Material Circulation, Energy Hierarchy, and Building Construction*

Howard T. Odum
Environmental Engineering Sciences
University of Florida, Gainsesville

Abstract

Materials and building construction were related to the use of energy and compared to the metabolism of forests. Because materials are coupled to the natural energy transformation hierarchy, material cycles in nature and in civilization are hierarchically organized, passing from dilute background levels in the geobiosphere to successive centers of concentration at several levels before dispersing in recycle. By putting all energy inputs on a common basis of one kind of energy required, the work of material processing was expressed as emergy (spelled with an "m"). As materials pass through successive building processes, more work is done, and the emergy per unit energy (transformity) and the emergy per unit weight increase, defining the position in the energy-materials hierarchy. Energy limitations cause the quantity of material concentrated to be inverse to the increase in concentration and emergy per mass. A numerical example was derived from geological data on the hierarchical, skewed distribution of metal ores.

From many sources, the emergy per mass of materials was compared, values ranging from 9000 sej/kg of air (solar emjoules per kilogram) to 6×10^{14} sej/kg for gold. Emdollars, an economic equivalent of emergy, were calculated by dividing emergy flows and storages by the average ratio of emergy to money for the United States for1997.

Policies were suggested for ecological engineering and industrial ecology based on processing materials to maximize production of real wealth (maximum empower). Emergy per mass can indicate when materials should be economically reused, economically reprocessed, beneficially recycled with subsidies, or recycled to environment. Total material accounting of nations can be improved by adding materials on the basis of their emergy per mass.

* Paper for the 1999 Rinker Eminent Scholar Workshop on Construction Ecology and Metabolism. Center for Construction and Environment, University of Florida, Gainesville.

The energy-materials hierarchy in trees, buildings, industries, and nations were represented with energy systems diagrams, with emergy per unit increasing from left to right. Representing one stage in the hierarchy, the metabolism of building life cycle was compared to a general systems model of living metabolism recognizing production, structural storage, depreciation-replacement of parts, consumption-replacement of residuals, destructive-recycle, and the impact of larger scale pulsing. Indices were compared for rainforest and a simplified village.

To represent sustainable, but pulsing construction and metabolism, minimodels of the life cycles of building and material processing were simulated. An overview model of construction and consumption of trees or buildings (RESTRUCT.bas) was simulated for varying frequencies of pulsing restart analogous to the production-consumption model of ecosystems. Simulation included emergy and transformity.

A simulation model including colonization by weedy growth specialists and quality construction and diversity (program MATBUILD.bas) was used to compare succession in ecology with evolution of human settlements. The result was a generalized pattern of successional stages with increasing quality, to be expected with any construction that starts with excess initial resources.

When construction utilizes concentrated materials, it receives the accompanying energy and emergy. Unsustainable world structures built in this century were based on using the high emergy of concentrated material and fuel reserves at a nonrenewal rate. For each stage in the period of decreasing structure and metabolism ahead, the lower concentrations of material for each hierarchical level may be estimated from the predicted empower.

Table of Contents

Page

1-Introduction and the Energy Hierarchy

At this turn of the century the buildings of civilization are aging, and construction is increasingly squeezed between shortages of cheap materials and energy and the scarcity of unpopulated environment for discarded buildings, wastes, and their impact. The need to develop a more holistic life-cycle pattern of building construction and material use was recognized with the Rinker Conference on Building Construction and Metabolism in Gainesville, Florida, in May, 1999. For its purposes this chapter uses the general principles of energy processing, biogeochemical cycling, and emergy evaluation (spelled with an "m") to explain the patterns of construction and recycle which emerge as sustainable in self organization on any system and any scale. With the help of analogous ecosystem examples, this paper suggests ways to improve building construction, economic management, and the handling of materials now and in the times of declining availability of fuels and virgin materials ahead.

Everyone can observe actions of human individuals with trial and error building, developing infrastructure, processing materials, and choosing according to prices. But at a larger scale, the smaller actions are selected for or eliminated according to what works in the aggregate. Thus, it is possible to determine what will be successful from basic principles of energy, matter, and information that can indicate the main features of successful self organization that will emerge. In the give and take of public affairs, people are rarely aware that the future patterns follow universal principles that will emerge after trials and failures within the political process. Stewart Brand (1994) described self organization of civilization with his book "How Buildings Learn," in spite of what architects were trying to do otherwise. What would be more ideal is to plan in the first place what is predictable.

First, let's review some concepts and definitions that can be used to measure and interpret the building cycle process, whether it is nature's construction of a tree or human construction of a city. The world of environment and human economy is made of items on different scale all together (Figure 1a). By conceptually separating items of similar scale, as shown in Figure 1b, the small things can be seen to have small territories of support and influence and are made and replaced rapidly. Larger items in Figure 1b have larger territories and take longer to grow and be replaced. The small and large are connected by the flows of energy during self organization of pattern and structure. According to energy systems concepts, self organization of nature and human society develops

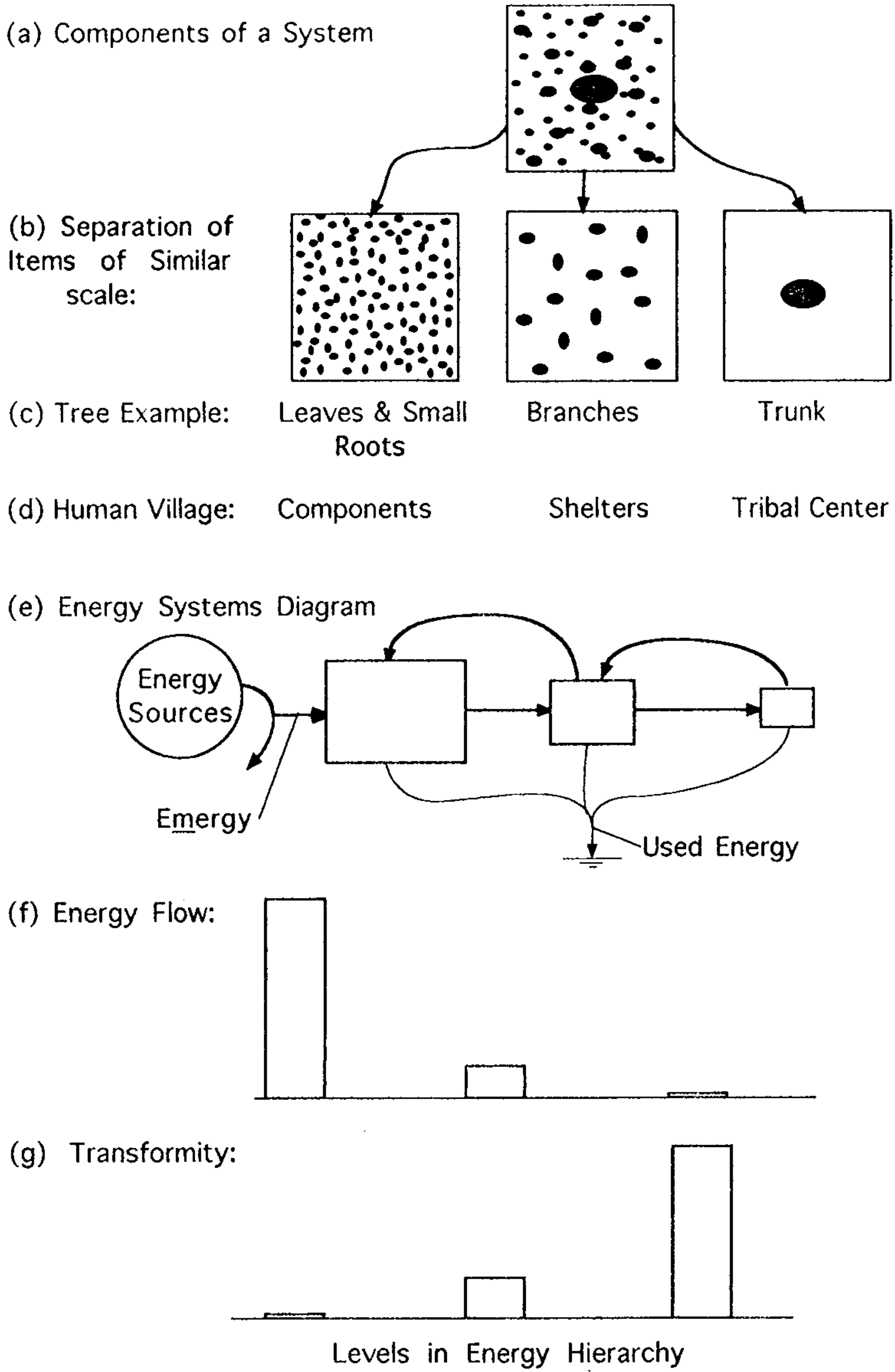


Figure 1. Energy hierarchy concept illustrated with one source and three energy transformation steps. (a) Components of three scales viewed together; (b) components of forest separated by scale; (c) components of a tree separated by scale; (d) components of a tribal village; (e) energy flows in an energy systems diagram; (f) flows of energy in the pathways from left to right; (g) transformity of the energy flows.

structures and processes on each scale of size and time, transforming energy of one scale to make the products for the next.

Energy Hierarchy

In brief, the processes of environment and economy can be arranged in a series according the successive energy transformations required to make one quantity from another (Figure 1e). Energy flowing in from the left builds units of structure and processing (the first box), with much of the degraded energy leaving the system as "used energy." Some of the transformed energy in the first box goes to support the next box and so on.

Tree Example

An example of energy hierarchy is a tree in the forest. Many leaves and small roots in Figure 1c send organic substances and materials to branches. The branches send products to the tree trunk. The energy flows are represented in the energy systems diagram in Figure 1e. Energy driving the process comes from the sunlight and wind (energy sources) on the left. At each step, work is done and much of the energy is degraded and is shown being dispersed (down pathways) as used energy that has lost its ability to do further work. At each step in the series, the quality of the energy transformed is increased. A joule of trunk wood energy is higher quality than a joule of original sunlight. It is more concentrated, more usable by the forest system.

Feedback Reinforcement

In Figure 1e, note the feedback pathways by which the blocks downstream to the right feed back materials and services to help operate the upstream blocks. These are pathways that reinforce and select those processes that contribute. These feedback pathways often have high quality materials or valuable control actions. For example, the branches support the leaves and the trunk supports the branches.

Human Village

A simple example involving human construction is a tribal village using materials and foods entirely from the forest as the energy source for their construction work (Figure 1d). The first box on the left is the forest structures and processes. The second box to the right is for humans building their family shelters. The third box to the right is the tribal center where people from the separate families use their materials and services to construct the tribal center's structure. The feedback by the tribal chief controls the family patterns, and the family work controls the processes in the forest that generate the materials and food.

Emergy Flow

In judging what is required for any pathway, it is incorrect to consider a calorie of chief's work equivalent to a calorie of organic matter from the forest. Although energies of different kinds cannot be considered equal in regard to the work they do, there is an easy way to put them on a common basis. Each energy flow can be expressed in the units of energy of just one kind that would have been necessary in direct and indirect processes to make it. The energy of that kind used for the comparison is called *emergy*, spelled with an "m," and the unit of measure is the *emjoule.* In the examples in Figure 1, there is only one source shown and all the other pathways receive its emergy flow. In other words, the flows through the blocks in this example all carry the same emergy, which is really a numerical "memory" of the source. In this paper we express the emergy in solar emjoules, abbreviated sej. The flow of emergy per unit time is called *empower,* with the units sej/time.

Transformity

The energy that is transformed and remains beyond a conversion process decreases through each transformation, because of the nature of energy dispersal (the second energy law). In Figure 1 the items further to the right in the scale of successive work contributions have the same emergy but have less energy (Figure 1f). The ratio of these two, emergy/energy, is defined as *transformity.* It increases from left to right and marks the position of anything in the energy hierarchy (Figure 1g).

Energy Quality Spectrum

Energy of higher transformity is said to be of higher quality because more was required to develop it and because uses have greater effects (for good or bad). For example, protein foods have higher transformity than vegetables. Genoni and Montague (1995) found potential toxicity also increasing with transformity.

Transformities range from 1 solar emjoule per joule for sunlight (by definition) to values 32 orders of magnitude larger for the genetic information of life. All energy flows and their transformations can be arranged in order of their transformity. Perhaps this principle should be recognized as a fifth energy law. Transformity marks position in the universal energy hierarchy. In representing data on graphs it is useful to arrange energy flows in order of their transformity, thus forming a distribution according to energy quality. All the diagrams and graphs in this paper are arranged from left to right in order of transformity.

2-Materials and the Energy Hierarchy

Materials and their cycles in the organization of systems are dependent on the flows of energy. Here we combine several concepts to explain the patterns of material distribution that result from the work of the energy hierarchy.

Material Cycles

Materials circulate through systems: water through the landscape, blood substances through the human body, and carbon through the biosphere. Estimating the rates of flow of a material and writing it on pathway diagrams is one of the standard ways of reporting data in a way that readers can visualize where flows are fast or slow. For example, biogeochemistry studies the circulation of the chemical substances, especially those that are incorporated into the production of organic matter by living organisms. For example, Figure 2 shows the circulation of material in a system which has three units of structure and processing. The numerical values on the pathways in this example are the flows of carbon into plant photosynthetic production of organic matter and transfer to consumers in a forest ecosystem.

Material Budgets

In many processes, a material may circulate without being changed into something else. In this case the material is said to be conserved. Inflows equal what is added to storage plus outflows. For example, chemical elements like carbon, phosphorus, and lead are usually conserved, being combined in different ways but not losing their identity as an element. Often diagrams of material cycles are drawn with numerical values of storages and flows for the system's average condition, as if the web of material flows was in a steady state. The evaluated diagram shows the system's "budget" of that material in the same way that average purchases and expenditures in a household are called a monetary budget. The pattern of organic biomass materials used and recycled in a forest tribal village is similar. On a larger scale, Adriaanse et al. (1997) published quantitative diagrams of materials budgets of nations.

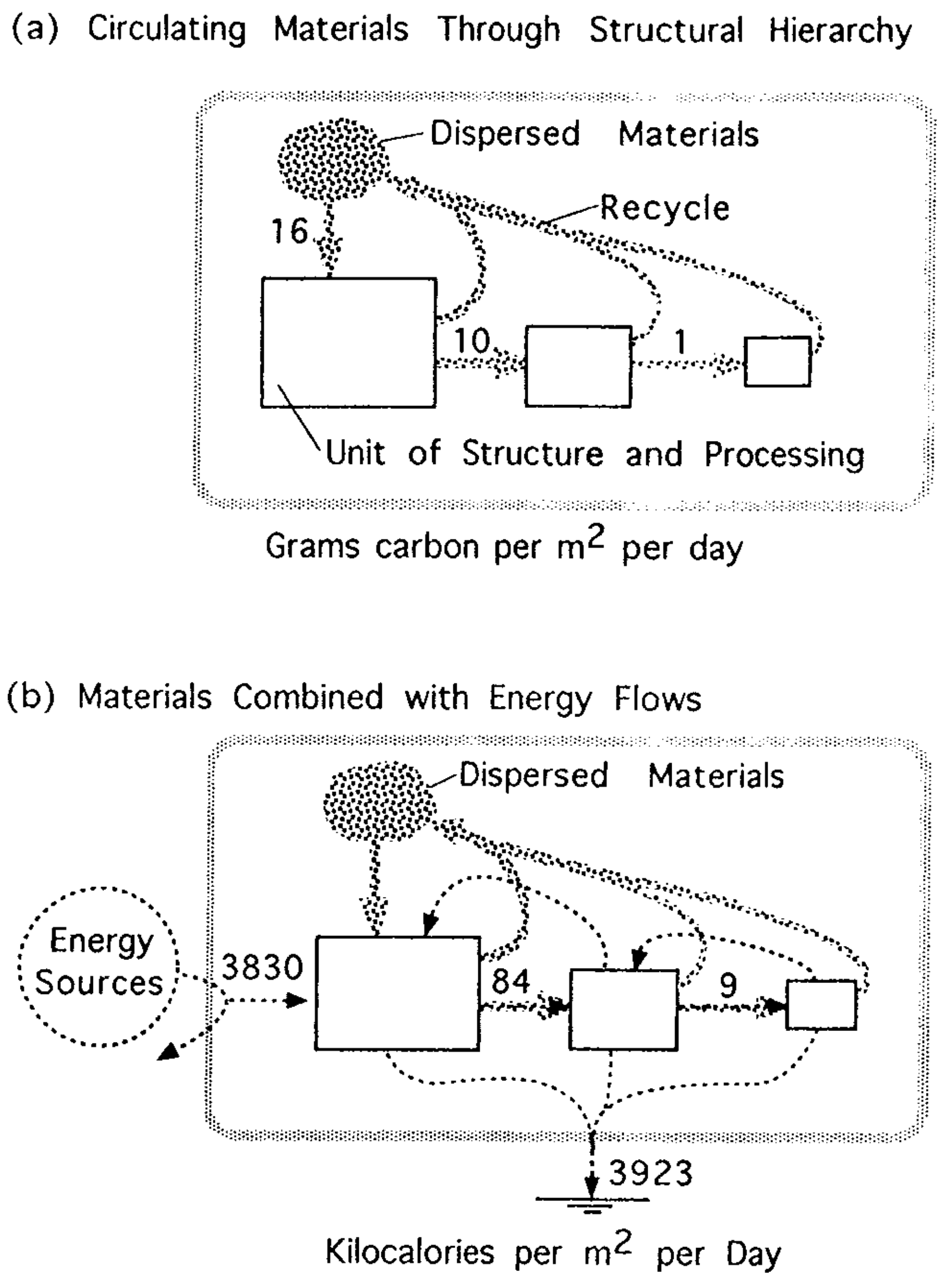


Figure 2. Materials and energy flows with a hierarchy of structural units of different scales. Numerical values are for circulation of carbon through three levels of a rainforest (1-leaves, 2-branches and roots and 3-tree trunks) (Odum, 1970). (a) Circulation of material; (b) combination of material and energy flows.

Coupling of Materials and Energy

In Figure 2b the circulation of material from Figure 2a is combined with the flows of energy from Figure 1. Both are necessary to the construction and operation of the system. Materials are said to be *coupled* to the energy transformations. Production processes can generate more useful products by incorporating materials into structural units that can use the materials, but work is required.

Energy Required for Concentrating Materials

Substances that are more concentrated than their environment tend to disperse and depreciate, a consequence of the second energy law. Conversely, to concentrate substances, available energy is required to do concentrating work. Most of the energy is degraded in the process and unable to do further work, while some energy is stored in the state of higher concentration (Increase in Gibbs Free Energy).

Figure 3a shows a gradient of increasing concentration from left to right. The spontaneous tendency is for the materials to disperse moving to the left in the gradient. In Figure 3b, outside available energy is shown doing the work of pumping materials from lower to higher concentration on the right. The available energy adds the emergy to the product. As expected from the second energy law, more energy is used up than is stored. Genoni (1998) provides a number of examples.

Since the available energy to the right of the energy transformation processes (production symbols) decreases, while the emergy increases, the transformity (emergy/energy) increases to the right. Since emergy is added to the materials as they are processed to higher concentration, the mass emergy (emergy/mass) also increases along the energy hierarchy (Figure 3c).

Spatial Convergence of Materials with an Energy Hierarchy

The self organization of systems of nature and humanity converge into small centers the energy that is initially spread over the landscape. Even though energy flow diminishes through each successive transformation (often in structural blocks--Figure 4a), converging the energy maintains a high concentration, capable of feedbacks that reinforce the contributing processes. Since the materials are part of the production and transformation process, they are also converged and concentrated into

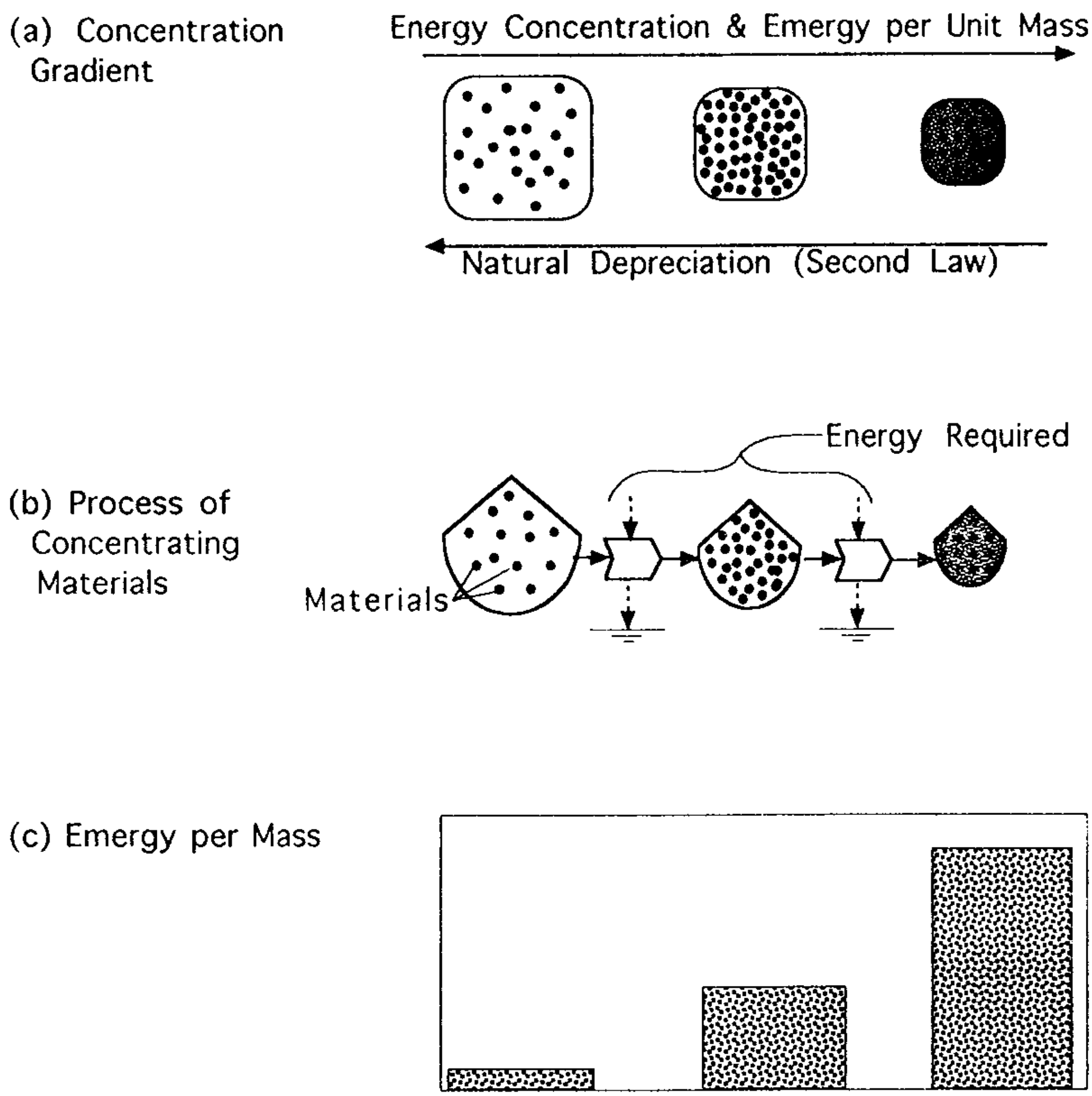
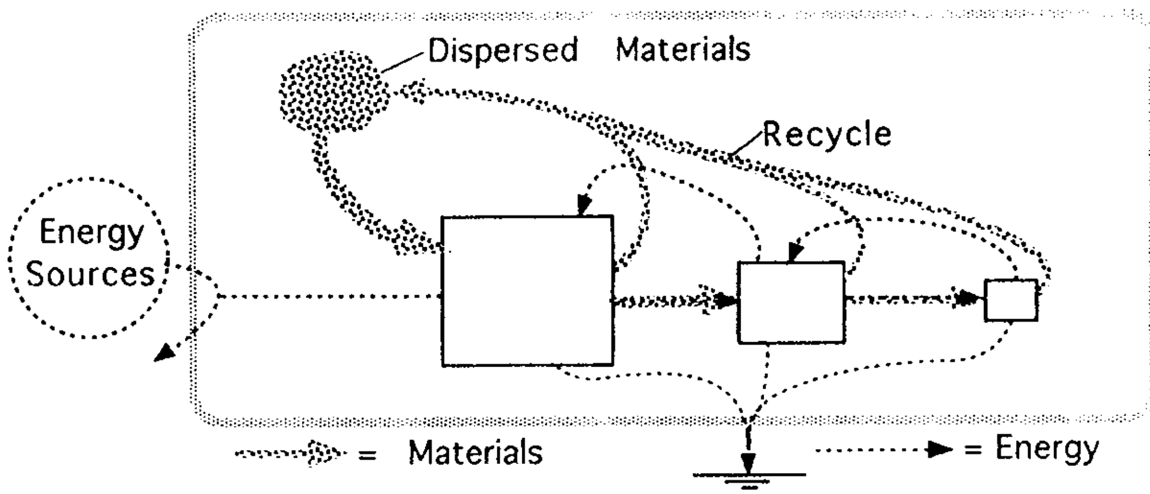


Figure 3. Energy and the concentrations of materials. (a) Sketch of concentration increase from left to right; (b) use of available energy to concentrate material; (c) increase in mass emergy (emjoules per gram) with concentration.

(a) Materials Combined with Energy Flows



(b) Spatial Convergence of Materials

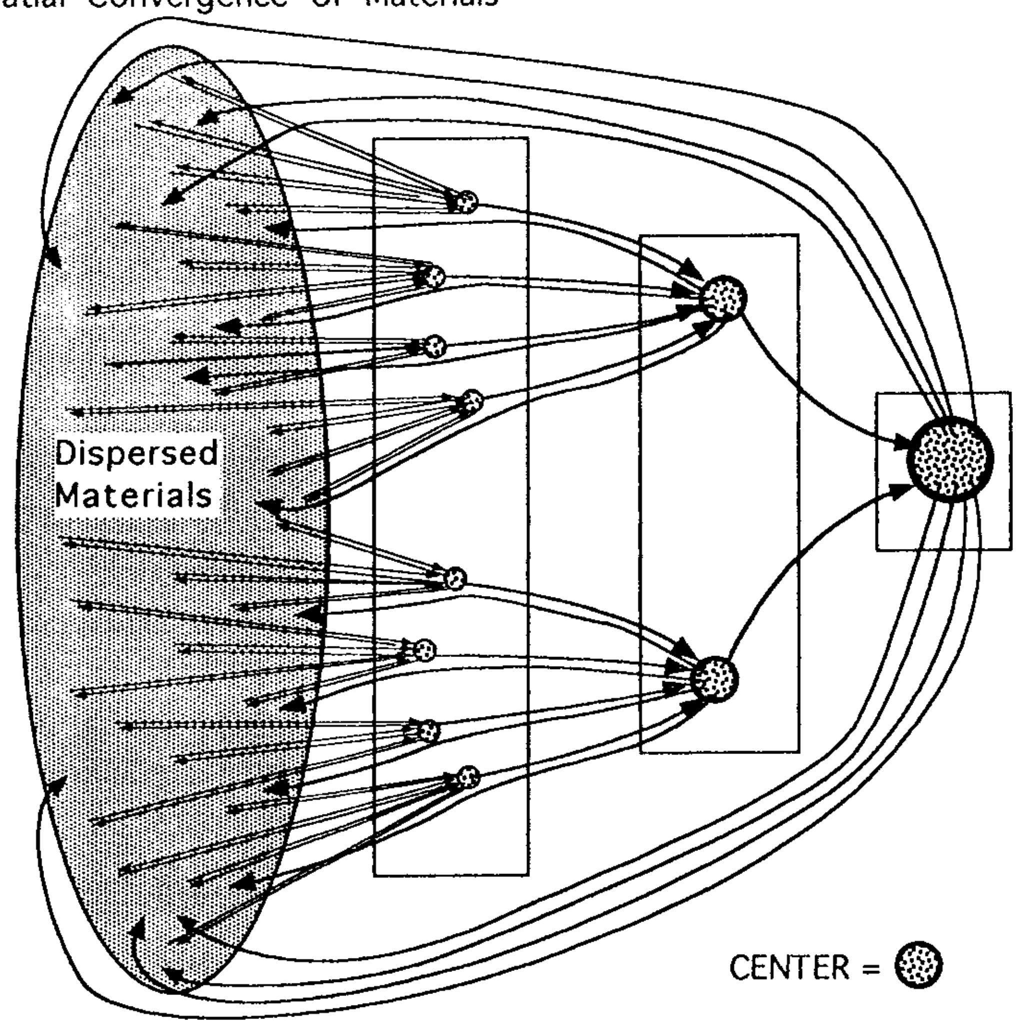


Figure 4. The spatial convergence and divergence in the concentrating of materials. (a) Energy systems diagram of energy and materials; (b) spatial pattern of material flows toward centers.

centers. Figure 4b illustrates some of the pathways of convergence and divergence as materials are processed to higher concentration in the centers and dispersed as lower concentration in the peripheral areas.

Inverse Relation of Material Flux and Emergy per Mass

Self organization gets additional performance by concentrating materials in ways in which the concentrations reinforce. However, the greater the concentration the more emergy is required per unit weight and the less material can be upgraded. In Figure 5, for a systems with constant empower, the quantity of material which can be processed in successive steps to a high emergy level is inverse to the emergy per mass. Thus, high concentrations are scarce because of the nature of the energy hierarchy and its coupling to materials.

In Figure 4 there is one source of energy and emergy. In order for the centers to have an increase in ability to feed back and reinforce, energy and materials have to be more concentrated in centers in each step. Figure 5 shows that concentrating materials with the same empower leads to less materials being transformed to higher level. Thus, some of the materials are recycled at each stage. The materials recycled are less concentrated and lower in transformity.

Coupling of Materials with Different Zones of the Energy Hierarchy

Materials of different kinds are found coupled with different levels of the energy hierarchy spectrum (Figure 5). Theoretically, more system performance results and a material contributes more when it interacts with energy that it can mutually amplify. By that concept, designs for material flows develop where energy flows interact with flows of somewhat higher or lower transformity. The kind of hierarchical pattern of material processing shown in Figures 3 and 4 may be at very different ranges of the energy hierarchy spectrum for different materials. Many heavy metals, for example, tend to go to the top of the biological range.

Figure 6 shows the way each material has its cycle and hierarchical skewed distribution occupying a zone in the universal scale of energy transformity. We sometimes call this plot an energy transformation spectrum.

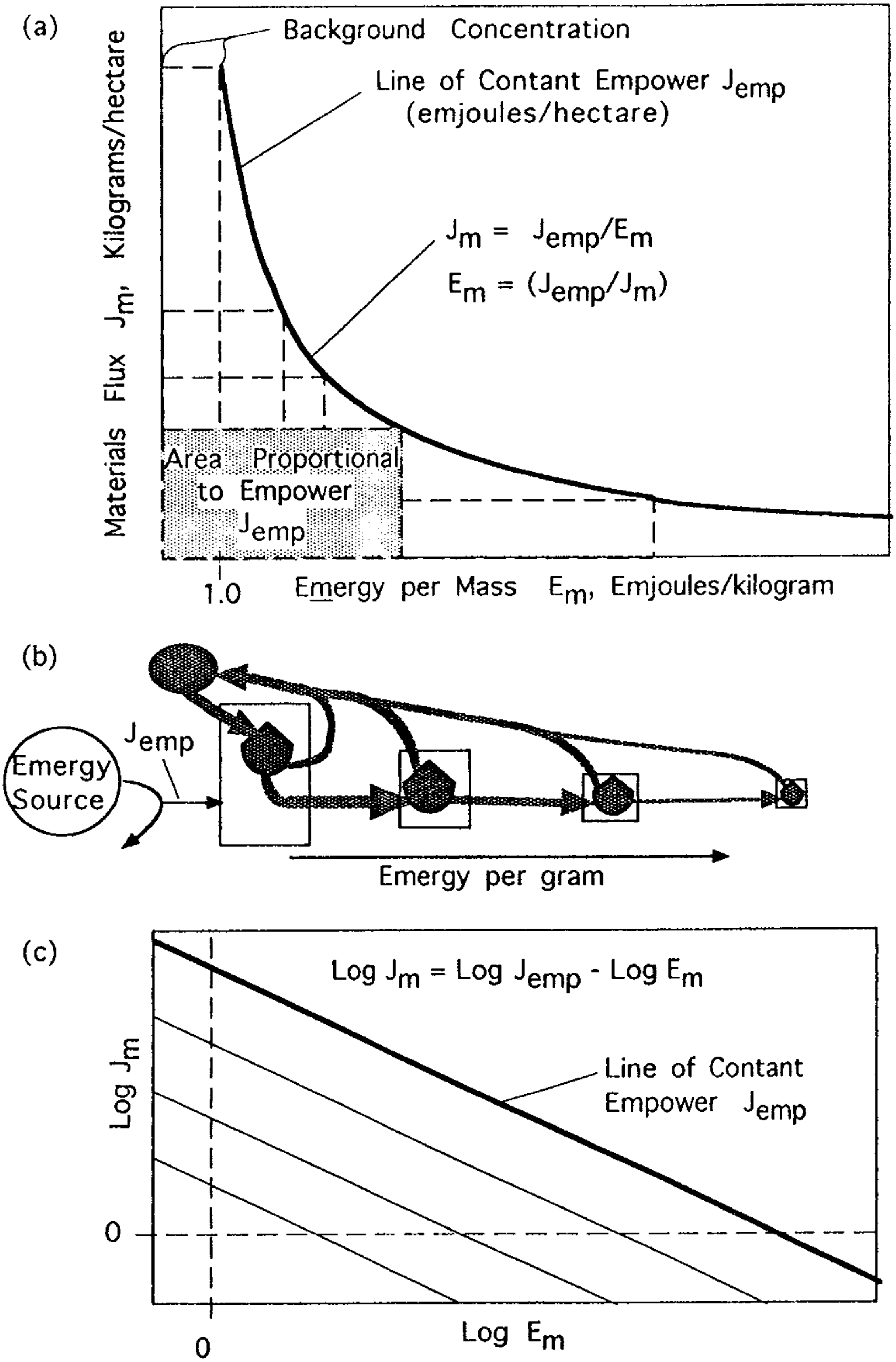


Figure 5. Flux of material which can be concentrated by successive energy transformations where empower is constant. (a) Inverse relation of material flux and emergy per mass; (b) energy system diagram with one emergy source; (c) relationships on double logarithmic plot.

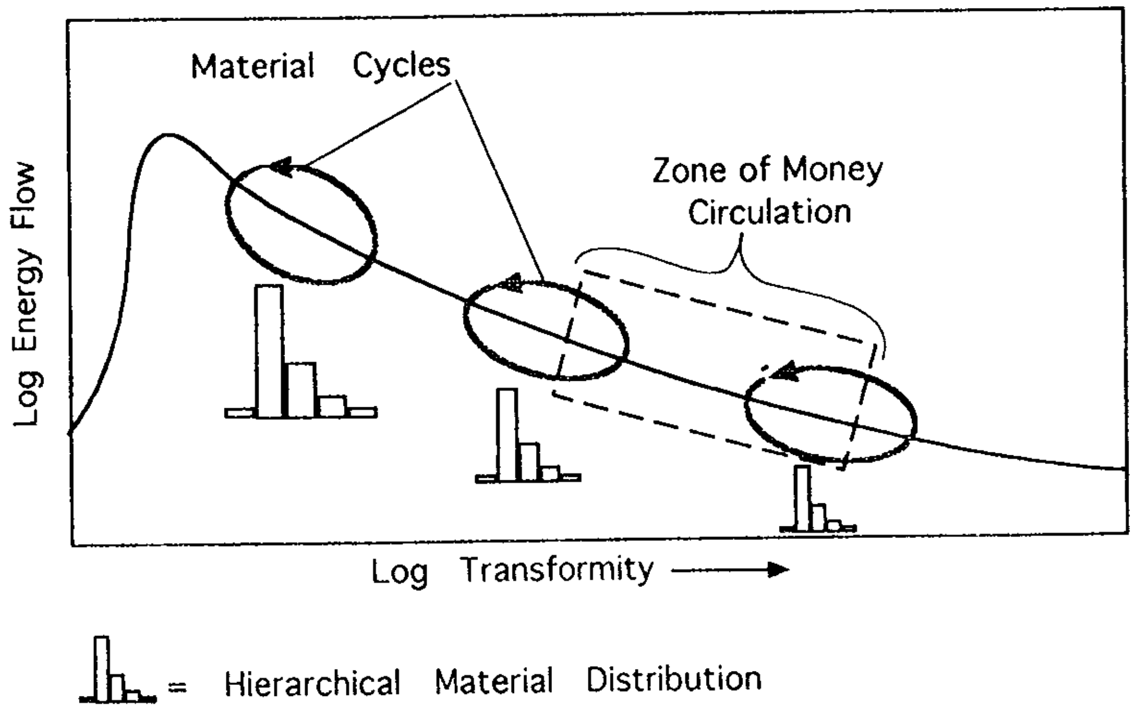


Figure 6. Energy hierarchy spectrum showing the zones of productive interaction for different material cycles in different transformity ranges.

Kinds of Materials and Their Emergy per Mass

The mass emergy (emergy per mass) indicates the energy role of materials. Like transformity, emergy per mass can be used for the horizontal axis of graphs and diagrams. For example, Figure 7 has the mass emergy values for many materials over many orders of magnitude as calculated in Appendix Table A1. The diagram suggests the natural range of the energy hierarchy in which each kind of material tends to be bound and contribute to the system operation.

The more abundant a material is in the geobiosphere, the higher the concentrations of that material in the levels of the energy hierarchy (Laskey, 1950). In general, it takes more emergy to concentrate materials that are initially scarce in the geobiosphere. In Figure 7, air and freshwater are on the left with low values, whereas scarce items like gold when concentrated are on the right with high emergy value.

A Sixth Energy Law for Materials

Classical thermodynamics (science of energy considered near equilibrium) has three generally accepted laws: 1-energy is conserved; 2-energy concentrations are spontaneously dispersed; and 3-the complexity of heat is zero at absolute zero (-273 degrees Celsius) when molecular motions cease. For open systems, Lotka (1922a,b) proposed the law stated in emergy terms as the maximum empower principle (see section 7 of this paper). I proposed a fifth law (Odum, 1996) recognizing the universal energy hierarchy--all energy transformations form a series marked by transformity.

In this chapter, to summarize the relationships relating material distributions to the energy hierarchy, I propose as a 6th energy law:

> Materials are coupled to the energy transformation hierarchy and circulate toward centers of hierarchical concentration, recycling to dispersed background concentrations.

3-Material Valuation

Because money only measures what is paid to humans for their work, market values do not measure the contribution of real wealth to the economy by the environment's work. To measure all of the real wealth contributed when materials are used, emergy and empower valuation is

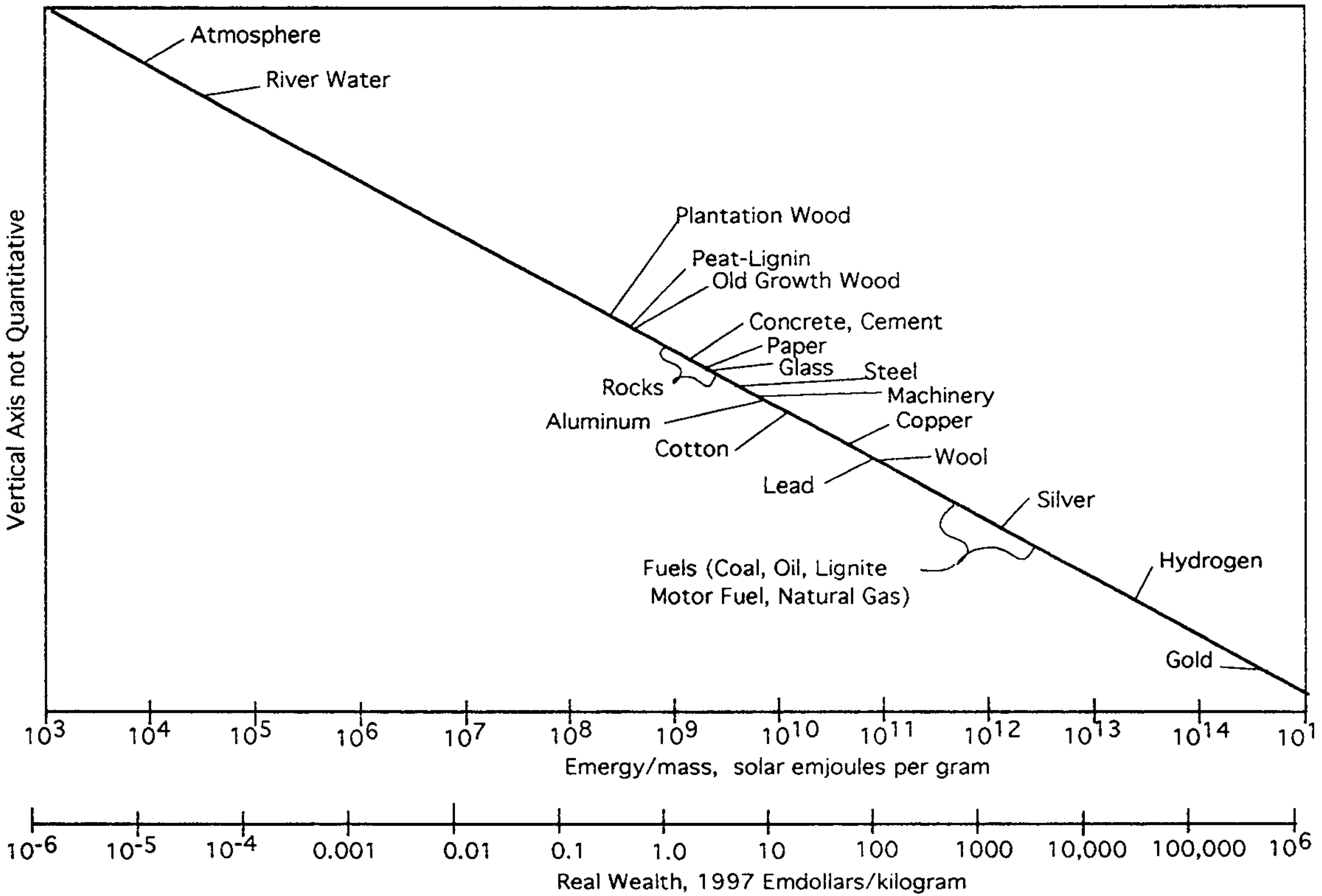


Figure 7. Mass emergy (emergy per mass) of various materials used in construction of civilization and nature. Included is a scale of equivalent emdollars per kilogram. See Appendix Table A1 for calculations.

necessary. These measures can be used to chose between alternative uses and processing of materials.

Emdollar Equivalent of Emergy

In order to relate emergy to economic values, a monetary equivalent of emergy is calculated called *emdollars*, the equivalent dollars of buying power. First an emergy/money ratio is calculated for the economy for the year. The total emergy used by the state or nation (annual emergy budget) is calculated by adding up the emergy of everything used. Then the annual emergy budget is divided by the gross economic product for that year. For example, for the United States in 1997 the average emergy/money ratio is 1.1 trillion emjoules per dollar. To express emergy values of materials or anything else in emdollars, divide by the emergy/money ratio.

Value of Material Concentrations

As we already explained in Section 2, the higher the concentration of materials, the more emergy it contains. The higher the concentration, the more emergy and emdollars are contributed to construction when materials are used that have already been concentrated. The emergy per mass values plotted in Figure 7 are those for typical concentrations ready for use.

Because emdollar values include both the services of nature and those of humans, they are usually higher than market values. Whereas humans and businesses have to use market values to keep their businesses economical, policies for the larger scale public benefit and its environment should use emdollars. Otherwise monetary decisions will benefit a part of the system while ignoring losses to the whole system.

As documented in geochemical texts, the materials of the earth are found in tiny quantities throughout the earth's crust, oceans, and atmosphere. These low concentrations of materials are the "background concentrations." Since they are the lowest concentrations on earth, they cannot diffuse to any lower concentration. Relative to their environment they have no available energy storage and their emergy value is zero. Figures 2 and 4 showed the coupling of energy to materials starting with processes concentrating materials from the background.

Emergy and Economic Geology of Ores

The skewed patterns of useful materials developed by geologic cycles have been related to market values and energy for mining and processing, one of the principles of economic geology. Curves of the quantity of ores as a function of concentration are used to estimate which reserves are commercial. Page and Creasey (1975) published curves on the amount of rock and fuels required to produce refined metal from ores of different metal concentration (Figure 8). The emergy in the rocks, the emergy in the necessary fuels from these graphs, and emergy from human service were added to calculate the total emergy to refine a gram of metal in Figure 8c. The rocks with lowest concentration of metal were given the emergy per mass of the average earth cycle (1 E9 sej/g) that is carrying low concentrations. Emergy in goods and services were calculated from 1975 costs given by the authors (70% for services and 30% for fuels) multiplied by emergy/money values for that year (7.6 E12 sej/$ from Appendix D in Odum, 1996). Figures 8c and 8a have similar shapes. More resources (emergy) are required to concentrate low concentration ores than those that were already more concentrated by the geologic work.

Back calculations were made with the relationship in Figure 8c so as to plot emergy stored by geological process as a function of concentration of metal. Emergy/mass from geological work for each concentration of metal in rock equals the total emergy/mass to concentrate metal from background rock minus the emergy of human services and fuels used. The total emergy per mass of fuels and services to concentrate metal from rock with background concentration (without metal-specific geologic work) is 19.9. E9 sej/g in Figure 8c.

For example, for ore with a copper concentration of 1.6% in Figure 8c:
Emergy/mass = (19.9 E9 sej/g) - (2.1 E9 sej/g + 1.72 E9 sej/g)
= 16.1 E9 sej/g

The results of these calculations generate a graph of emergy per gram for concentrations of metal in ores in Figure 9a, which also shows the very low concentrations of copper as a dispersed element in the ocean and the earth's crust. These are given a small emergy per mass value in proportion to their fraction of the earth cycle. The lowest concentrations are in the sea, without available energy relative to environment and thus no emergy. Equivalent 1999 emdollar values of these ores are also shown with the second scale for the vertical axis on the right.

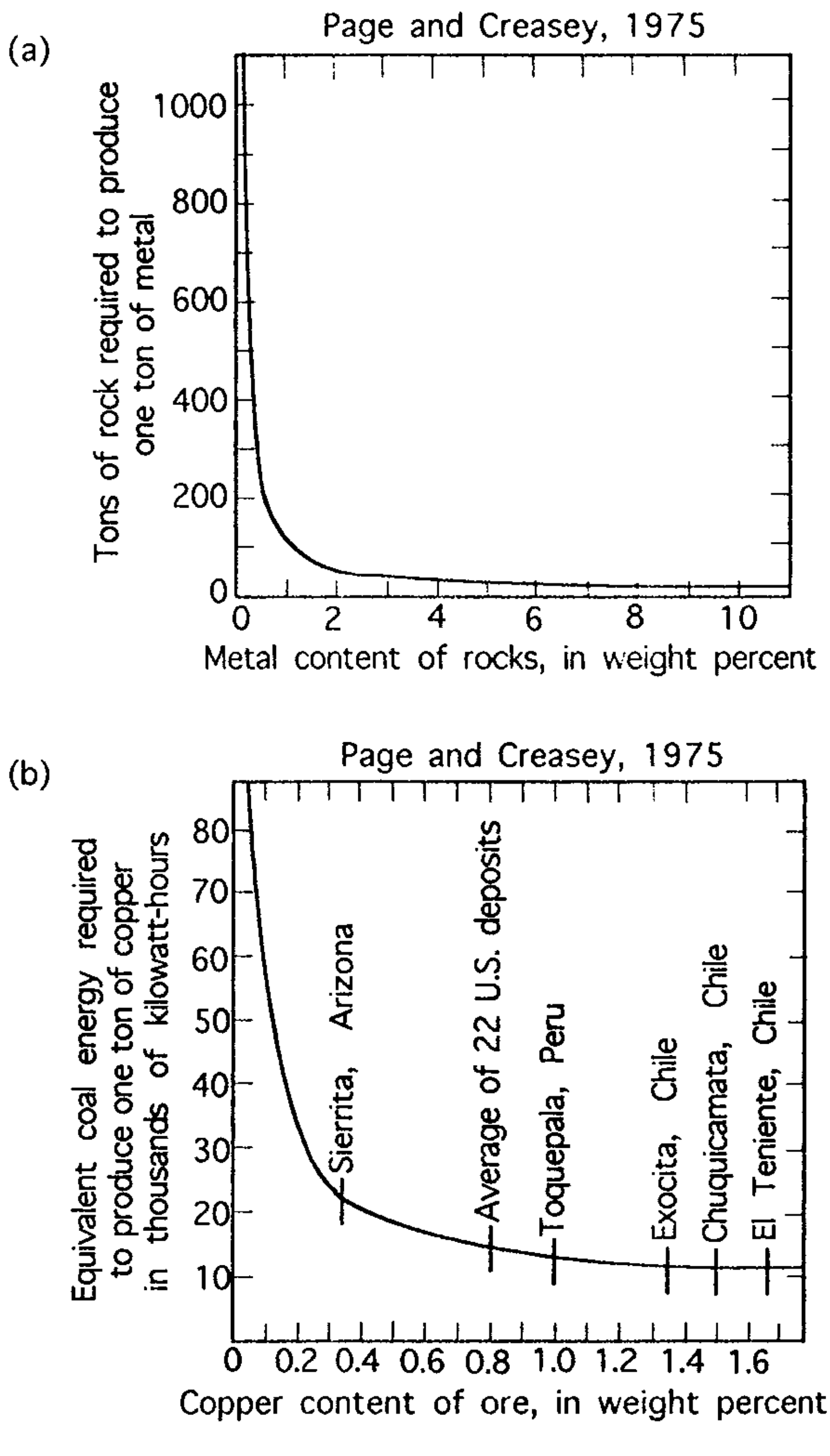


Figure 8. Quantity of resources required to make concentrated metal, modified from Page and Creasey (1975). (a) Rock required; (b) fuels required; (c) emergy required to concentrate metal ores derived from (b).

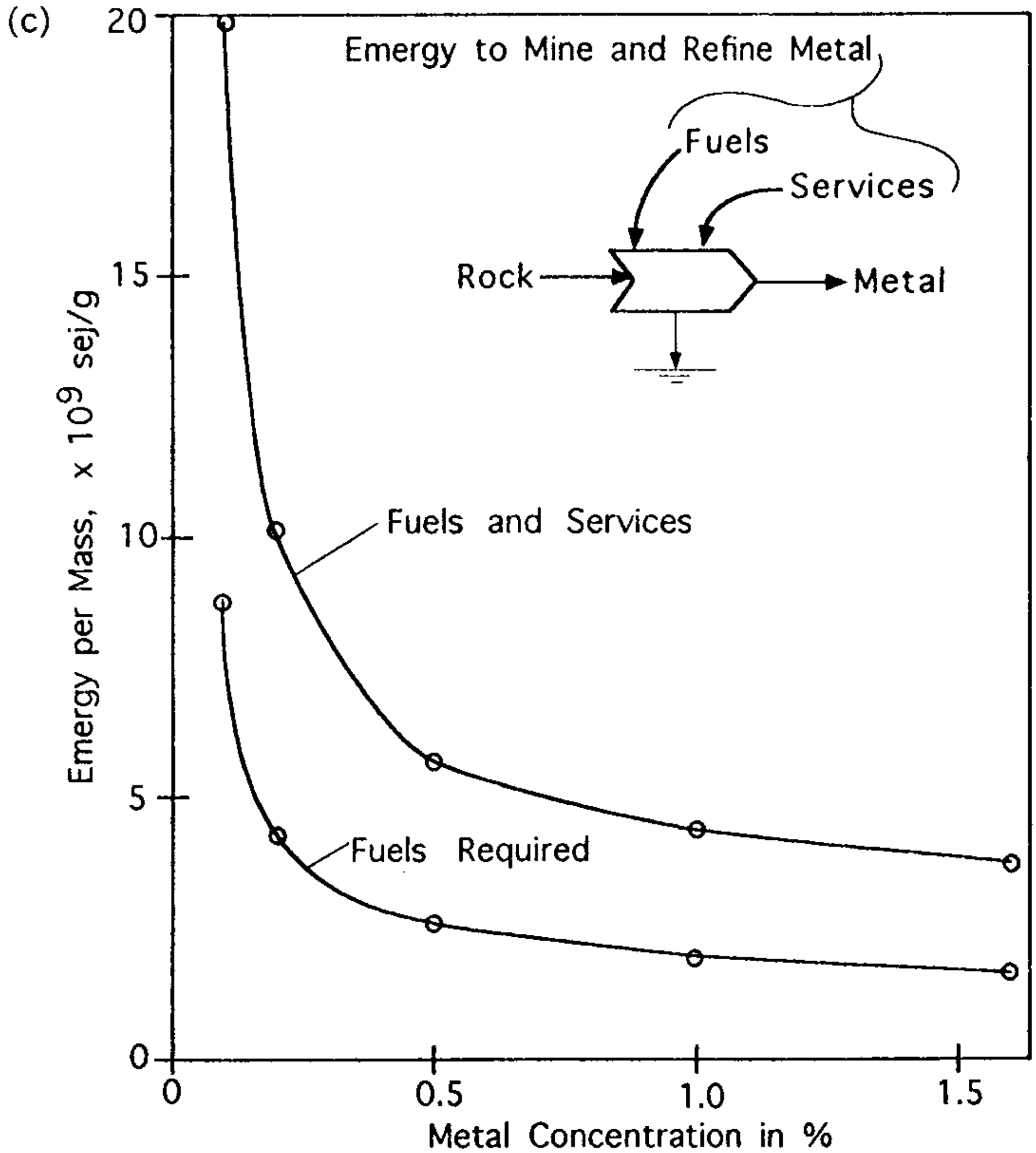
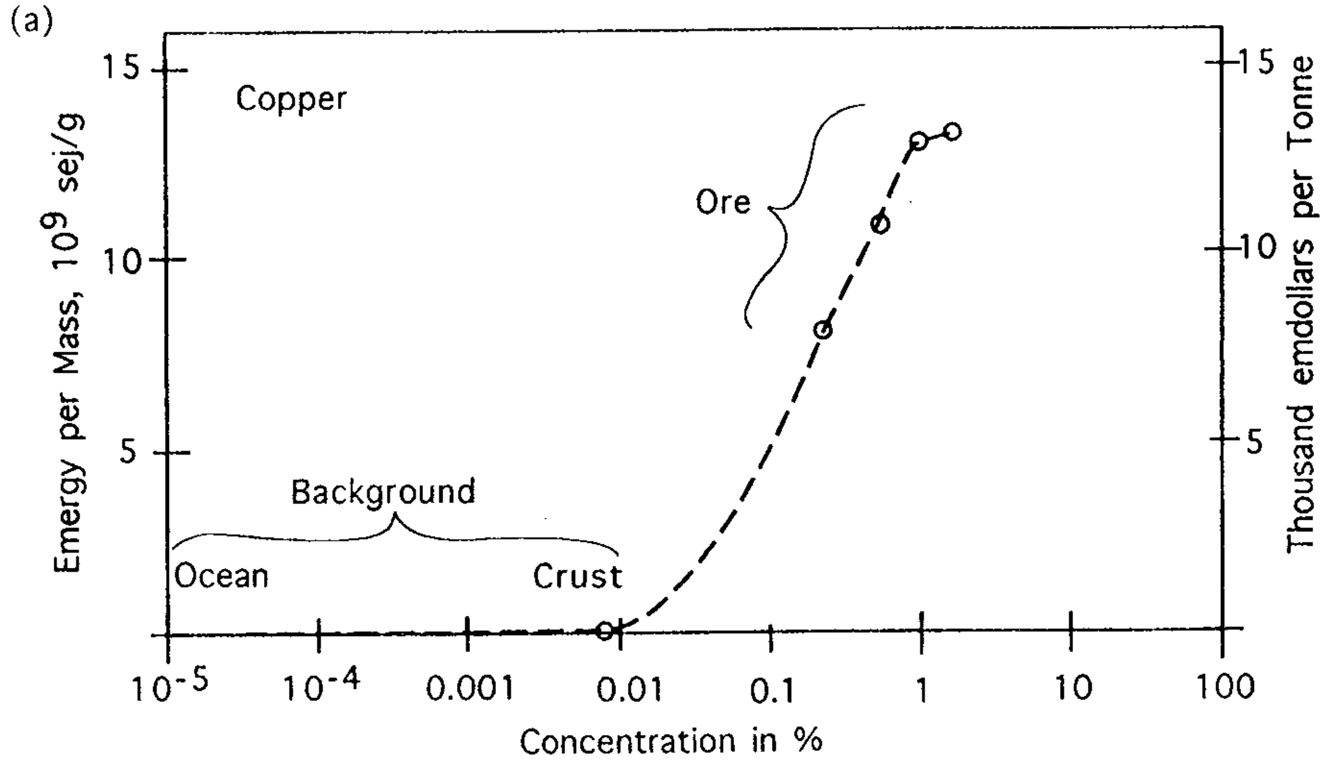


Figure 8 (continued)



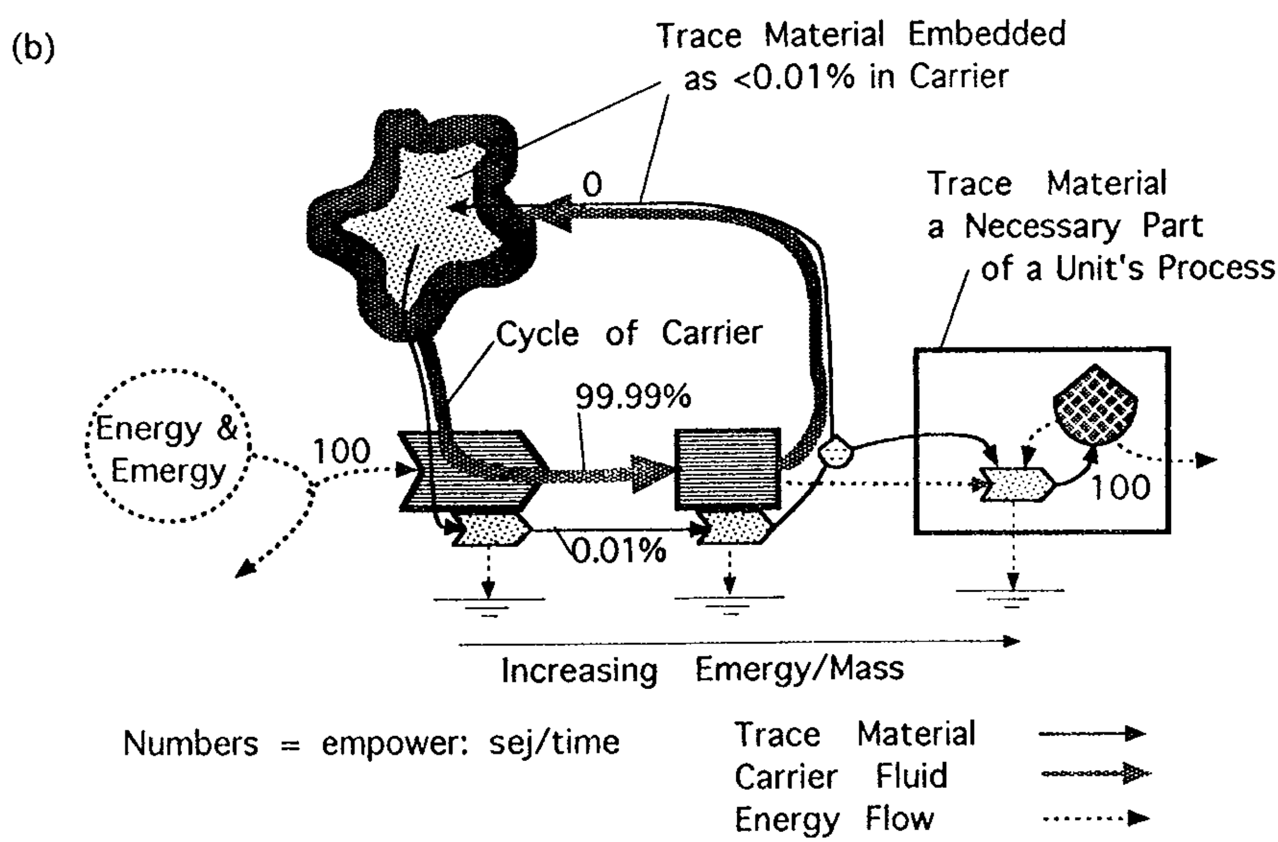


Figure 9. Emergy per mass of dilute and concentrated materials. (a) Emergy per mass and metal concentration calculated from Figure 9c; (b) energy systems diagram showing passive carrier and active production zones of material participation.

Critical Concentration for Material Contribution to Production

As Figure 9a suggests, there are two zones in the distribution of elements in the geobiosphere. On the left, very dilute materials are carried along with flows of air, water, and earth cycles in proportion to their fraction of these circulating masses with that fraction of the empower. At a higher concentration, the materials participate in autocatalytic productive processes in which use of their special characteristics is a necessary part. The relationship of energy and emergy to the material cycles is diagrammed in Figure 9b. On the left, materials are a small fraction of the carrying mass. But on the right the material is used to generate special products incorporating the emergy of the available energy used for the unit. The products carry the whole empower of the process with much higher emergy per mass. The critical concentration where autocatalytic process is using the material for its specific characteristics is analogous to the critical concentration of energy when flow switches from laminar to turbulence.

Figure 9b may help explain the break between materials that are not commercial and those of higher concentration that are economical, a property of ores noted by DeYoung and Singer (1961). Materials are commercial that are at higher concentration than the critical point in each cycle where the material is used for its special properties and the processes store substantial emergy.

Emergy-Concentration Graphs

To facilitate emergy-emdollar evaluations, graphs of emergy-emdollar value versus concentration like Figure 9a need to be constructed for common materials and building components. See Figure 10, for another example, the graph for emergy and concentration for lead (Odum, 1999).

Principles of Biogeoeconomics of Materials

Money circulates in that zone of the universal energy hierarchy where humans operate. Notice dashed line representing money circulation in the energy transformation spectrum in Figure 6. Carolyn Boggess (1994), studying the circulation of phosphorus in a Florida watershed, showed how the transformity zone of money circulation and market prices overlapped only the higher transformities of the circulation of phosphorus. Finding the range of transformities where a material cycle overlaps identifies the transformity range where material cycles are economical. For cycles at lower transformities, either economic subsidies or the work of ecosystems

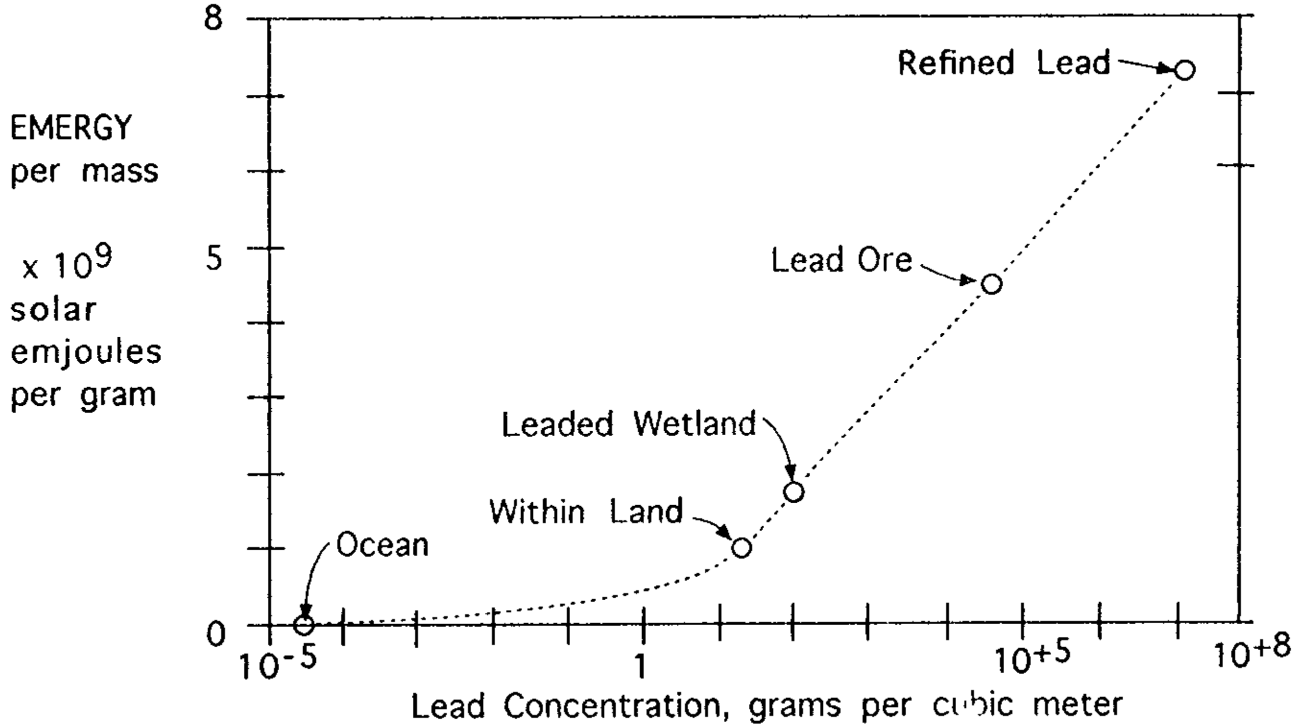


Figure 10. Emergy per mass as a function of lead concentration (Odum, 1999).

is required. For very high transformity materials such as gold, the economic market values are also high, but they undervalue the real wealth and thus can cause inappropriate uses.

Transformity and Toxicity

Genoni and Montague (1995) and Genoni (1997, 1998) showed the increasing toxicity and impact of materials with increased transformities. For materials like cocaine, with very high transformities and large impact, efforts to control the materials can cause black market monetary values to be greater than open market values. Perhaps, some very high transformity materials such as some found in chemistry laboratories may be outside the range of the human economy on the upper side.

Total Material Accounting

The Wuppertal Institute in Germany developed an interesting way of overviewing national economies by adding all material flows together on a weight basis including fuels. The overview analysis is not primarily concerned with budgeting the cycles of each kind of material. The flow values in Figure 11a are an example of the material budget assembled for West Germany (Adriaanse et al., 1977; Bringezu, 1997). The concentration of material flow is an index of environmental impact. Disturbances of the environmental materials, as in mining, are included as "hidden flows," a major part of each nation's annual total. The hidden flows in other countries supplying imports are regarded as a backpack ("rucksack") of embodied material responsibility, a materials footprint.

The material link to the economy was studied with material/money ratios. These have decreased in developed countries, interpreted as a decoupling of matter and money. Wernick et al. at this workshop (1999) also used ratios of material use (paper) to economic product to imply dematerialization. However, it is not that materials were used less, but that there was much accelerated circulation of money and money supply associated with increased urbanization and concentration of fiscal affairs.

Total material accounting aggregates materials with a range of real wealth values more than ten orders of magnitude (emergy/mass range in Figure 7). Material per unit energy was calculated by Hinterberger and Stiller (1998) to represent the coupling with energy, although energies of different transformities were considered the same. Other than fuels, the embodied energy in the materials and environment were not included.

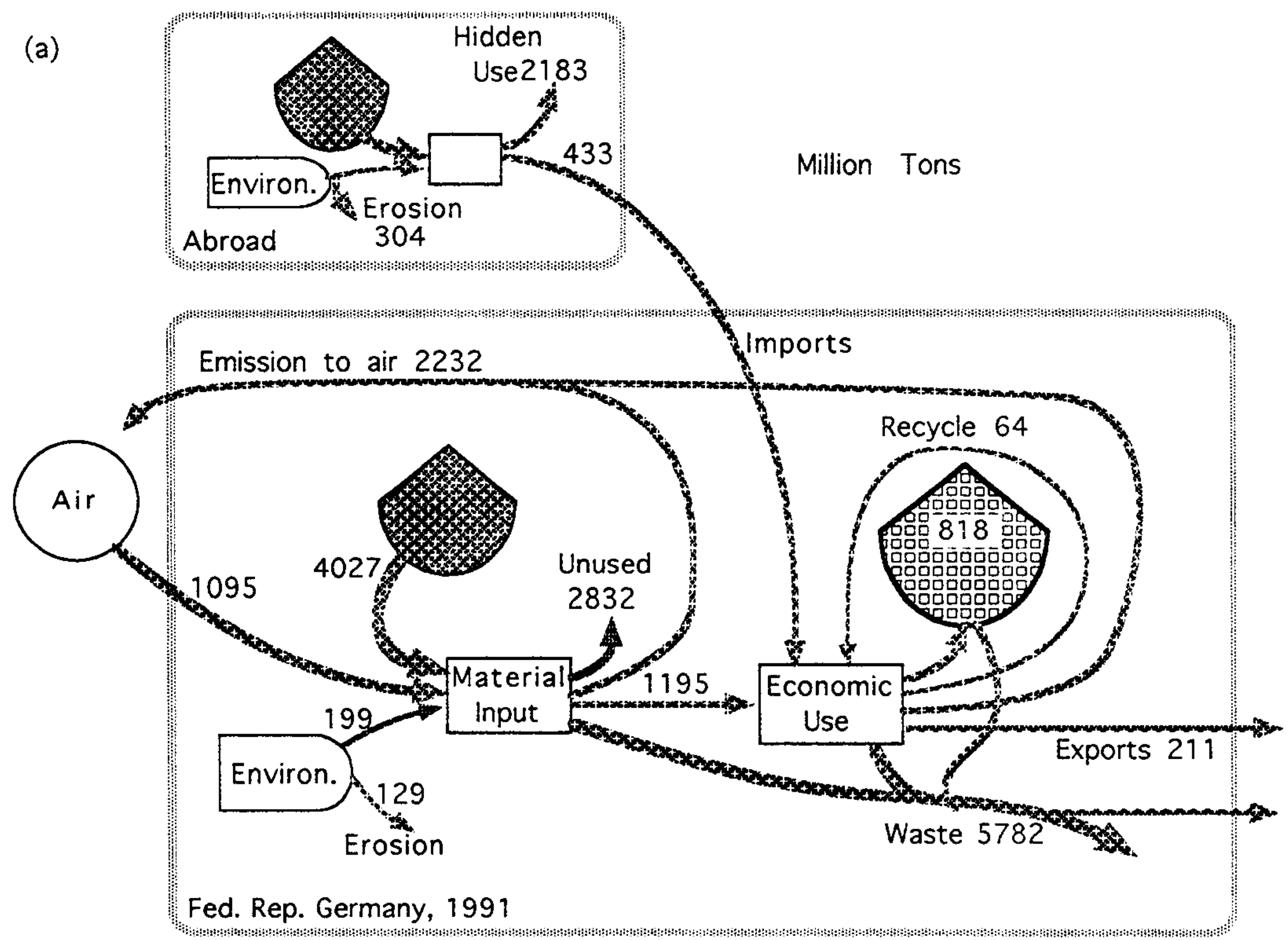
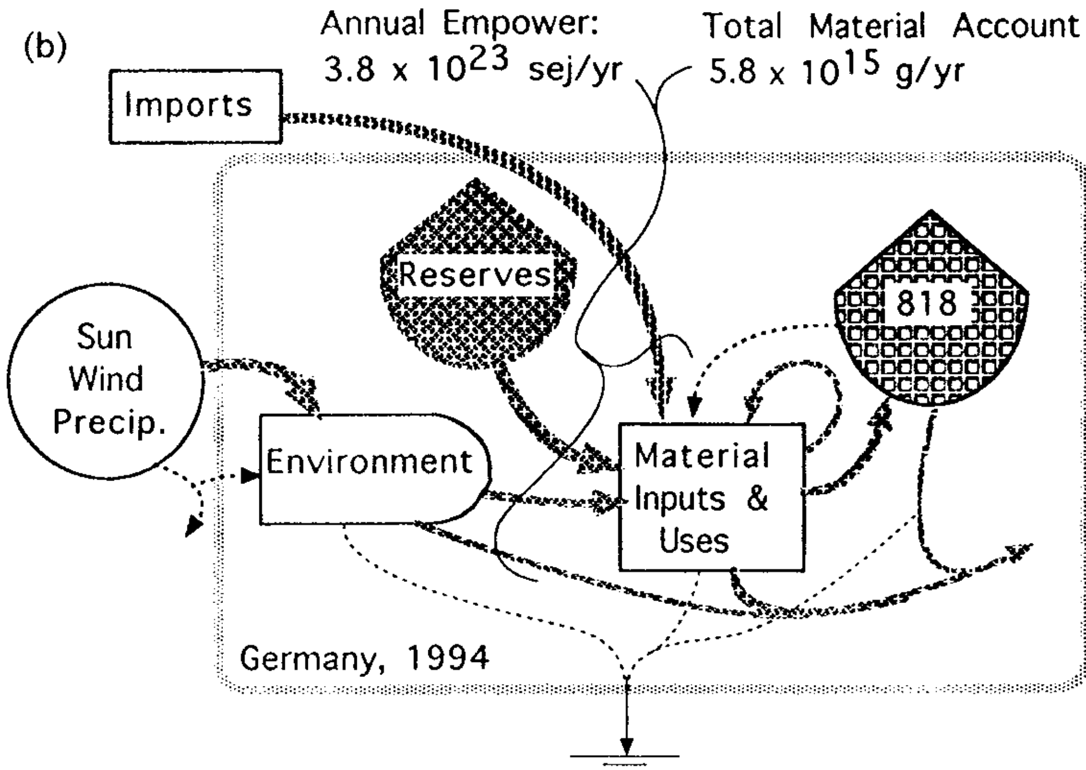


Figure 11. Aggregate material accounting of Germany from Wuppertal Institute (Adriaanse et al., 1997). (a) System diagram of the material flows given by S. Bringezu and H. Schutz; (b) overview of material account of Germany with energy sources and emergy evaluation added.

(b)



Emergy per Mass: $\frac{3.8 \times 10^{23} \text{ sej/yr}}{5.8 \times 10^{15} \text{ g/yr}} = 6.7 \times 10^{7}$ sej/g

Figure 11 (continued)

To relate the total material accounts to concepts in this paper, emergy was calculated for the total material account for Germany redrawn in energy systems form in Figure 11b. The fuel uses and imports to Germany in 1994 from Adriaanse et al. (1997) were each multiplied by their transformities and added to main flows of environmental empower from Bosch (1983). This total national empower was divided by the total material account to get a national emergy per mass index (6.7×10^7 sej/g). The value is intermediate between that for fluids (air and water) and that for solids of earth and buildings (Figure 7).

4-Metabolism and the Structural Unit

Each unit that develops in systems has similar patterns and processes in the way it utilizes materials and energy. The processing of materials and energy is called *metabolism* , and either the rate of energy processing or material processing can be used to represent the metabolism quantitatively. In Figure 12 the essence of a unit of system structure and its processes is enlarged to show the details of inputs to produce structure and the processes that decompose the structure and release the materials.

Figure 12a shows the series of structural units of an energy chain and its energy hierarchy. The first structural unit is enlarged to show the component flows and storages of metabolic structure and process (Figure 12b). The figure shows inflowing materials being incorporated in constructive production, returning to the pool of environmental materials, some by depreciation, some by parts replacement, some dispersed by the work the unit does for the outside, and some by removal and consumptive destruction arranged by the next level in the energy hierarchy. These processes are explained with Figure 12b as follows:

Construction (Production)

The incorporation of materials into a new product with the help of an energy source is called *production*. Construction of a tree or a building are examples. Note the pointed block symbol used to show the production process in Figure 12b. The rate of production is proportional to the local availability of the ingredients, and sometimes the shortage of a material or energy (limiting factor) slows down the process. Production also uses already-built structure to organize and control the addition or reuse of parts for growth and differentiation. For example, construction of initial foundations and frameworks in buildings guides the later finishing processes. As represented in Figure 12b the structure feeds back actions to implement the production process. Such feedbacks are called autocatalytic.

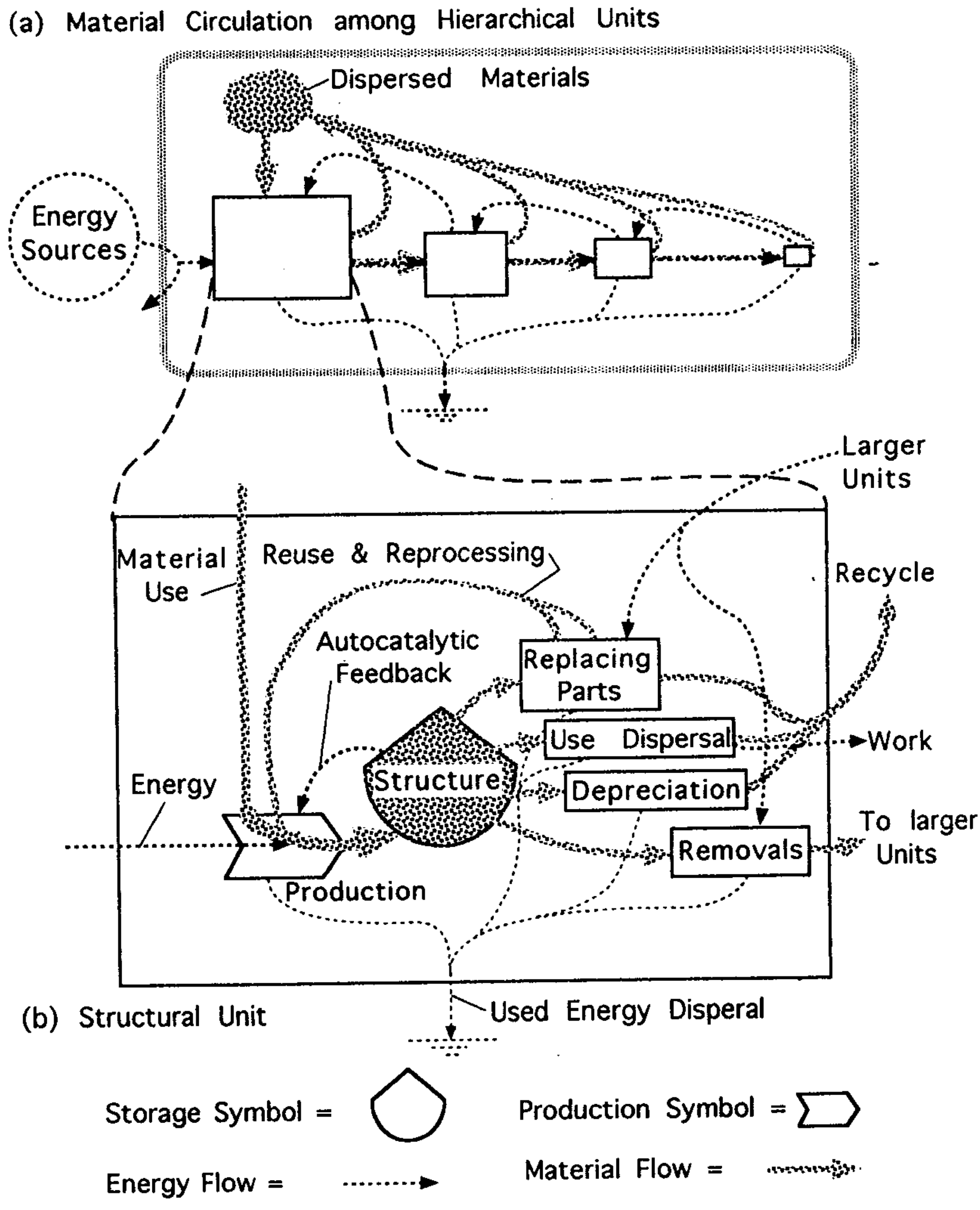


Figure 12. Pathways and metabolism of a typical structural units like those found on many scales. (a) Material circulation coupled to an energy hierarchy; (b) details of the pathways and storage of metabolism of one structural unit.

Depreciation and Material Release

A storage of materials that is more concentrated than the environment spontaneously disperses. Molecules of matter disperse due to their heat. Heat is the molecular motion present in everything, depending on the temperature. In other words, everything tends to diffuse apart (a property described by the second energy law). Sometimes matter is dispersed by reacting with other substances. The spontaneous loss of structure is called *depreciation*. Depreciation releases materials that had been previously bound into structure. Figure 12b shows the release of materials from depreciating structures being recycled outside of the unit.

Replacing Parts and Wholes

As structure depreciates, a part may become non-functional and have to be replaced. Replacing parts of something larger to keep it operating is called *maintenance*. Eventually, the larger parts of the structure become non-functional and also have to be removed and replaced. Replacing a whole unit is really maintenance at the next larger scale, where the unit being replaced is a part. As soon as a main structure is removed, function is interrupted until the replacement structure is reconstructed.

Material Dispersal from Use of Structures in Work

Any unit is part of a larger system to which it makes a contribution in product or service. The process of doing that work causes loses of structure and dispersal of materials also shown in Figure 12b. The total losses of structure is a sum of that which occurs without use plus the additional losses due to use of the structure in performing work for the surrounding system. The useful work carries emergy to the next system.

Destruction and Recycle

Depreciation by small scale processes such as diffusion and erosion is too slow to return large units into the material cycle. Systems develop a destruction process that uses energy and work from larger scales to disperse the structure while utilizing some of the stored energy. In ecosystems animals, microorganisms, and fire often supply this function. The equivalent operations in cities are the specialized business operations for removal and redistribution of parts, materials, and waste dispersal.

5-Life Cycle Minimodel

One way of seeing the similarities and differences among systems, is to make overview models, using systems languages that are more rigorous than using words that usually have many meanings. The energy systems language is used along with the equations for simulation which the diagrams define. Computer simulation of models is useful for finding the consequence of the structures and processes that have been included in a model. Simulation models are studied here to suggest answers to questions about structure and materials:

In ecosystems, all the processes of depreciation, maintenance, decomposition, destruction, are sometimes aggregated as the process of consumption represented with one block in Figure 13. In biological systems the materials released by all these processes collectively are sometimes called respiration. For overview purposes, a simple model of structure is a balance of production and consumption with materials recycling through the processes and structure (Figure 13a). This is a modification of the production-respiration procedure introduced for overall metabolism of ecosystems by the author in 1956. In ecosystems, respiration is the internal consumption that includes depreciation, maintenance, and work delivered to the outside of the unit.

Balance of Construction and Consumption

Let's use P for construction (production) and letter C for consumption, with both measured in the same units of materials processed. A system on the average may have a balance where P = C, and the P/C ratio is one. For example, a forest on the average may have its rate of carbon processing in production nearly equal to its rate of carbon recycle in all the consumption processes. A forest village on the average could have a balance between the organic matter drawn into the construction of shelters and village center and the return of disorganized organic parts and wastes back to the forest.

Equations for a Construction Minimodel RESTRUCT.bas

Diagramming a model with energy systems symbols and constraints generates a mathematical model that can be computer simulated. Figure 13b has the equations that express the behavior of the simplified overview model as drawn in Figure 13a. The equations are incorporated in a BASIC language simulation program RESTRUCT.bas (listed in Appendix Table A2).

Overview Simulation

After assigning values based on growth of short-lived trees to calibrate the model, simulations were run like that in Figure 13c. In a typical run the unit grows using outside energy to incorporate materials and develop structure. As structure develops it has autocatalytic action to facilitate further growth. The switching control in the model stops the growth when it reaches an upper threshold, after which the unit gradually loses structure due to the various processes of depreciation and consumption. Since loss of structure means loss of function, the switching action rebuilds the storage again when the storage reaches a lower threshold. At no point is the system in steady state, but if it is considered over a long period of time a repeating pattern is seen (Figure 13c), and average conditions may be calculated.

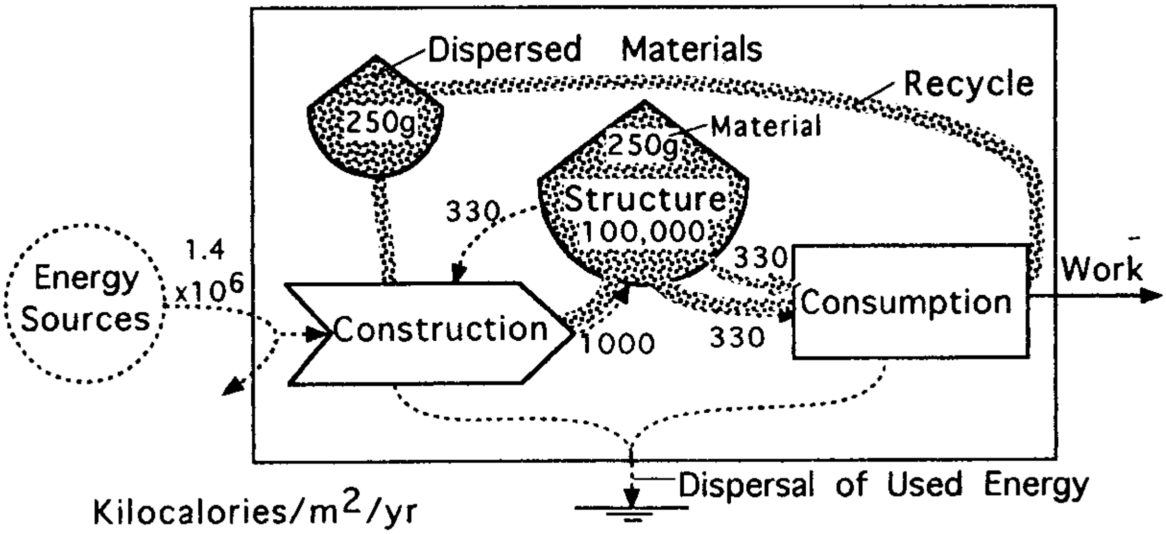
The model represents the growth of a short-lived tree, or the construction of a village dwelling from forest wood. The version shown here was calibrated for tree structure with values in Figure 13, but the results are similar when values are substituted for a village dwelling, but with more biomass and longer turnover time.

Emergy of Construction and Storage

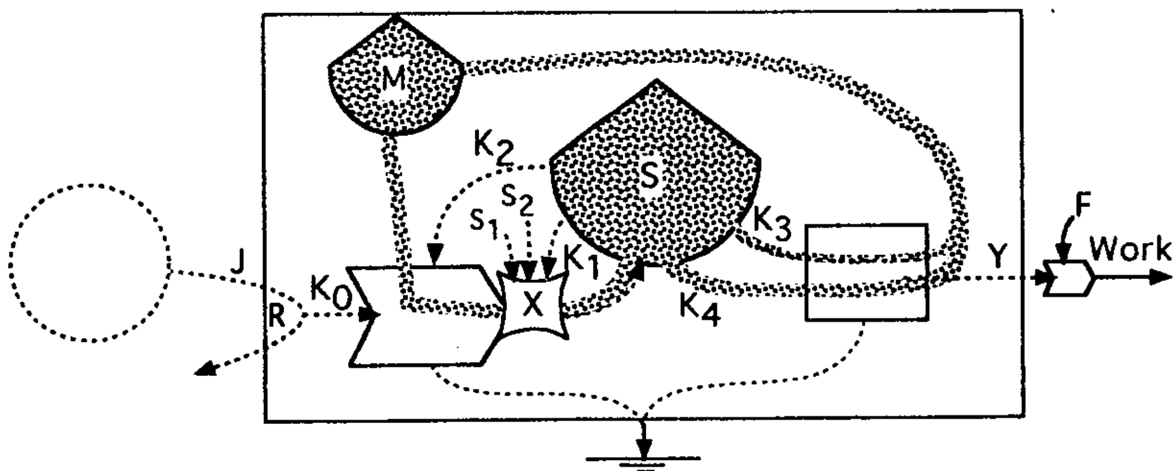
According to the definitions of emergy as all of what is required to make something, the emergy of construction is a sum of the inputs to the construction so long as construction is in action. Inputs of energy and materials are multiplied by emergy/unit to evaluate emergy inflows (the empower of gross production). Part of the emergy produced is used by the larger system in which the structure functions (assumed as a third of the input). The rest is dispersed in depreciation and the necessary maintenance replacement of parts (feedback work). The model in Figure 13 builds structure in bursts, the way humans build houses. It provides a disaggregated way of looking at ecosystems as the process of building and replacing organismic structures such as trees.

Emergy relationships are included in the minimodel RESTRUCT.bas in lines 300-350. For the storage in structure, emergy decreases if the stored structure loses part, either by depreciation, by supporting maintenance, or by removal to another system (Figure 12). The transformity of the structure is the emergy stored divided by the energy stored. The emdollars of real value stored in the structure is the emergy stored divided by the emergy per money for the designated year. The

(a) Construction-Consumption Minimodel



(b) Equations for Simulation



Unused Energy Inflow: $R = J - X*K_0*R*M*S$

and therefore: $R = J/(1 + X*K_0*M*S)$

If Total Material T_m is Constant and fr is the fraction in S:

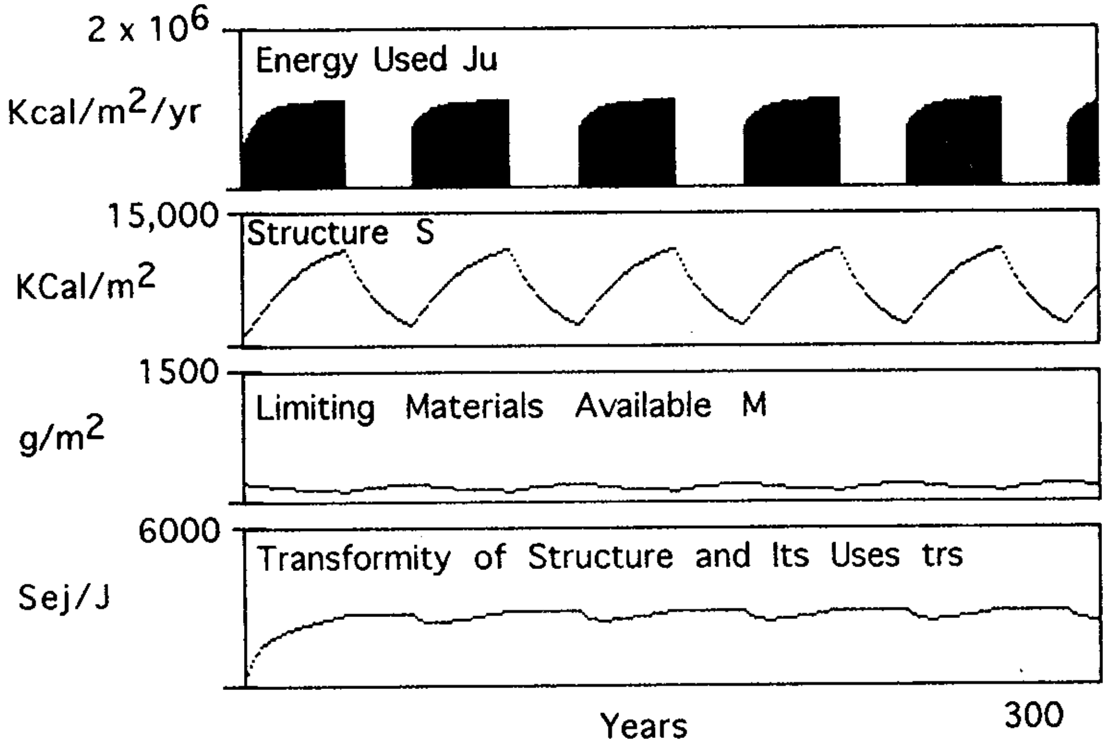
$$M = T_m - f_r * S$$

Rate of Change of Storage S is Inflow minus Outflow:

$$dS/dt = X*K_1*R*M*S - X*K_2*R*M*S - K_3*S - K_4*F*S$$

Switching Action X: If $S < S_1$ THEN $X = 1$; IF $S > S_2$ THEN $X = 0$

Figure 13. Simplified overview model of construction (production) and consumption. (a) Systems diagram including energy and materials; (b) equations derived from the diagram; (c) typical simulation of the pulses of construction, depreciation, and replacement.



(c)

Figure 13 (continued)

transformity of the structural storage is plotted on the lower panel of Figure 13c.

One term in the equation represents the use of the structure by the next larger system. The services or products (yield Y) carry the transformity of the storage. Replacing and repairing frequently keeps a high level of structure and helps maximize performance at the scale of the model and the larger scale to which its output is directed.

Useful Destruction

The removal and forced recycle of materials of structure by an outside system is destruction from the point of view of the smaller unit. From the larger perspective the destruction is useful, contributing to overall empower production by preventing materials from become a limiting factor. The more frequent the withdrawals of structure by the larger scale, the less structure and stored emergy is maintained, but more empower is transferred to the next level. Areas that are frequently disturbed develop smaller units with faster turnover. The appropriate structure for maximizing performance depends on the climate of interruption

6-Structural Stages and Succession

The building of structure and replacing it in cycles was considered in Section 5, but there is more that happens when ecosystems and human settlements develop. There is a sequence of stages, each contributing for the time when its conditions are appropriate. In ecology, the sequence of stages is called *succession*, and stages in developments of human structures appear to be analogous. Availability of materials affects these stages and the diversity of units that develop.

Excess Resource Specialist and Low Diversity

Especially when there is an initial excess of available resources of energy and/or materials, initial production (construction) is rapid with flimsy and short-lived structures. In ecosystems, weedy growth specialists prevail at first because they can maximize growth and function early. Because they grow rapidly, they overgrow other kinds of development, and the result is a low diversity. Human settlements that develop first in colonizing an area with large material reserves are analogous. Examples are new colonies and mining towns. Diversity of occupations is small.

Excess resource specialists predominate the mining of rich earth reserves shown on the left side of Figure 14.

Efficient Recycle and High Diversity

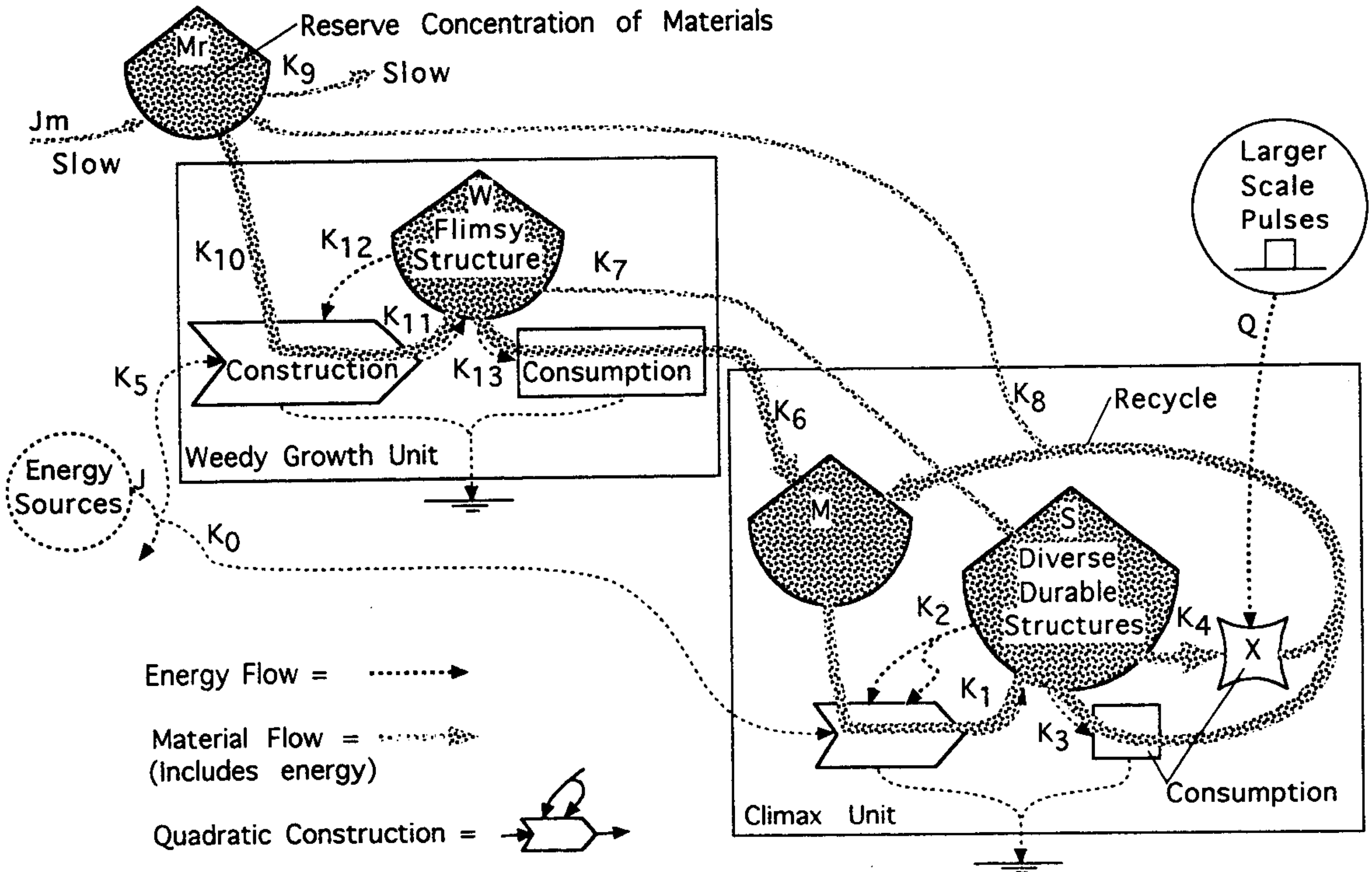
After the excess energy and materials have been incorporated into structures and storage, the weedy specialists are no longer adapted and are replaced by construction of longer-lasting units that are efficient in recycling the necessary materials for longer sustainability. Greater efficiency is achieved by a diversity of units. In ecosystems there is increase in biodiversity. In human settlements there is an increase in variety of occupations and accompanying diversity of structures. The colonizing of America by European immigrants developed growth specialists, the capitalist economy, with simple structures that were predominant in the last century. In this century there has been increasing efficiency and diversity of structures and functions. The processing of materials is shifting from the exploitive processing on the left In Figure 14 to the reuse-reprocessing-recycle pattern on the right.

Complexity of materials also increases. Keitt (1991) found emergy of rainforest diversity increasing with scale.

Simulation of Life Cycle and Succession

To better understand the interplay of growth and succession of buildings in the kind of scenario ahead, the construction-consumption minimodel from Figure 13 was expanded as Figure 14a (program MATBUILD.bas listed in Appendix Table A3. The equations that are inherent in the systems diagram are listed in Figure 14b. For the initial run it was calibrated for the building of woody structures using wood from forests. (Appendix Table A4 contains the numerical values used for calibration. Storages were normalized--expressed as 100 or 1000 at full development.)

Referring to Figure 14a, the reserve of materials Mr in the upper left corner is available for the exploitation of accelerated, nonrenewable use by the rapid growth specialists that prevail when there is a resource excess. Once the weedy structures W develop, these beginnings support more sustainable climax units S on the lower right that have less depreciation, longer turnover time, and more efficient reuse of materials. At longer intervals, the central units of the next larger system outside the systems diagram cause a destructive consumption and removal when they pulse.



(a) Model MATBUILD for Simulating Renewable Construction That Starts with a Reserve of Stored Materials

Figure 14. Simulation model of succession, climax, and restart MATBUILD that starts with a reserve of materials. (a) Energy systems diagram; (b) equations in the program; (c) typical simulation run.

(b) Equations for the model MATBUILD simulating material in building settlements that include reserves and units for weedy growth and climax.

Remainder of Unused Energy: $R = J - K_0*R*M*S*S - K_5*R*M_r*W$

And $R = J/(1 + K_0*M*S*S + K_5*M_r*W)$

Material Available in Climax Unit: $M = T_m - f_r*S$

Rate of Change Equations:

Reserve of Stored Materials Mr: $dM_r/dt = J_m + L_8*S - K_9*M_r - K_{10}*R*M_r*W$

Weedy Structure W: $dW/dt = K_{11}*R*M_r*W - K_{12}*R*M_r*W - K_7*W - K_{13}*W$

Climax S: $dS/dt = K_1*R*M*S*S + K_7*frw*W - K_2*R*M*S*S - X*K_4*Q - K_3*S$

Total Materials in Climax T_m: $dT_m/dt = frw*K_6*W + frw*K_7*W - K_8*fr*S$

Figure 14 (continued)

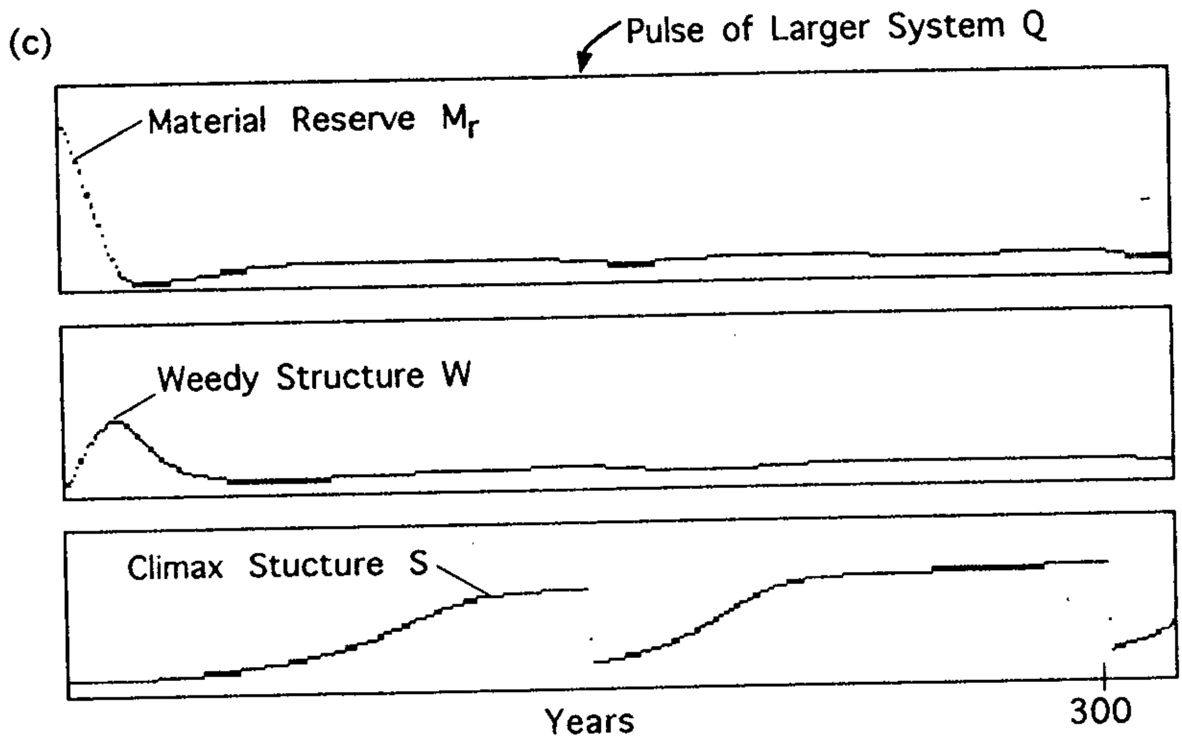


Figure 14 (continued)

Figure 14c shows a typical run. The top graph shows the rapid depletion of the reserve as the weedy structure grows in the second panel. The lower panel shows the slower growth of the climax units that displaces most of the successional weedy structure. Then at 150 years the system is partially restarted by the pulse of the surrounding system. The system repeats its pattern, except the reserve available for growth was less.

Figure 14c is a general system model that relates structure and metabolism for any system. For example, the model applies to the smaller scale of growth of a forest that starts with an initial reserve of phosphate nutrients. With appropriate calibration, it also applies to the historical situation when an agrarian economy discovered the use of metals available from the reserves built by earth processes.

7-Ecological Engineering Insight

Ecological engineering fits human civilization into environment so that they mutually reinforce. Fitting the building enterprises into civilization and environment is part of the new field of *Industrial Ecology*. The principles relating materials to energy hierarchy provide suggestions for policy. It ought to be possible to use understanding more and trial and error less.

Maximum Empower Principle

The *maximum empower principle* is a unifying concept that explains why there are material cycles, autocatalytic feedbacks, successional stages, spatial concentrations in centers, and pulsing over time. Designs prevail that maximize empower. The concept predicts that systems like forest production and building construction that emerge in competitive trial and error, develop patterns that maximize performance on all their scales. The principle is a refinement of Lotka's 1922 Maximum Power Principle, which considered maximum energy use (power) at one scale. Systems prevail that utilize all available emergy sources, including stored concentrations of materials, wherever they are available. By this principle complex, high quality, diverse construction should replace fast and flimsy structure when resources are no longer enough to support net growth (simulation example in Figure 14).

Principle of Upscale Overview

Understanding and management of any process requires overview at the next larger scale. For example, building industries need policies for an area large enough to include the complete cycle of their materials. The overview needs to include the longer time for the life cycle of construction and reconstruction. An example of the larger view of construction cycles was provided at this Rinker Conference by Connie Grenz of Collins Pine Company of Portland, Oregon. She explained how provision was made for longer sustained productivity rather than short term exploitation profit. In Figure 15, her diagram of components and material flows was modified to include energy sources. Items were arranged left to right according to the energy hierarchy.

Characteristics for Zones in the Energy Hierarchy

Evaluating emergy per mass and transformities identifies the zone of a building enterprise in the energy hierarchy. The zone helps indicate the properties of design for the system to be sustainable, such as the territory of support and replacement time, or vice versa, the territory and replacement times determines the emergy per mass of materials that are appropriate. The high emergy per mass and heavy permanent buildings of cities grade out to the temporary houses and trailers along the spatial hierarchy of our landscapes.

Adapting To Pulses

The large scale pulses of the earth include earthquakes, volcanic actions, catastrophic storms, disease epidemics, and economic storms. For building cycles to be most effective in the production that they support, their life cycles need to fit the frequency of the storms. For smaller pulses, there are mechanisms of rapid repair. For example, tropical rainforests in hurricane belts develop mechanisms of rapid restoration such as fast regrowth of foliage and conservation of mineral cycles. The shared information (genetic and learned) necessary to repair and replace is the highest transformity of the building system for which continuity is required.

For the less frequent, more catastrophic pulses, the forest is adapted to initiate rapid restart of the trees. In other words, the amount of structure that it is productive to sustain on the average is a function of the size and frequency of pulsing impacts received from the larger scale (a function of their position in the energy hierarchy). The adapted forest uses the energy of the pulses to accomplish the necessary replacement of structures. By analogy, hurricane destruction could help urban renewal where coastal structures are appropriate.

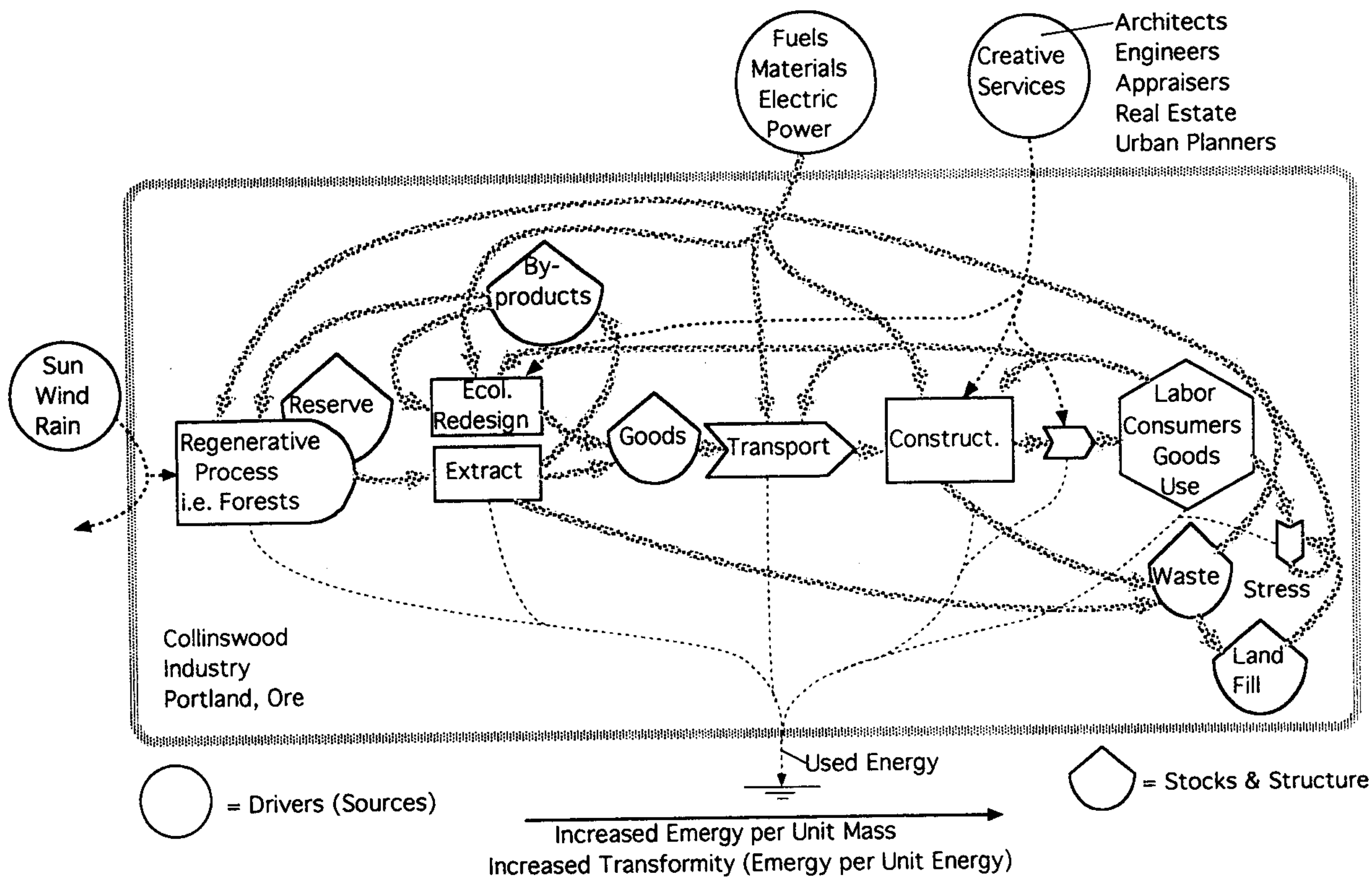


Figure 15. Energy system diagram of the Collinswood Pine Industry of Portland, Oregon, showing the renewable regenerative forest processes on the left described by C. Grenz.

William Odum et al. (1995) simulated a minimodel in which pulse energy, while causing destruction, also contributed to construction. There was an optimum pulse energy for maximum net contribution to structure. When pulse energy was large, less structure was maintained, but the throughput of empower (gross production) increased.

Finding the optimum emergy in building structure means building patterns that minimize repair costs for small pulses but can be repeatedly rebuilt between the larger pulses. In 1967, in order to explain the small biological structure in oceanic ecosystems (mostly plankton), the author provided a graph of the unit metabolism required for maintaining ecosystems (assuming 10% efficiency of construction) as a function of intervals between catastrophic pulses. Fitting building construction to the earth's climate of catastrophic pulses is well underway, adapting building codes and insurance premiums to various areas by trial and error.

The Cement of Forests

A remarkable property of the forest building cycle is the cement of a tree, the lignin, humic substance found in various degrees of polymerization and aggregation. The lignin is a third of a tree, cementing all the functional parts together. When the tree falls, the structure is shredded by animals and bacteria and the lignin is released as blackwaters or stored as peat. In pulp and paper mills, machines shred the trees and the lignin is in the wastewaters. The cement of forest construction has its own useful cycle. In human villages built of wood, recycle of materials was aided by the natural mechanisms of shredding and material return to environment.

For the massive permanent construction of civilization, a cement is needed that is useful throughout the building cycle. When it is time to replace a building, we blow up the structure and try to reuse the building materials, which is not easy because the cement of concrete construction does not disaggregate on schedule. However, initiatives to use less dense cements were offered at this conference.

Policy on Returning Wastes to the Environment

Where waste materials are too dilute to be economically reused or reprocessed, they require public management. If the emergy/mass is high enough to be of public benefit to reprocess (or conversely would impact public environmental values), tax benefits or other incentives can be used to help pay for reprocessing. But very low concentrations have to go back to the environment, but not to just any ecosystem. Ecological engineering studies have discovered that the wetland ecosystems of many kinds all over the world have special designs and lignin chemistry of peat for filtering, denaturing, or holding in their peats the potentially toxic substances such as heavy metals and organic toxic compounds (Odum et al., 1999). A complete life cycle for building construction may often require a wetland ecosystem in its loop. Many of the wastes of building construction are incompatible with the ecosystems of rivers, lakes and oceans. The emergy per mass helps identify the appropriate zone of the earth for material release.

8-Global Materials and Construction

Building construction and material use by our civilization is limited by the energy hierarchy and the global cycles of materials. Figure 16 summarizes the necessary symbiosis of earth processes and human construction in use of the global cycle of materials. Figure 16a shows the series of transformations that provide the materials of our structures, starting with the slow work of the earth in concentrating stored reserves on the left. Materials such as aluminum or iron are concentrated and increase in emergy values from left to right. Human uses start when materials are mined and processed into stocks available to the building industries. Next, construction incorporates materials in buildings, and they are eventually released to the global cycle at the end of the building life cycle. Human services are involved only on the right side of the global hierarchy. They are paid for with circulating money, as shown by the countercurrent of dashed lines in Figure 16b.

Emergy Criteria for Reuse, Reprocessing, or Environmental Recycle

When old structures are taken out of use, three pathways for materials are required (right end of Figure 16b). The highest quality components with some repair can be reused. Those remnants which are still concentrated can be fed back for reprocessing. The appropriate pathway for the least concentrated waste materials is recycling to the natural earth processes capable of incorporating them in natural storages, sometimes benefiting ecosystems.

Emergy per mass of a material can indicate which of these pathways will benefit the system by contributing more while using emergy of fuels and services least. For example, low concentrations of carbon have emergy per mass values like those of the environment, where there are processes that can process low concentrations. Materials with highest mass emergy

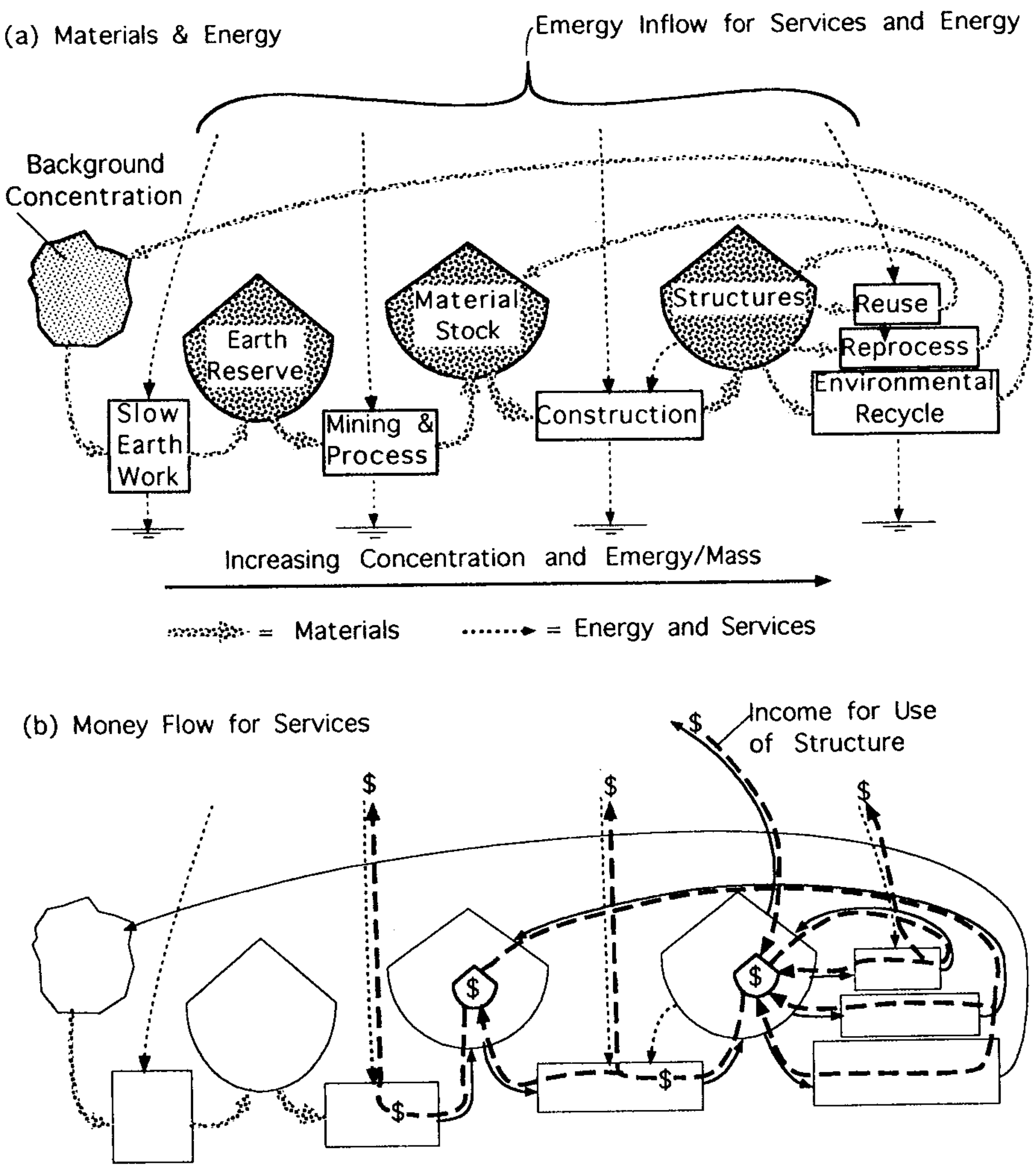


Figure 16. Main pathways of material processing and storage in the system of earth and economy. (a) Material flows, reserves, stocks and structures are shaded. Flows of energy are finely dotted lines. (b) Money circulation shown as a dashed line overlay of those pathways with human service.

are economical, whereas those with lower emergy per mass may require some regulations and incentives from society. Otherwise, discarded materials will accumulate in slums and land fills, displacing lands and poisoning waters, an unsustainable condition.

Material Basis of Civilization

As most people understand, the growth of our civilization in the last two centuries has been based on rapid use of stored earth reserve of materials and energy. Since we are using the reserves of materials that had been accumulated by earth processes faster than they are being replaced, they are called nonrenewable. (They are actually very slowly renewed.) When the nonrenewable reserves are less, construction will depend on the reuse and reprocessing type of recycle (on the right in Figure 16a), but these require fuels and services that also become limited.

Pulsing Paradigm

In systems of all kinds and scales, observations show that the normal pattern is not steady state for long. The usual sequence is growth to a maximum high diversity state followed by removal and regrowth again. In other words, systems in the long run prevail by using a pulsing pattern to generate more. The simple cycle of building and replacement simulated in Figure 13c is an example.

Items on a small scale pulse often, whereas items on a larger scale pulse less frequently. Note the units and territories of different size in Figure 1. The items of a smaller scale pulse many times before they are impacted by the pulse of the larger scale system in which they are a part. For example, the leaves of the forest grow and fall frequently, whereas the whole tree is replaced and restarted less frequently. In human settlements, the smaller structures are built and replaced frequently, whereas the larger structures and districts have longer lives.

Building Life Cycle and the Pulse of the Civilization

On the global scale, the whole civilization is in a pulse based on use of the nonrenewable reserves of energy and materials. We can develop more efficient life cycles for the buildings appropriate for a particular level of available energy and emergy. But the structure and diversity of the buildings that can be sustained is a moving target, rising in this century, declining again in the next.

Adapting Construction for the Prosperous Way Down

For the time ahead when the reserves (energy and materials) are less and the growth economy has ended, self organization has to adapt the buildings and material processing. For a prosperous way down, population has to be reduced at the same rate as the supporting empower. Reuse and reprocessing will replace most mining. Buildings will become more permanent and diverse (See Part 6). The global excess of structure and infrastructure may not be sustainable, but the materials of excess structure that is no longer needed can be reprocessed to help form the more sustainable patterns of a lower energy world. Values of emergy per mass can be used to select the materials that can be sustained in time of lower empower.

In Summary

In spite of, and because of human creativity and purpose, civilization and the ecosystems build structure and recycle according to principles of energy hierarchy. Evaluating emergy of materials and buildings indicates where they belong in the landscape, more concentrated in centers. Simulation of mini-models of building life cycles show how growth of biological structure and building construction follow similar principles of metabolism. Both operate in construction pulses. For the balance of our season of nonrenewable growth and the turndown to sustainable lower levels of structure and production ahead, emergy-emdollar evaluation provides a scale of value for public policy on materials and human settlements.

Appendix Table 1
Emergy of Materials

Item	Transformity x 10^3 sej/J	Emergy/Mass x 10^9 sej/g	1997 Em$ per kg[1]	Source Note
Environment				
Rain	18	9×10^{-5}	8×10^{-5}	2
Typical river water	48.5	0.24	0.21	2
Peat	19.0	0.36	0.31	2
Harvested pine logs	8.0	0.24	0.21	2
Wood chips	15.6			5
Rainforest logs	32.0	0.39	0.33	2
Rainforest wood chips	44.0	0.54	0.46	2
Rocks				
Granite	--	0.50	0.43	2
Global sediments	--	1.0	0.85	2
Mountain rocks	--	1.12	0.96	2
Metamorphic rock	--	1.45	1.23	2
Volcanic rocks	--	4.5	3.9	2
Building				
Lumber	42	0.88	0.75	3
Concrete block	--	1.35	1.15	4
Softwood plywood	57	1.21	1.03	3
Hardwood plywood	69	1.44	1.23	3
Particleboard	158	2.4	2.1	4
Ready-mixed concrete	--	1.44	1.23	3
Cement	--	1.98	1.69	3
Flat glass	--	1.90	1.62	3
Glass	--	4.7	4.0	4
Float glass	--	7.9	6.8	3
Ceramic tile	--	3.1	2.7	3
Brick	--	2.22	1.9	3
Slag	--	7.0	6.0	3
Plastics	96	3.3	2.8	3

Abbreviations: sej = solar emjoule; J = joule; g = gram;
kg = kilogram = 10^3 g; Em$ (1997) = 1997 U.S. emdollars

Appendix Table 1
Emergy of Materials (continued)

Item	Transformity x 10^3 sej/J	Emergy/Mass x 10^9 sej/g	1997 EmS per kg[1]	Source Note
Paper	142	2.1	1.8	6
High density polyethylene	--	5.3	4.5	3
Raw rubber	393	5.5	4.7	13
Polyvinyl Chloride (PVC)	--	5.9	5.0	3
Vinyl floor	194	6.32	5.4	3
Cotton	865	14.4	12.3	7
<u>Metals</u>				
Pig iron	--	2.8	2.4	3
Steel	--	4.2	3.6	3
Steel	--	10.7	9.2	10
Machinery	--	6.7	5.7	2
Aluminum ingots	--	16.9	14.4	2
Aluminum sheet	--	12.7	10.9	3
Copper	--	51.3	43.9	10
Lead	--	73.4	62.7	11
Wool	3840	80	68	9
Silver	--	1,400	1,196	10
Gold	--	589,000	503,418	12
<u>Fuels</u>				
Lignite	37	444	380	2
Coal	40	1,160	991	2
Crude oil	54	2,322	1,984	2
Natural gas	48	2,640	2,256	2
Moter fuel	66	2,904	2,482	2
Electric power	170	--	--	2
Hydrogen	203	25,172	21,514	2

Abbreviations: sej = solar emjoule; J = joule; g = gram;
kg = kilogram = 10^3 g; Em$ (1997) = 1997 U.S. emdollars

Source Notes for Appendix Table 1

1 Em$/kg in column 4 calculated as follows:
(Mass Emergy in column #3)(1000 g/kg)/(1.17×10^{12} sej per 1997 U.S.$)

2 Odum (1996a) Appendix A

3 Buranakarn (1998) Ph.D. Dissertation with R.W. Drummond and M.T. Brown

4 Haukoos (1995)

5 Doherty (1995)

6 Keller (1992)

7 Odum et al. (1987)

8 Odum (1996b)

9 Odum (1984)

10 Industries in 17th Century Sweden (Sundberg, U., J. Lindegren, H.T. Odum, and S. Doherty, 1994)

11 Pritchard (1992)

12 Bhatt (1986) in Odum (1991)

13 Odum et al. (1983)

Appendix Table A2
BASIC Program RESTRUCT.bas for the Construction Minimodel in Figure 13

```
4 REM RESTRUCT.bas  (Tree Production & Consumption, H.T.Odum)
10 LINE (0,0)-(320,60),,B
20 LINE (0,70)-(320,120),,B
30 LINE (0,130)-(320,180),,B
35 LINE (0,190)-(320,250),,B
40 REM Coefficients
50 fr = .01
60K0=.0000036
70 K1= 2.86E-09
80 K2= 8.57E-10
90K3=.03
95 k4=.03
100 REM Starting Values and Sources
105S=1000
110J=1400000!
115 F = 1
120S1 = 2000
125 S2 = 9000!
130Tm=200
135 T = .1
137 Trj = 1
140 REM Scaling factors
150 dt = 1
160T0 = 1
170S0 = 250
180 Mg = 25
190 trs0 = 100
200 REM Start of Loop
210 IF S<S1 THEN X = 1
220 IF S>S2  THEN X = 0
230 M=Tm-fr*S
235 IF M<.0001 THEN M= .0001
240 R=J/(1+X*K0*M*S):REM unused energy
250 ju=J-R: REM Energy used in Construction
260 Y = k4*F*S:REM Energy output to larger system
270  dS=X*K1*R*M*S-X*K2*R*M*S  -K3*S-Y
280 S = S + dS*dt
300 REM Emergy and Transformity Equations
310 emj = ju * Trj:REM input emergy used
320 IF dS>0 THEN dEms = emj -Emy
325 IF dS<0 THEN dEms = dS*Trs
330 Ems = Ems + dEms*dt:REM emergy stored in S
340 Trs = Ems/S: REM Transformity of Storage S
350 Emy=Trs*Y:REM Emergy of output to larger sytem
360T=T+dt
```

Appendix Table A2
Program RESTRUCT.bas (continued)

```
400 REM Plotting
410 PSET(T/T0,120-S/S0): REM Structure
420 IF X = 0 GOTO 440
430 LINE (T/T0,60)-(T/T0,60-.00003*ju): REM Energy used
440 PSET(T/T0,180-M/Mg): REM Available materials
450 PSET (T/T0,250-Trs/trs0):REM Yield to other systems
460IFT/T0<320GOTO200
```

Appendix Table A3
Basic Program MATBUILD.bas for Simulating the Minimodel of Materials in Succession in Figure14 Calibrated with Appendix Table A4

```
4 REM MATBUILD.bas  (Material in Building Succession & Climax),
H.T.Odum Aug, 1999)
10 LINE (0,0)-(320,60),,B
20 LINE (0,70)-(320,120),,B
30 LINE (0,130)-(320,180),,B
40 REM Coefficients
50 frw = .5
55 fr = 1
60 K0=9E-08
70 K1=.0000005
72 K2=.0000001
74 K3=.01
76 K4 = .5
78 k5 = .0009
80 K6 = .16
82 k7 = .02
84 k8 = .001
86 k9 = .01:REM -?
88 K10 = .01
90 k11 = .01
92 k12 = .001
94 k13 = .08
100 REM Starting Values
105 S=100
110 J=1
115 Jm= 1
117 Q= 1
120 Mr=100
125 W = 5:REM Weedy, flimsy structure
130 Tm =500
140 REM Scaling factors
150 dt = 1
160 T0 = 1
170 S0 = 20
180 Mr0 = 2
190 W0 = 2
```

Appendix Table A3 (continued)

```
200 REM Start of Loop
205 Z = Z +1
210 IF  Z > 150 THEN X = 1 :REM Introduces Large scale pulse
215 IF Z>150 THEN Z = 1
220 IF Z > 2/dt THEN X = 0
230 M=Tm-fr*S
235 IF M<.001 THEN M= .001
240 R=J/(1+K0*M*S+k5*Mr*W):REM unused energy flow
245 DMr = Jm -k9*Mr -K10*R*Mr*W +k8*fr*S
250 DS=K1*R*M*S*S +k7*frw*W-K2*R*M*S*S -K3*S-X*K4*S*Q
255 DTm = frw*K6*W +frw*k7*W -k8*fr*S
260 Dw = k11*R*Mr*W -k12*R*Mr*W -k7*W -k13*W
265 S = S + DS*dt
270 Mr = Mr +DMr*dt
275 Tm = Tm +DTm*dt
280 W = W +Dw*dt
290 T=T+dt
300 REM Plotting
310 PSET(T/T0,180-S/S0): REM ClimaxStructure
320 PSET(T/T0,120-W/W0):REM Weedy Structure
330 PSET(T/T0,60-Mr/Mr0): REM Material Reserve
350 IF T/T0<320 GOTO 200
```

Appendix Table A4
Spreadsheet for Calibration of MATBUILD.bas

Inflows	Energy J =	1
	Material Jm =	1
Forcing	Pulses Q =	1
Starting states	Material reserve Mr =	100
	Weedy structure W =	100
	Climax structure S=	1000
	Climax material Tm=	1100
	Available material M	100
Remainder	Energy R =	0.1
Products	R*M*S*S =	10000000
	R*Mr*W =	1000

Coefficients				
Material fraction in weedy structure frw =		0.5		
Material fraction in climax structure fr =		1		
Energy use by weeds	K0*R*M*S*S =	0.9	and K0 =	0.00000009
Climax struct. prod.	K1*R*M*S*S =	5	and K2 =	0.0000005
Use of struct. in prod.	K2*R*M*S*S =	1	and K2 =	0.0000001
Climax struct. cons.	K3*S =	10	and K3 =	0.01
Pulsed consumption	X*K4*S*Q=	500	and K4 =	0.5
Energy use by climax	K5*R*Mr*W =	0.9	and K5 =	0.0009
Mat. from weed cons.	K6*frw*W =	8	and K6 =	0.16
Weed to climax	K7*W =	2	and K7 =	0.02
Climax to mat. reserve	K8*fr*S =	1	and K8 =	0.001
Mat. reserve slow out	K9*Mr =	1	and k9 =	0.01
Weed use of reserve	K10*R*Mr*W =	10	and K10 =	0.01
Weed production	K11*R*Mr*W =	10	and K11 =	0.01
Weed feedback	K12*R*Mr*W =	1	and K12 =	0.001
Weed consumption	K13*W =	8	and K13 =	0.08

References

Adriaanse, A, S. Bringezu, A. Hammond, Y. Moriguchi, E. Rodenburg, D. Rogich, and H. Schutz. 1997. Resource Flows: The Material Basis of Industrial Economies. World Resources Institute, Washington DC. 65 pp.

Bhatt, R. 1986. Calculation table from unpublished report of policy research project, L.B.J. school of Public Affairs, Austin, TX ("Policy Implication of Gold Emergy"), published in Odum (1991).

Boggess, C.F. 1944. The Biogeoeconomics of Phosphorus in the Kissimmee Valley. Ph.D. Dissertation, Environmental Engineering Sciences, Univ. of Florida, Gainesville. 234 pp.

Brand, S. 1994. How Buildings Learn, What Happens After They Are Built. Penguin Books, NY. 243 pp.

Bringezu, S. 1997. "From quantity to quality: material flow analysis." pp. 43-57 in Regional and National Material Flow Accounting: From Paradigm to Practice of Sustainability, ed. by S. Bringezu, M. Fischer-Kowalski, R. Kleijn, V. Palm. Proceedings of the ConAccount Workshop 21-23 Jan, 1997, Leiden, Netherlands. Wuppertal Special; 4, Wuppertal Institute, Wuppertal, Netherlands

Buranakarn, V. 1998. Evaluation of Recycling and Reuse of Building Materials Using the Emergy Analysis Method. Ph.D. Dissertation, Dept. of Architecture, Univ. of Florida, Gainesville. 251 pp.

DeYoung, J. and D.A. Singer. 1961. "Physical factors that could restrict mineral supply." Economic Geology, 75th Anniversary Volume, pp. 939-954.

Genoni, G.P. 1995. "Influence of the energy relationships of trophic levels and of elements on bioaccumulation." Ecotoxicology and Environmental Safety 30:203-218.

Genoni, G.P. 1997. "Towards a conceptual synthesis in ecotoxicology." Oikos 80:96-106.

Genoni, G.P. 1998. "The energy dose makes the poison." EAWAG News 45 (November):13-15.

Haukoos, D.S. 1995. Sustainable Architecture and Its Relationship to Industrialized Building. M.S. Thesis, Univ. of Florida, Gainesville.

Hinterberg, F. and H. Stiller. 1999. "Energy and Material Flows." pp. 275-286 in Advances in Energy Studies, Energy Flows in Ecology and Economy, ed. by S. Ulgiati. Museum of Science, Rome, Italy. 641 pp.

Keitt, T.H. 1991. Hierarchical Organization of Energy and Information in a Tropical Rain Forest Ecosystem. M.S. Thesis, Environmental Engineering Sciences, Univ. of Florida, Gainesville. 72 pp.

Keller, P.A. 1992. Perspectives on interfacing paper mill wastewaters and wetlands. M.S. Thesis. Environmental Engineering Sciences, Univ. of Florida. 133 pp.

Laskey, S.G. 1950a. "Mineral-resource appraisal by the U.S. Geological Survey." Colorado School Mines Quart. 43(1A):1-27.

Lotka, A.J. 1922a. "Contribution to the energetics of evolution." Proc. Natl. Acad. Sci. 8:147-151.

Lotka, A.J. 1922b. "Natural selection as a physical principle." Proc. Natl. Acad. Sci. 8:151-154.

Odum, H.T. 1956. "Primary production in flowing waters." Limnol. and Oceanogr. 1:102-117.

Odum, H.T. 1967. "Biological circuits and the marine systems of Texas." pp. 99-157 in Pollution and Marine Ecology, ed. by T.A. Olson and F.J. Burgess. Interscience, John Wiley, NY.

Odum, H.T. 1970. "Summary, An emerging view of the ecological system at El Verde, Puerto Rico." pp. I-191 through I-277 in A Tropical Rainforest, ed. by H.T. Odum and R.F. Pigeon. Division of Technical Information, Atomic Energy Commission, Oak Ridge, TN. 1600 pp.

Odum, H.T. and E.C. Odum, eds. 1983. Energy Analysis Overview of Nations. Working Paper WP-83-82. International Institute for Applied Systems Analysis, Laxenburg, Austria. 469 pp.

Odum, H.T. 1984 "Energy Analysis of the Environmental Role in Agriculture." pp 24-51 in Energy and Agriculture, ed. by G. Stanhill Springer-Verlag, NY, 192 pp

Odum, H.T., E.C. Odum and M. Blissett. 1987. Ecology and Economy: "Emergy" Analysis and Public Policy in Texas. Policy Research Project Report #78. Lyndon B. Johnson School of Public Affairs, The University of Texas, Austin. 178 pp.

Odum, H.T. 1991. "Emergy and biogeochemical cycles. pp." 25-65 in Ecological Physical Chemistry, ed. by C. Rossi and E. Tiezzi. Proceedings of an International Workshop, Nov. 1990, Sienna Italy. Elsevier Science, Amsterdam.

Odum, H.T. 1996a. Environmental Accounting, Emergy and Decision Making. J. Wiley, NY. 373 pp.

Odum, H.T. 1996b. "Economic impacts brought about by alternations to freshwater flow." pp 239-254 in Improving Interactions Between Coastal Science and Policy. Proceedings of the Gulf of Mexico Symposium, National Research Council, National Academy Press. 346 pp.

Odum, H.T., W. Wojcik, L. Pritchard, Jr., S. Ton, J.J. Delfino, M. Wojcik, J.D. Patel, S.J. Doherty and J. Stasik. 1999. Wetlands for Heavy Metals and Society. Book Manuscript for CRC Press, Boca Raton, FL

Odum, W.E., E.P. Odum, and H.T. Odum. 1995. "Nature's Pulsing Paradigm." Estuaries 18(4):547-555.

Page, N.J. and Creasey, S.C. 1975. "Ore grade, metal production and energy. Journal of Research," U.S. Geological Survey 3:9-13.

Pritchard, L. 1992. The Ecological Economics of Natural Wetland Retention of Lead. M.S. Thesis, Environmental Engineering Sciences, Univ. of Florida, Gainesville. 138 pp.

Sundberg, U., J. Lindegren, H.T. Odum, and S. Dohergy. 1994. Forest Emergy Basis for Swedish Power in the 17th Century. Scandinavian Journal of Forest Research, Supplement No. 1. 50 pp.

Wernick, I.K., R. Herman, S. Govind and J.H. Ausbel. 1999. Materialization and Dematerialization Measures and Trends. Workshop Reader for the 10th Rinker International Conference. Sch. of Building Construction, Univ. of Florida, Gainesville.

Figure Legends

Figure 1. Energy hierarchy concept illustrated with one source and three energy transformation steps. (a) Components of three scales viewed together; (b) components of forest separated by scale; (c) components of a tree separated by scale; (d) components of a tribal village; (e) energy flows in an energy systems diagram; (f) flows of energy in the pathways from left to right; (g) transformity of the energy flows.

Figure 2. Materials and energy flows with a hierarchy of structural units of different scales. Numerical values are for circulation of carbon through three levels of a rainforest (1-leaves, 2-branches and roots and 3-tree trunks) (Odum, 1970). (a) Circulation of material; (b) combination of material and energy flows.

Figure 3. Energy and the concentrations of materials. (a) Sketch of concentration increase from left to right; (b) use of available energy to concentrate material; (c) increase in mass emergy (emjoules per gram) with concentration.

Figure 4. The spatial convergence and divergence in the concentrating of materials. (a) Energy systems diagram of energy and materials; (b) spatial pattern of material flows toward centers.

Figure 5. Flux of material which can be concentrated by successive energy transformations where empower is constant. (a) Inverse relation of material flux and emergy per mass; (b) energy system diagram with one emergy source; (c) relationships on double logarithmic plot.

Figure 6. Energy hierarchy spectrum showing the zones of productive interaction for different material cycles in different transformity ranges.

Figure 7. Mass emergy (emergy per mass) of various materials used in construction of civilization and nature. Included is a scale of equivalent emdollars per kilogram. See Appendix Table A1 for calculations.

Figure 8. Quantity of resources required to make concentrated metal, modified from Page and Creasey (1975). (a) Rock required; (b) fuels required; (c) emergy required to concentrate metal ores derived from (b).

Figure 9. Emergy per mass of dilute and concentrated materials. (a) Emergy per mass and metal concentration calculated from Figure 9c; (b) energy systems diagram showing passive carrier and active production zones of material participation.

Figure 10. Emergy per mass as a function of lead concentration (Odum, 1999).

Figure 11. Aggregate material accounting of Germany from Wuppertal Institute (Adriaanse et al., 1997). (a) System diagram of the material flows given by S. Bringezu and H. Schutz; (b) overview of material account of Germany with energy sources and emergy evaluation added.

Figure 12. Pathways and metabolism of a typical structural units like those found on many scales. (a) Material circulation coupled to an energy hierarchy; (b) details of the pathways and storage of metabolism of one structural unit.

Figure 13. Simplified overview model of construction (production) and consumption. (a) Systems diagram including energy and materials; (b) equations derived from the diagram; (c) typical simulation of the pulses of construction, depreciation, and replacement.

Figure 14. Simulation model of succession, climax, and restart MATBUILD that starts with a reserve of materials. (a) Energy systems diagram; (b) equations in the program; (c) typical simulation run.

Figure 15. Energy system diagram of the Collinswood Pine Industry of Portland, Oregon, showing the renewable regenerative forest processes on the left described by C. Grenz.

Figure 16. Main pathways of material processing and storage in the system of earth and economy. (a) Material flows, reserves, stocks and structures are shaded. Flows of energy are finely dotted lines. (b) Money circulation shown as a dashed line overlay of those pathways with human service.