of the same function at different scales, is lowered by the replacement of local manufacturers by enterprises distributing goods at larger scales (national or global).

Benyus (1997) coined the word "biomimicry" to describe the use of lessons from the natural world to develop a concept of sustainability for humankind. One example she provides is the powerful natural adhesives produced by mussels to anchor themselves to rocks in strong ocean currents and how scientists are studying the biological processes that are used in their synthesis. By learning about the chemistry of natural systems, the potential exists to create whole new classes of materials that are strong and lightweight yet can be decomposed into harmless substances when they have outlived their use. Benyus suggests that the questions that should be put to new innovations and the industrial systems that produce them, if they are to mimic nature are: Does it run on sunlight? Does it use only the energy it needs? Does it fit form to function? Does it recycle everything? Does it reward cooperation? Does it bank on diversity? Does it utilize local expertise? Does it curb excess from within? Does it tap the power of limits? Is it beautiful?

Industrial ecology and metabolism

Industrial ecology can be defined as the application of ecological theory to industrial systems or the ecological restructuring of industry (Rejeski 1997). In its implementation it addresses materials, institutional barriers, and regional strategies and experiments (Box 1.1) (Wernick and Ausubel 1997). Industrial metabolism is the study of the flow of materials and energy from the natural environment, through the industrial system, and back into the environment. It is directed at understanding the flows of materials and energy from human activities and the interaction of these flows with local ecosystems, regions, and global biogeochemical cycles (Erkman 1997).

As noted by Graedel and Allenby (1995), the rejection of the concept of "waste" is one of the most important outcomes of global biogeochemical cycles. In an ideal industrial system, both renewable and non-renewable materials would be utilized in a closed loop to minimize the input of virgin resources. Products degraded by age or service would be designed to be reverse-distributed back to industry for recycling or remanufacturing.

Box 1.1 Issues confronting the implementation of industrial ecology

1. The material basis
   - choosing the material
   - designing the product
   - recovering the product
2. Institutional barriers and incentives
   - market and institutional
   - business and financial
   - regulatory
3. Regional strategies and experiments
   - geographic, economic, political
   - industrial symbioses

The processes creating the loops would be designed for zero solid waste to include zero emissions to water and air. Renewable resources would also be used in a closed-loop manner to the maximum extent possible and follow the same zero waste rules as for non-renewables. Renewable resources, being biological in origin, could be recycled by natural processes as simple biomass that could serve as nourishment for biological growth.

According to Richards and Frosch (1997), "... industrial ecology views environmental quality in terms of the interactions among and between units of production and consumption and their economic and natural environments, and it does so with a special focus on materials flows and energy use." They also go on to note that the integration of environmental factors can occur at three scales:

- microlevel (the industrial plant);
- mesolevel (corporation or group operating as a system);
- macrolevel (nation, region, world).

It is interesting to note that these three levels are identical to the levels at which natural systems are studied for their function.

Industrial ecology has evolved in two major directions since it became well known in the late 1980s. The first direction is the evolution of the concept of eco-industrial parks (EIPs) from "industrial symbiosis" to a much broader range of sustainability benefits. Under the rubric of industrial symbiosis, companies exchange otherwise useless waste as resources. The cluster of companies exchanging energy, water, and material by-products at the Kalundborg EIP in Denmark is the most frequently cited success story of industrial symbiosis. The EIP concept has rapidly evolved beyond mere symbiosis to encompass broader ideas of sustainability and may include shared workforce training, daycare centers, business incubators, provision of cleaner production consulting services, and collaboration with community leaders to establish public–private partnerships that benefit the local populace. Extending the concept of benefit sharing to regional scale can hypothetically result in "islands of sustainability."

The second major direction of industrial ecology is the optimization of materials flows by increasing resource productivity or dematerialization. The notion of a service economy which sells services instead of the actual material products is considered the *sine qua non* of this strategy, alternatively referred to as "systemic dematerialization." One of the questions facing industrial ecology is whether corporations can profit more from closing materials loops and behaving environmentally responsibly or through built-in obsolescence and open materials cycles (Erkman 1997). Perhaps a more fundamental question for industrial ecology is how to achieve a transition to a clean, highly resource-efficient industry while maintaining the viability of the economy and the profitability of corporations.

Industrial ecology also embraces the emerging new discipline known as design for the environment (DFE), which has as its goal the creation of artifacts that are environmentally responsible. DFE can be defined as a practice by which environmental considerations are integrated into product and process engineering procedures and which considers the entire product life cycle (Keoleian and Menerey 1994). A fundamental goal is balancing environmental, business, and technical considerations in product and process design. The term "green design" is used interchangeably with DFE, and is defined as " ... not a rigid set of product attributes, but rather a decision process whose objectives depend upon the specific environmental problems to be addressed" (Office of Technology Assessment 1992). There are several complementary terms frequently used to describe various aspects of DFE: design for disassembly, design for remanufacturing, design for recycling, design for reuse, and others. They have as their common denominator the consideration of environmental effects and resource efficiency in the design of artifacts. This proactive approach to creating objects that can be readily adapted, removed, reprocessed, recycled and reused, embodies the concept of "front-loaded" design (Wilson *et al.* 1998). Front-loaded design has implications related to the coding of information in the genetic structure of an organism that dictates its life stages from inception to maturation and decline, including the ability to adapt to changing environmental conditions. The practice of coding materials according to chemical composition so that they can be more readily recycled when the product is disassembled has utility for the construction industry in closing materials flows loops in a cost-effective manner. The fuller design for energy efficiency, materials efficiency, and human and environmental health can only be achieved by encoding a "natural" lifespan within the materials and design of buildings.

Another related endeavor, ecological design, is also becoming a part of the tools included in a broad vision of industrial ecology and is defined as " ... any form of design that minimizes environmentally destructive impacts by integrating itself with living processes" (Van Der Ryn and Cowan 1996). Examples of ecological design are sewage treatment systems that use constructed wetlands to process wastewater, homes that use dimensional lumber from sustainably managed forests, and agricultural practices that mimic natural plant communities. According to Van Der Ryn and Cowan, ecological design uses three key strategies to protect critical natural capital: conservation, regeneration, and stewardship. Conservation acknowledges the finiteness of resources and is directed at reducing the rate of their consumption. Repairing the damage done to ecological systems is the strategy of regeneration and is evidenced on a large scale by the ongoing effort to restore the natural flow characteristics of the Florida Everglades. Stewardship or deliberate care of ecosystems is a long-term commitment and marks an attempt to change the fundamental attitudes of humanity to nature. Ecological design is based in place and knowledge of local ecosystems to include energy and materials flows. In terms of materials use, ecological design consists of "Restorative materials cycles in which the waste from on process becomes food for the next; designed-in reuse, recycling, flexibility, ease of repair, and durability" (Van Der Ryn and Cowan 1996).

Ecologically sustainable architecture and construction

In the modern era of building design, several key figures emerge as the initiating forces whose ideas have coalesced into today's ecologically sustainable architecture. Among them are Frank Lloyd Wright, Richard Neutra, Lewis Mumford, Ian McHarg, and Malcolm Wells.

Frank Lloyd Wright's early education was under the tutelage of his mother, who employed Friedrich Froebel's Nature-based training. This early exposure to natural systems had a powerful influence on his life and architecture. The young Wright learned Nature's forms and geometries and " ... as a result of his training [Wright] was far more interested in designing the world than in representing it; designing understood as discerning the underlying structure of nature and building on it" (McCarter 1997). As the prophet of "organic architecture," his goal was to create buildings that were " ... integral to the site, to the environment, to the life of the inhabitants, integral with the nature of the materials ..." (Wright 1954).

Richard Neutra, a pupil of Wright, starts off his seminal work, *Survival through Design* (1954), with the following statement on the contemporary condition of man's relationship with nature:

> Nature has too long been outraged by design of nose rings, corsets, and foul-aired subways. Perhaps our mass-fabricators of today have shown themselves out of touch with nature. But ever since Sodom and Gomorrah, organic normalcy has been raped again and again by man. That super-animal still struggling for its own balance.

Neutra points out how badly flawed human products are compared with Nature's offerings. Nature is dynamic while human artifacts are static and cannot self-regenerate or self-adjust. While nature evolves "naturally," progress in the human sense takes deliberate effort, energy, and considerable motivation. Human artifacts generally follow the precedents in Nature anyway; for example, a reinforced concrete structure bears more than glancing similarity to the skeletal structure of a vertebrate. Even coloration to stimulate interest in a building mimics the shades and tones of flora and fauna seeking to procreate. Nature' s form and function emerge simultaneously, while humans must first create a building's form and then allow it to function. Imitating nature is more than flattery on the part of humankind, it is also copying systems that function in an extraordinarily successful fashion. Neutra was also able to recognize what is now referred to as *biophilia*, by advocating close connections between living spaces and the "green world of the organic" (Neutra 1971).

Lewis Mumford articulated the problematic drift from preindustrial cities that were sensitive to Nature and geographic conditions to post-industrial versions that ignored Nature and sprawled, destroying compact urban forms as well as the countryside. He advocated the employment of *ecotechnics*, technologies that rely on local sources of energy and indigenous materials in which variety, craftsmanship, and vernacular are important, not only adding to our ecological consciousness, but also emphasizing beauty and aesthetics (Luccarelli 1995). An updated version of this thinking includes the concepts of *bioregionalism* and *biourbanism*, infrastructure design that maximizes the "free work" that natural systems can provide. Stormwater handling, clean-up of phosphate pollution from agriculture, and sanitary sewage treatment could all be handled by wetlands and other natural systems, eliminating much of the need for the typical infrastructure needed for these purposes (Williams 1999).

Until rather recently, the planning of the built environment existed in isolation, as has, to a great extent, been the case with many human endeavors. McHarg (1969) noted the glaring deficiencies in planning:

> The first was the absence of any knowledge of environment in planning – this was a totally applied socio-economic process. The next was the lack of integration within the environmental sciences. Geologist, meteorologists, hydrologists and soil scientists were informed in physical science, unknowing of life. Ecology and the biological sciences were only modestly aware of physical processes. Scientists in general had not revealed any interest in values nor in planning; and finally, there was no theory attempting to address the problem of human adaptations

Malcolm Wells (see Chapter 12) favors a fairly straightforward approach to ecological design, i.e. simply submeging buildings into the ground so that the surface of the planet is minimally affected by the buildings. He contends that the surface above the earth-covered buildings can still provide the same services as they did before the construction of the building. In his book *Gentle Architecture* (1981), Wells asks an important question: "Why is it that every architect can recognize and appreciate beauty in the natural world and yet so often fail to endow his own work with it?" He often criticized the greatest architects of that time of failing to be aware of or moved by the biological foundations of both life and art.

Since the beginning of the 1990s, many organizations worldwide have been articulating a concept, commonly known as sustainable construction, that seeks to change the nature of how the built environment is designed, built, operated, and disposed of. It is in some ways a return to the basics advocated by Wright, Neutra, Mumford, McHarg, and Wells, a return to organic, Nature-based design. Sustainable construction considers the life cycle of the built environment as a seamless continuity, from design through disposal. It can be defined as "the creation and maintenance of a healthy built environment using ecologically sound principles." Its goals are to maximize resource efficiency and minimize waste in the building assembly, operation, and disposal processes. Sustainable construction seeks to dovetail into the global sustainable development movement by moving construction industry onto a path where it adheres to principles that are able to provide a good quality of life for future generations. In doing so, the sustainable construction effort is considering how to alter construction materials cycles to reduce their environmental and resource impacts.

Executing the concept of sustainable construction poses numerous difficulties. For example, contemporary architecture's efforts relative to materials analysis and their sustainability aspects generally rely on vague criteria, resulting in a great deal of imprecision. Many of these criteria are intuitive and perhaps even sensible. A typical approach is to specify, as much as possible, materials that are natural and renewable, that are local and indigenous, and which have low embodied energy (Steele 1997). Specifying local materials has been cited as climatically appropriate, supportive of the local economy, and more economically viable (Zeiher 1996). An additional criterion that often appears in contemporary guides to "green" building materials is to avoid the use of synthetic materials. What is meant by "synthetic" is not clearly defined. Concrete could be said to be synthetic, yet variants of modern concrete have been used during all of recorded history. Metals, especially alloys, which constitute the bulk of metals in use, could also be considered synthetics. Plastics clearly fit this category in spite of their potential benefits and the fact that some varieties can be made from biomass.

In many countries, there are now references available to aid in the selection of low-impact, green building materials. The Environmental Policy of the Royal Australian Institute of Architects provides several principles for guiding materials selection. Principle 2 of the Environmental Policy calls for architects to minimize the consumption of resources and is accompanied by recommendations on how to implement this principle via use of renewable resources, recycling buildings and using recycled components, and designing for durability (Lawson 1996). *The Green Guide to Specifications* (UK Post Office Property Holdings) categorizes materials based on environmental issues: (1) toxic pollutants in manufacturing; (2) primary energy used in extraction, production, and transport; (3) emissions; (4) material, water, and oil resources; (5) reserves of raw materials; (6) wastes generated; and (7) various recycling aspects (Shiers *et al.* 1996). The resulting table of ratings (A, B, or C, with A being the best and C the worst rating) for each material or system contains sixteen ratings based on the environmental issues as well as cost, maintenance frequency, and replacement intervals. This depiction of materials performance, fairly typical of information being provided to building professionals, provides a large array of data and editorial opinions. Unfortunately, the various units of data (embodied energy, extracted materials mass, emissions rates) are incommensurable, i.e. they are unable to be reduced to a smaller number of factors that are tractable. Consequently, making decisions based on these data is quite difficult and subjective.

The American Institute of Architects' *Environmental Resource Guide* (ERG) provides excruciating detail on the life cycle effects of a wide range of materials and guidance on how to select the best product in terms of its overall environmental performance, but it does not address conventional criteria such as cost, performance, and availability (Demkin 1997). Many other current materials rating systems provide similar counsel but are far more subjective than objective. Again, they are all ultimately compromised by the inability to combine units of energy, mass, and toxicity into a single rating that is meaningful. Additionally, by focusing almost solely on environmental impacts, they do not provide a useful decision system for materials selection. This is not to say that these references lack worth as they do serve as a means of enlightening building industry professionals on the wide range of effects their work products are having both on Nature and their human occupants.

The result of these problems is that materials selection is easily the most difficult and contentious area of sustainable construction. Clearly, a method or system for selecting "green" building materials that extends beyond life cycle analysis is needed, one that is grounded in natural systems principles and focusing on the fate of the materials at the end of their life cycle. Ultimately, the problem is to move to a much deeper integration of ecological ideas into design.

Defining construction ecology and metabolism

Efforts to change the materials cycle in construction are hampered by many of the same problems facing other industries. The individuality and long life of buildings poses some additional obstacles. Three fundamental difficulties arise when considering closed-loop materials cycles for buildings:

1. Buildings are not currently designed or built to be eventually disassembled.
2. Products constituting the built environment are not designed for disassembly.
3. The materials constituting building products are often composites that make recycling extremely difficult.

These difficulties also increase resource consumption by the construction industry, because building components must be frequently replaced, buildings may experience different uses during their lifetimes, and they periodically undergo renovations or modernization. In each case, the inability to readily remove and replace components results in significant energy inputs to alter building systems, and large quantities of waste are the result. For example, renovation of commercial structures in the USA produces of the order of 200 kg/m^2 of waste.

In terms of energy consumption, contemporary buildings designed to just meet energy codes in the USA use energy at a rate of about 30 kWh/m^2 per annum, although best practices indicate that as low as 3 kWh/m^2 annually is readily achievable. New building technologies reported in Germany suggest that homes can be designed to use less than 15 kWh/m^2 /year for heating, while Swedish studies suggest that heating energy can be reduced to less than 1 kWh/m^2 /year.

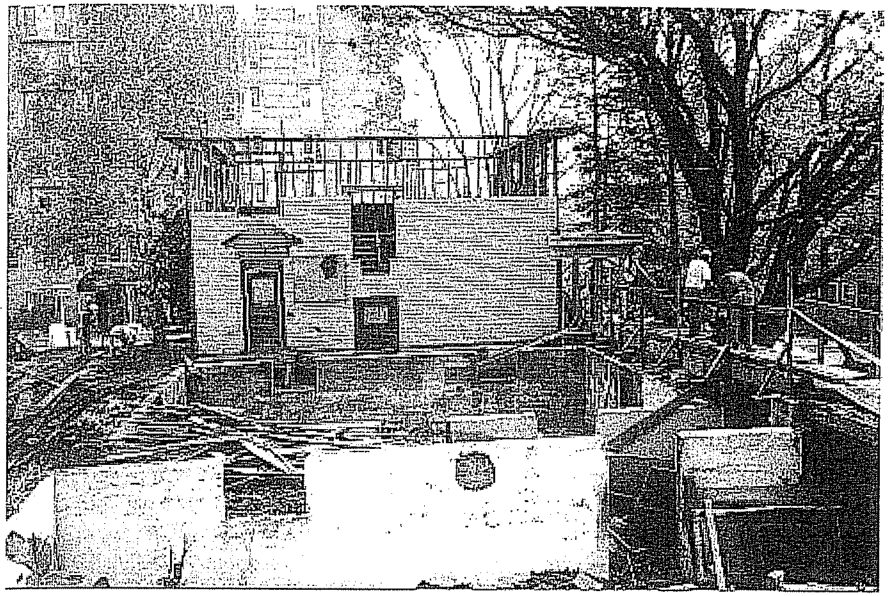

Figure 1.5 A block of five houses being disassembled in Portland, Oregon, by Deconstruction Services, Inc.

Clearly, a new concept for materials and energy use in construction industry is needed if sustainability is to be achieved. As noted at the start of this chapter, industrial systems in general are beginning to take the first steps toward examining their resource utilization or metabolism, and beginning the process of defining and implementing industrial ecology. In this same spirit, a subset of these efforts for construction industry, construction ecology, would help accelerate the move toward integrating in with Nature and behaving in a "natural' manner. Construction ecology should consider the development and maintenance of a built environment (1) with a materials system that functions in a closed loop and is integrated with eco-industrial and natural systems; (2) that depends solely on renewable energy sources; and (3) that fosters preservation of natural system functions. Construction metabolism is resource utilization in the built environment that mimics natural system metabolism by recycling materials resources and by employing renewable energy systems. It would be a result of applying the general principles of industrial ecology and the specific dictates of construction ecology.

The outcomes of applying these natural system analogues to construction would be a built environment (1) that is readily deconstructable at the end of its useful life; (2) whose components are decoupled from the building for easy replacement; (3) composed of products that are themselves designed for recycling; (4) whose bulk structural materials are recyclable; (5) whose metabolism would be very slow because of its durability and adaptability; and (6) that promotes health for its human occupants.

The deconstruction or disassembly of buildings and material reuse is one area of endeavor in which there has been a great upswing in activity and interest in the past few years. For example, a non-profit corporation in Portland, Oregon, employs several crews on a full-time basis to take apart houses and recover materials for resale in the do-it-yourself (DIY) market (Figure 1.5). Similar efforts are under way in numerous countries around the world, to include building systems that are able to be disassembled and reused (Kibert and Chini 2000). The next stage must be to reconsider building component design, creating products that are easily disassembled and made from constituent materials able to be recycled.

Summary and conclusions

The result of a shift toward construction ecology and its corresponding metabolism creates a host of issues and problems to be resolved. Can construction be readily dematerialized in the sense recommended by the Factor 10 Club? Can a construction ecology and metabolism be implemented without significant changes in national policy that alter national accounting systems and internalize environmental costs? What lessons from natural systems are feasible for application to the built environment? What are the roles of synthetic materials in construction ecology? How can construction materials production and recycling be integrated with the other components of the industrial production system? These are all difficult questions that must be answered to move forward into an era approximating sustainability in the built environment. Nonetheless, examining nature and ecological systems for patterns of energy and materials metabolism for their potential adoption into human systems can provide a substantial improvement on current methods of attempting to green the built environment.

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Part 1

The ecologists

Jan Sendzimir

Systems ecologists recognize the courage of builders who reach beyond their normal horizons to learn from the world surrounding the built environment. How might knowledge of ecological processes help us better harmonize the life cycles of buildings with the dynamic ways in which the environment builds and recycles structures? Ecologists have waged a similar battle for the past half-century to draw the attention of natural scientists from molecules to cells to organisms to populations to communities to landscapes to the biosphere. Specialists and generalists eternally implore one another to reset their sights and focus anew. The challenge of assessing how an activity fits within the environment is both easier and more difficult. It is easier because far more people genuinely want to understand the environment now that a series of crises (climate change, acid rain, ozone hole) have brought the consequences of human endeavor home to them. It is more difficult because closer scrutiny shows a far more complex picture than originally imagined, to the point where surprise and uncertainty appear unavoidable. Science may not deliver the certainty ("the smoking gun") that many feel is necessary to act on, but it can help us frame our questions and our activities in much more intelligent ways as we examine our dynamic and complex biosphere.

What are the key drivers of this age? The importance of industrial machinery seems to fade as we increasingly recognize the ascending role of biological complexity. Our popular appreciation of this emerges in the modern urban myth about a car mechanic scorning a surgeon, telling him that his high fees are unjustified because his work is no more complicated than a valve job. The surgeon replies that the mechanic will appreciate surgery better if he tries to do the valve job next time with the engine running. But this appreciation is stuck decades past at the level of the organism. How can we begin to understand the interplay between millions of organisms, species, and communities within the interweaving cycles of materials, nutrients, water and energy? Four ecologists take this challenge up from a systems perspective in the following chapters. They offer a variety of views on how systems (ecological and otherwise) persist through cycles of building and destruction before suggesting how to apply these ideas in managing the processes that create, recycle and resurrect human shelter.

Each of the authors brings unique experience to the application of systems science in understanding natural and human systems. Starting from meteorology and geochemistry, H.T. Odum (Chapter 2) built many of the key foundations of what is currently known as systems ecology. It would be an exacting task to determine what discipline H.T. Odum has *not* integrated into systems thinking over the past fifty years. The ease and clarity with which his chapter weaves together many fields into an elegantly simple working approach reflects a profound and comprehensive understanding that has been fundamental to the development of more than one generation of ecologists.