Available online at www.sciencedirect.com
SCIENCE DIRECT®
Ecological Modelling 189 (2005) 49–71
ECOLOGICAL MODELLING
www.elsevier.com/locate/ecolmodel

Theory of urban energetics and mechanisms of urban development

Shu-Li Huang *, Chia-Wen Chen

Graduate Institute of Urban Planning, National Taipei University, Taipei, Taiwan 10433

Received 20 August 2004; received in revised form 16 February 2005; accepted 29 March 2005
Available online 2 June 2005

Abstract

The interrelationships between energy and civilization was proposed in the late 19th century [see Martinez-Alier, J., 1987. Ecological Economics. Blackwell, Oxford]. Geddes [Geddes, P., 1915. City in Evolution. Williams and Norgate Ltd., London] also proposed the concept of linking energy flow with urban development in the early 20th century. Many recent studies of the relationship between urban development and energy have been limited to the use of fossil fuels; energy theories have seldom been used to study the evolution of urban systems. The purpose of this paper is to help develop theories of urban energetics and contribute to the understanding of the mechanisms of urban development. We use the concepts from systems ecology [Odum, H.T., 1983. Systems Ecology. Wiley, New York] and emergy theory [Odum, H.T., 1996. Environmental Accounting: Emergy and Environmental Decision Making. Wiley, New York] to relate the driving energies of urban systems to their structure, economy and organization. Hypotheses of urban energetics including changes in the diversity of emergy sources, changes in urban metabolism, energy hierarchy, and relation between emergy and money flows are proposed and tested based on past research results on Taiwan cities (Huang, S.-L., Odum, H.T., Chang, S.-L., 1996. Ecological energetic evolution of urban system, A Report to the Chiang Ching-Kuo International Scholar Exchange Foundation (RG008-D-'92). Graduate Institute of Urban Planning, National Chung-Hsing University, Taipei, Taiwan (in Chinese); Huang, S.-L., 1998a. Urban ecosystems, energetic hierarchies, and ecological economics of Taipei metropolis. J. Environ. Manage. 52, 39–51; Huang, S.-L., Lai, H.-Y., Lee, C.-L., 2001. Energy hierarchy and urban landscape system. Landscape Urban Plan. 53, 145–161]. Thereafter a system model of urban ecosystem is developed to investigate the relationships between energy flows and urban development. The preliminary findings of this research indicate that intensive and diversified emergy sources build up the structure and enhance metabolism in urban areas. Four mechanisms of urban energetics are also addressed as a result of simulations: energy convergence; urban-subsidized environmental flows; external-dependency system; maximum power system.

Keywords: Ecological economics; Emergy; Simulation; Urban energetics

1. Introduction

Development of urban areas has been shown to follow similar pattern all around the world (Odum and Odum, 1981, 2001; Odum, 1983). The early human

* Corresponding author. Tel.: +886 2 25009713; fax: +886 2 25054954.
E-mail address: shuli@mail.ntpu.edu.tw (S.-L. Huang).

0304-3800/$ – see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.ecolmodel.2005.03.004

settlements were small villages surrounded by agricultural lands. As population and resource use increased, the urban areas expanded and surrounding agricultural lands were then converted to urban uses. The existence and maintenance of an urban region, and of its internal structure depend on the flows of goods and services in, out and throughout the city. While urbanization is well established as a focus of study in the social sciences, it has been used less frequently as a focus in the disciplines related to ecology (Jaakson, 1977). A systems approach can be used to conceptualize urban regions as an entities with interacting natural environments and urban economy. Using energy as a common numerator to evaluate the work of nature, either with or without including humans, is an attractive choice in the analysis of interacting ecological and economic systems.

Haines (1986) reviewed research on the investigations of the relationship between efficiency of fossil fuel consumption and spatial configuration of the urban form. However, the importance of an energy theory and of research activities on the relationship between energy flow and urban development has been ignored. Urbanization here is viewed from the point of ecological energetics. The study of urban energetics has developed from the work of Geddes (1854–1932), who was one of the first authors to correlate periods of human history with energy use. Geddes' proposal for studying the evolution of cities on the basis of tracing energy flows nearer to a true human ecology than that of the misnamed human ecology of the Chicago urban ecology school, ca. 1920 (Martinez-Alier, 1987).

Odum and Peterson (1972) related the complexity of cities to ecological principles and energy flows. In order to evaluate nature's service to human society, the ecological energetic analysis was proposed as a complement to economic accounting (Odum, 1971, 1988, 1996). Energy requirements by human beings and energy characteristics of cities based on fossil fuels were further addressed by Odum and Odum (1981). The relationship between spatial organization and energy hierarchy of city-regions, and its implication to urban planning has also been addressed by Huang (1998a,b), Huang et al. (2001) and Odum and Odum (2001). However, an integrated theory of the interdependence of urban development and energetic flow remains to be established.

In this paper we use concepts and principles from systems ecology and theories of emergy to address spatial and temporal organization of urban systems and the dependence of the urbanization process on quantity and quality of driving energies. In the next section we provide brief definitions of words and concept. Some concepts from ecological energetics are discussed in Section 3 to establish hypotheses of urban emergy theory. Emergy synthesis of the Taipei area is performed in Section 4 to provide a basis of testing hypotheses of urban energetics. In Section 5, the stated hypotheses are further elaborated and tested using data of Taiwan cities. A system model using Odum's energy circuit language is then developed in Section 6 to represent Taipei's ecological economic system. Section 7 discusses the simulation results and the mechanisms of interrelationships between energy flows and urban development.

2. Definitions

Transformity and *emergy* were introduced by Odum (1996) to take into account the quality of energy inherent in the hierarchy of system components. Further discussion and definitions can also be found in Brown and Ulgiati (2004).

Energy. Sometimes referred to as the ability to do work. Energy is a property of all things which can be turned into heat and is measured in heat units (BTUs, calories, or joules).

Emergy. An expression of all the energy used directly and indirectly in the work processes that generate a product or service in units of one type of energy. Solar emergy of a product is the emergy of the product expressed in equivalent solar energy required to generate it.

Transformity. The ratio obtained by dividing the total emergy that was used in a process by the energy yielded by the process. Transformities have the dimensions of emergy/energy (sej/J). A transformity for a product is calculated by summing all of the emergy inflows to the process and dividing by the energy of the product. Transformities are used to convert energies of different forms to emergy of the same form. Sometimes other units are also used (sej/g; sej/h) depending on the context.

Emjoule. The unit of measure of emergy, "emergy Joule". It is expressed in the units of energy previously used to generate the product; for instance the solar emergy of wood is expressed as joules of solar energy that were required to produce the wood. The abbreviation for solar emjoules is sej.

Empower. Emergy flow per unit time (sej day^{-1}).

Empower density. Empower per unit area (sej day^{-1} m^{-2}).

Non-renewable emergy. The emergy of energy and material storages like fossil fuels, mineral ores, and soils that are consumed at rates that far exceed the rates at which they are produced by environmental processes.

Renewable emergy. The emergy of energy flows of the biosphere that are more or less constant and reoccurring, and that ultimately drive the biological and chemical processes of the earth and contribute to geological processes.

Self-sufficiency. The percent of total emergy use that is from local sources.

In addition to the terms given above, several ratios, or indices defined next are used to evaluate the global performance of a process as follows (Fig. 1).

Emergy yield ratio (*EYR*). The ratio of the total emergy driving the process to the emergy investment from outside. The ratio is a measure of a process ability to exploit the resources by means of an outside investment, thus providing an additional, potential contribution to the economy.

Environmental loading ratio (*ELR*). The ratio of nonrenewable and imported emergy use to renewable emergy use. It is an indicator of the pressure of a transformation process on the environment and can be considered a measure of ecosystem stress due to a production (transformation activity).

Emergy investment ratio (*EIR*). The ratio of emergy fed back from outside a system to the indigenous emergy inputs (both renewable and non-renewable). It evaluates if a process is a good user of the emergy that is invested, in comparison with alternatives. It is linked to the EYR by the relation EYR = 1 + (1/EIR).

Emergy/money ratio (*EMR*). The ratio of total emergy flow in the economy of a region or nation to the GDP of the region or nation. The EMR is a relative

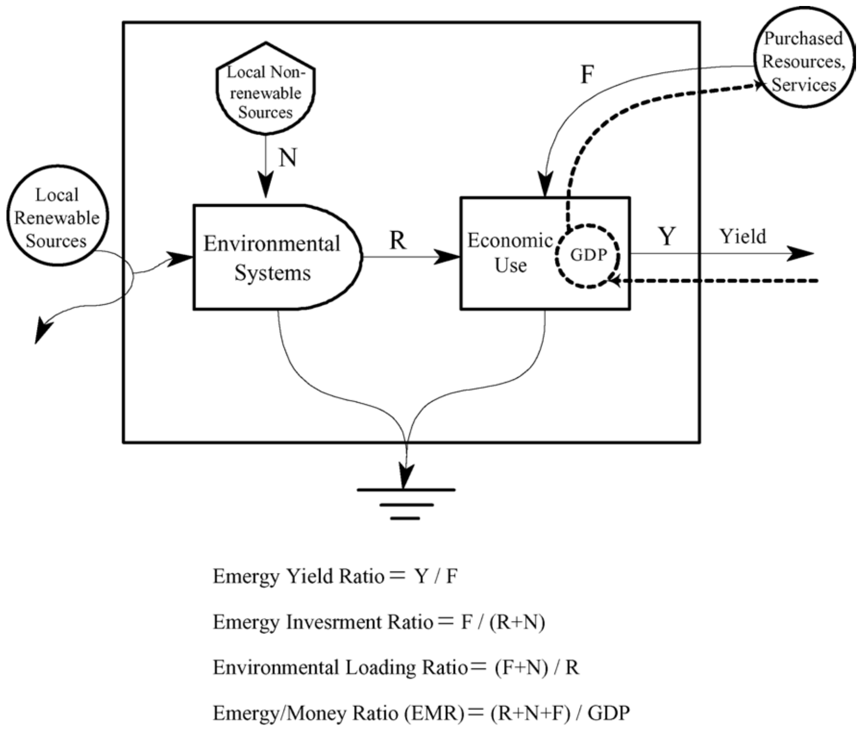


Fig. 1. Emergy-based indices and ratios to evaluate sustainability, monitoring and technology toward environmental sound innovation.

measure of purchasing power when the ratio of two or more nations or regions are compared.

Emdollar (*or EM*$). A measure of the money that circulates in an economy as the result of the investment of a given amount of money. In order to obtain the emdollar value of an emergy flow or storage, the emergy is divided by the emergy to money ratio for the investigated national economy.

3. Emergy and urban system

From viewpoint of ecological energetics, ecological and social systems are analogous (Odum, 1971, 1983), we could apply the laws describing growth, depreciation, and interaction of ecological systems to social systems. Development of physical systems is characterized by local increase of organization on the local scale at the expense of increase of disorder on the larger scale, while living systems evolve toward greater functional complexity. Complex system theory (von Bertalanffy, 1968) is about understanding the creative power of self-organizing systems, and it lays the theoretical foundation for understanding the processes by which matter, organisms and ecosystems organize themselves into complex far from equilibrium structures (Prigogine et al., 1977). The theory of dissipative structures suggests that self-organization is due to dissipation; synergestics suggests that this is due to cooperation between parts of the system (Portugali, 1997).

Odum introduced a general systems energy circuit language (Odum, 1971, 1983) which combines open system thermodynamics with system kinetics and represents system hierarchy by positioning components from left to right on diagrams. Ecosystems self-organize and develop hierarchical patterns with symbiotic closed feedback loops for structural reinforcement and a division of labor. Odum proposed that the maximum empower principle is the mechanism of self-organization, which can be stated as: during self-organization, system designs develop and prevail that maximize empower, energy transformation, and those uses that reinforce production and efficiency (Odum, 1995; Odum and Odum, 2001). The basic idea is that systems which can draw more resources and use them properly to maintain structure will out-compete systems that have fewer resources to drive their activities. The autocatalytic design can illustrate how the maximum power principle operates.

Urban systems like biological systems, are far from thermodynamic equilibrium. All living systems self-organize into characteristic designs with hierarchical energy transfer, recycling of material, feedback control, and autocatalysis. These characteristics and the inflows of energy and materials and outflows for exchanging goods and services are equally important in a biophysical view of urbanization. Using these properties, we suggest that the processes of urbanization are far more than just the birth and growth of cities. Once a city or region is viewed as a system, it is possible to incorporate "emergy" into its conceptualization and to thread together urban and natural systems. In this way, we can utilize a well-developed body of concepts, principles, and techniques of evaluation to gain a better understanding of the combined system of humanity and nature, in general, and urban systems in particular.

In urban ecosystems, as in all self-organizing systems, the path of energy transformation and dissipation and the paths of material flows are determined by production and consumption. At each step of energy transformation, most of the available energy is degraded and dispersed as a necessary consequence of the second law of thermodynamics in order to generate a smaller amount of energy of another type for the next step in the hierarchy. An urban ecological structure and its organization can be thought of as resulting from photosynthesis by plants and life-support services provided by the natural environment combined with non-renewable resource consumption and further generation of urban services. This structural organization culminates in the geographical distribution of different land use activities and the accumulation of assets within those land uses. Money circulates within urban systems as a means of purchasing nonrenewable energies and exchanging goods and services with exterior economic systems. Furthermore, urban ecosystems develop hierarchical spatial patterns to organize the urban economy and its surrounding environment geographically to increase productivity.

4. Emergy synthesis of the Taipei area

In order to explain how emergy synthesis of an urban system can be performed, this section uses the

Taipei area as a case study, and the results are also used as a basis for testing the hypotheses of urban energetics (Section 5). Using Odum's energy diagram, the conceptual urban ecological economic system of the Taipei area can be represented as in Fig. 2. The circular symbols outside the boundary of the Taipei area are causal influences from outside sources. Energetic flows interconnect renewable sources, the forest and human-subsidized agricultural system, utilities, and industrialized urban systems. The renewable energies of the sun, wind and rain power the two producer systems' life support functions, which in turn are transmitted to urban consumers. The Tansui River, the major river in Taipei, receives stream inflows from its two main upstream tributaries of the Tahan Creek and Keelung River. The dams and reservoirs in the upstream areas of the Tansui River were constructed to ensure a reliable water supply for the urban metropolis.

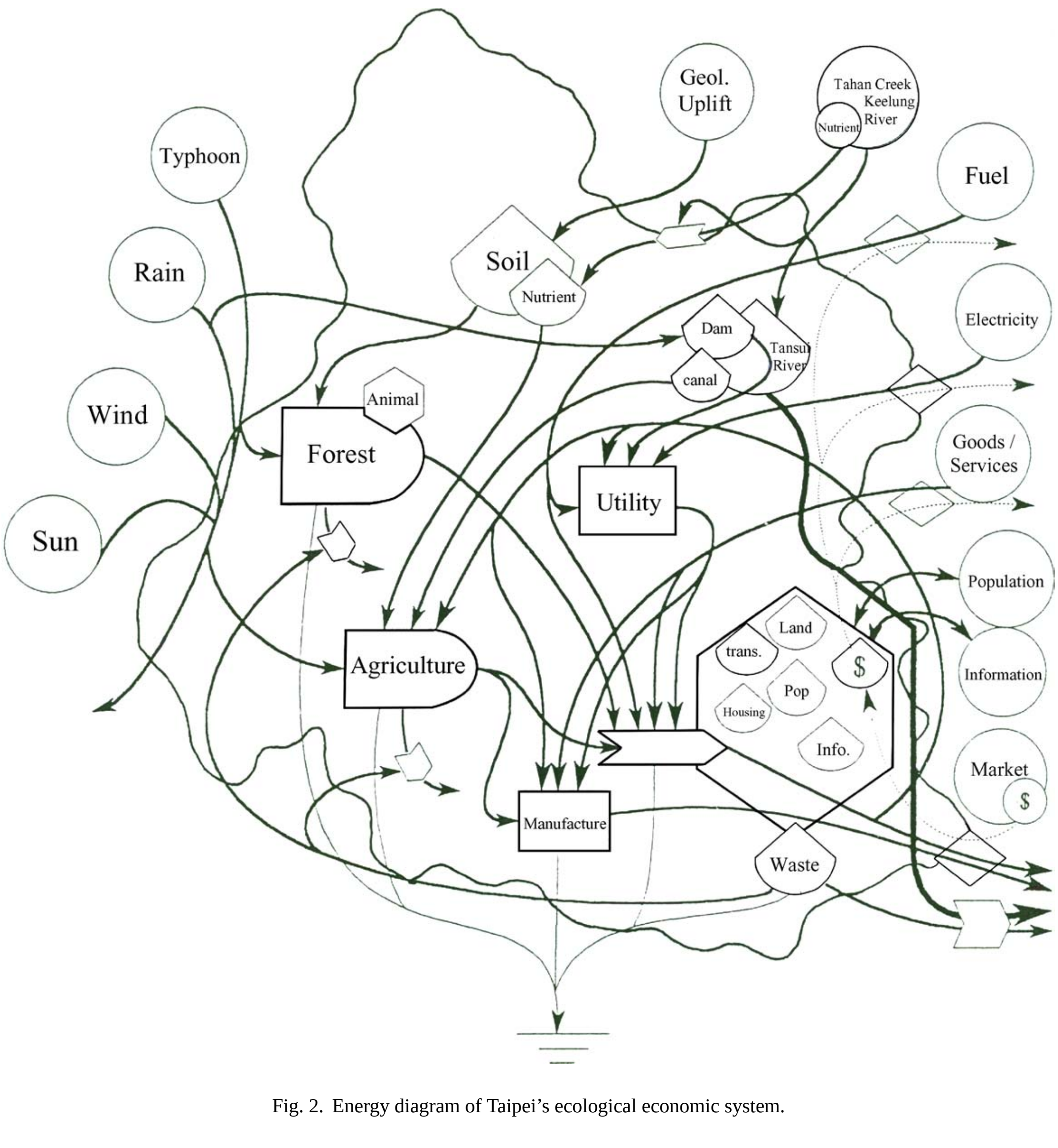


Fig. 2. Energy diagram of Taipei's ecological economic system.

In addition, the dams also generate hydroelectricity. Due to the levee and dikes constructed along the down-stream portion of the Tansui River to protect the urban area from floods exceeding return periods of 200 years, Taipei's urban metropolis is separated from the Tansui River by levees without direct interaction with the river. Fuels, electricity and goods and services imported from elsewhere are the major driving forces behind the economic growth in the urban area. Exports of goods and services produced in the city are very important to the productivity of its urban economy. The urban system has to purchase fuels, materials and services that are not available in the Taipei area. Wherever there is energy and resource consumption, there is an accompanying production of waste. Stress caused by the inadequate treatment and accumulation of waste affects the life-support ecosystems in a negative way.

Based on a preliminary understanding of the ecological economic system of the Taipei area, a category of items of energy flows such as renewable, locally

Table 1
Emergy synthesis table of resource and economic flows of Taipei area in 1998

Item	Raw data	Solar transformity (sej/unit)	Solar emergy (sej)	Emdollar values (1998 US$)
Renewable sources				
1. Sunlight (J)	9.81×10^{18}	1	9.81×10^{18}	4.05×10^{6}
2. Wind, kinetic (J)	3.30×10^{18}	623	2.06×10^{21}	8.49×10^{8}
3. Rain, geopotential (J)	2.53×10^{13}	8888	2.25×10^{17}	9.29×10^{4}
4. Rain, chemical (J)	3.96×10^{16}	15444	6.11×10^{20}	2.53×10^{8}
5. Tide (J)	1.63×10^{13}	23564	3.84×10^{17}	1.59×10^{5}
6. Wave (J)	5.81×10^{16}	25889	1.51×10^{21}	6.22×10^{8}
7. Geological uplift (J)	1.58×10^{10}	29000	4.57×10^{14}	1.89×10^{2}
8. Wood consumption (J)	1.65×10^{12}	34900	5.77×10^{16}	2.38×10^{4}
9. Typhoon (J)	9.45×10^{12}	41000	3.87×10^{17}	1.60×10^{5}
10. Upstream inflow (J)	5.20×10^{15}	41068	2.14×10^{20}	8.82×10^{7}
11. Stream flow (J)	3.52×10^{16}	41068	1.44×10^{21}	5.97×10^{8}
12. Stream sedimentation (g)	1.15×10^{13}	1.71×10^{9}	1.96×10^{22}	8.09×10^{9}
13. Stream organic matter (J)	5.18×10^{12}	19000	9.84×10^{16}	4.06×10^{4}
14. Hydroelectricity (J)	2.74×10^{15}	159000	4.35×10^{20}	1.80×10^{8}
Non-renewable sources from within Taipei				
15. Coal (J)	2.90×10^{15}	39800	1.16×10^{20}	4.77×10^{7}
16. Net top soil loss (J)	2.11×10^{13}	62500	1.32×10^{18}	5.44×10^{5}
17. Soil erosion (T)	5.58×10^{5}	1.71×10^{15}	9.54×10^{20}	3.94×10^{8}
Imports and outside sources				
18. Goods (US$)	3.55×10^{10}	1.98×10^{12}	7.02×10^{22}	2.90×10^{10}
19. Services (US$)	6.45×10^{9}	1.98×10^{12}	1.28×10^{22}	5.28×10^{9}
20. Coal (J)	2.81×10^{17}	39800	1.12×10^{22}	4.61×10^{9}
21. Petroleum product (J)	4.99×10^{17}	66000	3.29×10^{22}	1.36×10^{10}
Exports				
22. Goods (US$)	3.75×10^{10}	2.42×10^{12}	9.07×10^{22}	3.75×10^{10}
23. Services (US$)	5.98×10^{9}	2.42×10^{12}	1.45×10^{22}	5.98×10^{9}
Resource consumed				
24. Coal (J)	2.76×10^{15}	39800	1.10×10^{20}	4.55×10^{7}
25. Petroleum product (J)	4.99×10^{17}	66000	3.29×10^{22}	1.36×10^{10}
26. Electricity (J)	1.06×10^{17}	159000	1.69×10^{22}	6.9×10^{9}
Waste produced				
27. Solid waste (J)	1.13×10^{16}	1800000	2.04×10^{22}	8.43×10^{9}
28. Waste water (J)	2.23×10^{15}	665714	1.48×10^{21}	6.12×10^{8}
Dollar flow				
29. GDP (US$)	7.31×10^{10}	2.42×10^{12}	1.77×10^{23}	7.31×10^{10}

nonrenewable, imported sources, exports, etc, were listed for the study of Taipei's status in terms of its ecological economic interface and the consequences of urban development. As shown in Table 1, each item of the annual flows that are important for studying Taipei's ecological economic system was evaluated, using data for 1998, in raw units (e.g. energy, mass, or US$) which are typical for that class of input. The solar emergies of each of the flows were obtained from the product of the raw data and the solar transformities. Emdollar values of each of the flows were then calculated in units of US$ for that particular year. Comparison of the emergy values among listed items can reveal the relative contribution of each input and output to Taipei's urban economy. Due to the highly urbanized characteristics of the Taipei area, the emergy flows from renewable sources and local nonrenewable sources to the Taipei area are relatively small as compared to imported fuels and goods and services. However, the ability to attract outside high emergy in fuels, goods and services depends on being able to match these inputs with environmental interactions.

In order to have a perspective of the evolving pattern of emergy use in Taipei, data from 1936, 1951, 1966, 1981 and 1991, representing different stages of Taipei's political status, were also used for emergy synthesis. Based on the evaluation of principal emergy flows (e.g. *R*, *N*, *F*, *G*, *P*2*I*3, *U*, etc.), Table 2 summarizes the evolving ecological economic system of the Taipei area. Currently, Taipei's ecological economic status is characterized by: (1) heavy reliance on imported fuels, and goods and services; (2) high empower density and high environmental loading. Specifically, the Taipei area operated its activity on 1.4% renewable sources in 1998, and its emergy self-sufficiency ratio was 0.024 (items 1 and 3 of Table 2). The empower density had increased from 3.25×10^{18} sej km^{-2} in 1936 to 75.90×10^{18} sej km^{-2} in 1998 (item 6 of Table 2). A high emergy/money ratio was found in the less developed regions, in which more emergy to support the economy comes directly from the natural environment without payment of money. As the economic activity in Taipei is driven mainly by imported emergy of fuels, goods and services, its emergy/money ratio was rel-

Table 2
Emergy indices overview of the evolving ecological economic system of Taipei area

Emergy index	Expression	Quantity					
		1936	1951	1966	1981	1991	1998
Emergy source							
1. Fraction used, locally renewable	R/U	0.35	0.35	0.16	0.08	0.02	0.014
2. Fraction of use that is free	$(R+N0)/U$	0.45	0.46	0.22	0.11	0.03	0.020
3. Emergy self-sufficiency	$(R+N0+N1)/U$	0.67	0.72	0.62	0.19	0.03	0.024
4. Fraction of purchased emergy used	$(F+G+P2I3)/U$	0.33	0.28	0.39	0.81	0.97	0.980
5. Fraction of imported service emergy	$P2I3/U$	0.13	0.00	0.01	0.06	0.12	0.102
Emergy intensity							
6. Empower density (10^{18} sej/km^2)	U/area	3.25	3.20	6.83	14.18	53.20	75.90
7. Ratio of concentrated to rural use	$(F+G+P2I3+N1)/(R+N0)$	1.21	1.16	3.54	8.07	37.12	50.10
8. Per capita emergy used (10^{15} sej)	U/P	6.25	5.80	5.71	5.35	16.16	20.80
9. Per capita fuel emergy used (10^{15} sej)	F/P	1.35	1.51	2.78	3.56	5.03	6.52
10. Ratio of electricity emergy used	Elect/U	0.00	0.02	0.05	0.16	0.11	0.13
Ecological economic interface							
11. Ratio of export to import	$(N2+B+P1E3)/(F+G+P2I3)$	1.66	1.00	1.66	0.26	0.71	0.83
12. Ratio of waste to renewable emergy	W/R	0.42	0.47	1.38	5.76	11.35	41.72
13. Ratio of waste to total emergy used	W/U	0.15	0.17	0.23	0.47	0.21	0.58
14. Emergy/money ratio (10^{12} sej/US$)	U/GDP	44.47	36.19	24.19	2.07	1.84	1.73
15. Emergy investment ratio	$(F+G+P2I3+N0+N1)/R$	1.89	1.85	5.08	11.31	53.02	70.84

B: exported products; Elect: electricity used; *F*: imported fuels; *G*: imported goods; GDP: gross domestic products; *I*3: dollars paid for imported service; *N*: indigenous non-renewable flows (*N*0 + *N*1); *N*0: dispersal rural (e.g. soil loss); *N*1: concentrated use (e.g. hydroelectricity); *N*2: exported of raw materials; *P*1: emergy/money ratio; *P*2: world emergy/money ratio; *P*: population; *R*: renewable emergy flow; *U*: total emergy used (*R* + *N*0 + *N*1 + *F* + *G* + *P*2*I*3); *W*: waste.

atively small in 1998 – 1.73×10^{12} sej/$ (item 14 of Table 2) – compared to the world average approximately of 2.00×10^{12} sej/$.

The emergy investment ratio (item 15 of Table 2) is the ratio fed back from the economy to the emergy from free, locally renewable resources. A highly developed region has a higher investment ratio. As shown by Table 2, the emergy investment ratio of the Taipei area in 1998, 70.84, is significantly greater than that of Taiwan as a whole (9.04). The reason for this high emergy investment ratio in the Taipei area is the necessity of importing the emergy of fuels, goods and services to maintain its economic viability. From the viewpoint of emergy synthesis, the economy in the Taipei area has evolved from a rural society in the 1930s to a highly urbanized society with extremely low emergy self-sufficient status.

5. Hypotheses of urban energetics

In this section, a series of specific non-alternative hypotheses are derived from the emergy perspective of urban ecological economic system development. They are as follows:

Hypothesis I. The self-sufficiency of urban areas with respect to their source of emergy decreases with the urbanization process. During the urbanization process, the diversity of emergy sources driving urban systems increases at first, then decrease due to the heavy reliance on fossil fuel.

Hypothesis II. During the process of urban growth, urban productivity is greater than the energy consumed in emergy terms, and information flows of the product of urban structure and the input to support the urban life continue to increase. Due to the increase in the accumulation of urban structure, the efficiency of production decreases.

Hypothesis III. Cities have the highest empower density in the hierarchy of ecosystems. During the process of urban development, empower density and transformity of land uses increase. Owing to the reliance on imported goods and services, the emergy investment ratio of urban areas increases and emergy self-sufficiency decreases with increases in density.

Hypothesis IV. As urbanization increases, the circulation of money also increases, faster than the increase in emergy flows, decreasing the buying power of currency.

Hypothesis V. The organization of emergy flows in urban systems is arranged in a spatial hierarchy with the highest emergy use close to the urban center.

Hypothesis IV. The fragmentation of landscapes on the urban periphery that results from urbanization will affect the distribution of emergy flows.

Hypotheses I–IV are related to the principle of urban ecological economic system and they will be further elaborated and tested in this section.

5.1. Emergy sources

The energy required to maintain the observed structure of a city comes from two principal sources, the life supporting services of its surrounding natural environment and the import of fossil fuels and goods and services from other economic entities. Over the last two centuries, urbanization has been closely tied to the use of fossil fuels. Coal gave rise to industrial society and oil made massive urbanization possible. Whereas rural communities rely primarily on local supplies for food, water and, to a lesser degree, fuel, cities must import these commodities from areas over long distances.

The quantity of energy needed to drive an urban system is closely related to the city's urban and social structure and economic activity. Fig. 3 shows the total driving energy sources of the Taipei area during the past 60 years, expressed as emergy. During the earlier stages of Taipei's urban development, renewable emergy sources contributed a significant percentage of emergy use in urban area; the self-sufficiency of emergy use was higher than 60% before 1960s. Over the years, fossil fuel use at first tended to increase the diversity of emergy sources. However, the present heavy reliance on fossil fuels has lowered the diversity of the city's emergy sources (see for example, Fig. 4). Fig. 5 is a graph of diversity of emergy sources versus population density for Taiwan's 39 city-regions. The graph shows the relationship between emergy diversity and intensity of urbanization indicating that natural areas have the lowest emergy diversity index and rural regions with

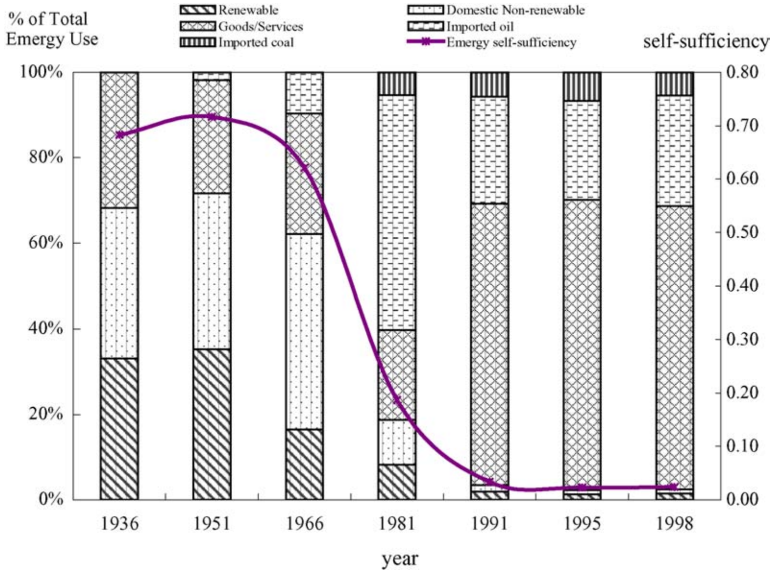


Fig. 3. Emergy budget and self-sufficiency of Taipei area.

medium population density have the highest diversity index of emergy sources. As the intensity of urbanization increases, the diversity index decreases and starts to level off due to the similar pattern of heavy reliance on fossil fuels in urban areas (see Fig. 5).

5.2. Urban metabolism

Like human metabolism, the physical and biological processes of a city are characterized by extensive demand for energy, food and other resources, and by outputs of goods and services and wastes: a concept first suggested by Wolman (1965). The city's process is based on the laws of thermodynamics and as a result a balance sheet of inputs and outputs can be constructed. The approach of quantifying urban metabolism has been proposed in many urban studies since 1960 to assess the consequential environmental effects of urbanization (see for instance Wolman, 1965; Douglas, 1983; Girardet, 1996).

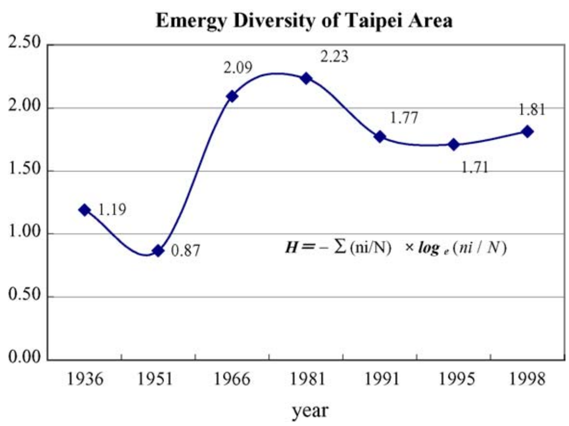


Fig. 4. Emergy diversity of Taipei area.

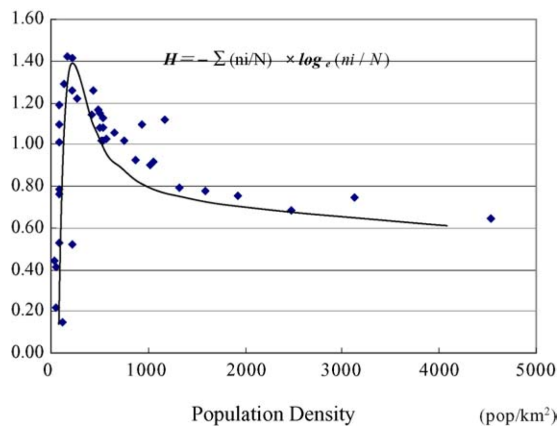


Fig. 5. Emergy diversity and urbanization of Taiwan cities.

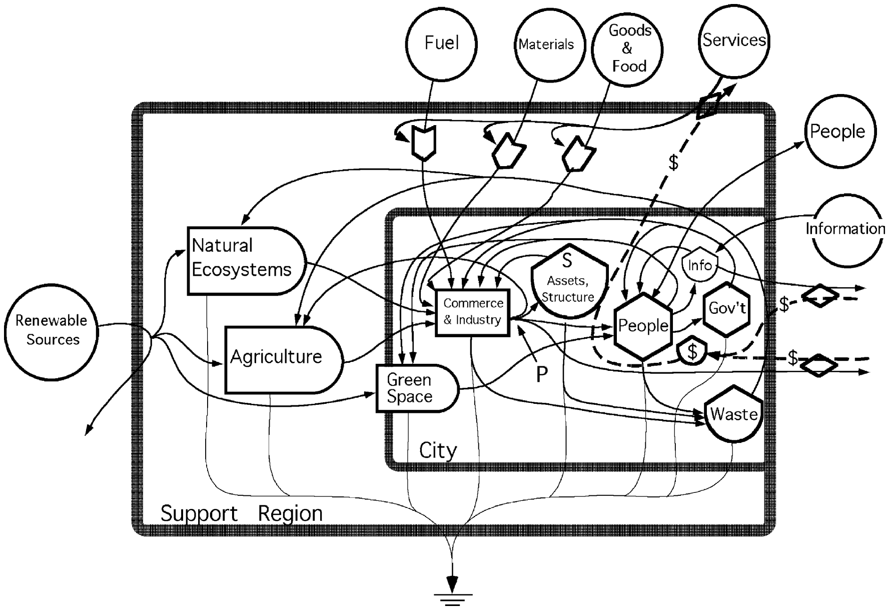


Fig. 6. Energy system diagram of city and its support region.

The existence of a city or town, and the maintenance of its internal structures depend on the inflow and outflow of goods and services and populations. As depicted in the city diagram in Fig. 6, energy, materials for construction, foods and goods, information, and people flow into the urban system. Flowing out are finished products, services, wastes, and information. The essential driving force that maintains the urban assets and its structure is that of the economic exchange with the outside world. Similar to the increase of biomass during ecosystem succession, urban structure (*S*) also increase during its process of development. The productivity (*P*) of an urban system can be regarded as the increase of urban assets or as the magnitude of economic activity. Due to the accumulation of urban structure (*S*), the ratio of *P*/*S* decreases as the urban system reaches its urbanized state (see Fig. 7), which has similar characteristics of ecosystem's decreasing *P*/*B*. The consumption of energy and resources in a city can be regarded as its respiration (*R*) similar to an ecosystem's respiration. After converting Taipei area's economic activity and resource consumption into equivalent emergy units, Taipei's productivity (*P*) is recognized to be greater than its resource consumption (*R*) (Fig. 8). Taipei's *P*/*R* ratio has varied widely in the past but appears to be stabilizing around 2.5 recently.

The emergy value of waste flows in Taipei increased sharply during its stage of rapid economic growth (Fig. 9). This phenomenon indicates that our present urban-industrial civilization is vastly accelerating the process of entropy with unpromising resolution for the future of life on earth.

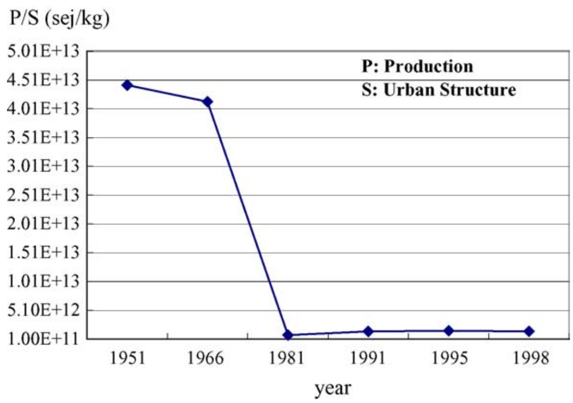


Fig. 7. *P*/*S* ratio of Taipei area.

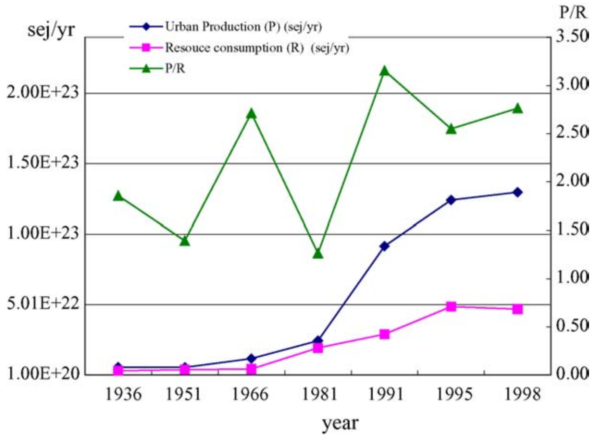


Fig. 8. Urban production and resource consumption of Taipei area.

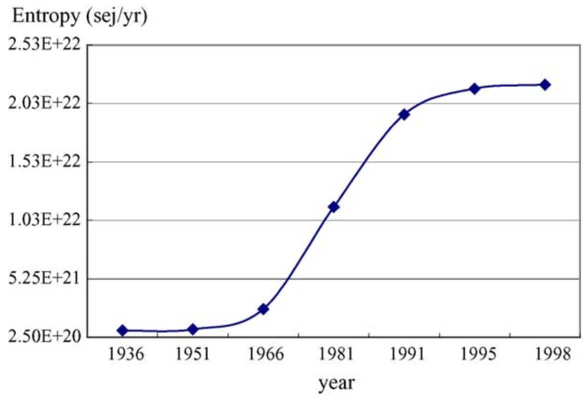


Fig. 9. Entropy of Taipei area.

5.3. Energy hierarchy

Since the definition of an ecosystem is a community of organisms and their physical environment interacting as an ecological unit, viewing the urban system as an ecosystem raises the important question of where humans fit into such a structure. Are humans simply the top predators in ecosystems, or do urban systems represent an entirely new level of energy flow and organization? Humans differ from the top predator group by one very important activity, i.e. they engage in trade, exchange energy and materials across the boundary within which they reside, thereby creating a new and larger organization. An example of such an organization is the hierarchical landscape system of villages, towns, and cities (Christaller, 1933). Large population centers have a much greater range of functions and goods and services than the smaller centers. Cities consume resources that are mainly produced by smaller villages and towns.

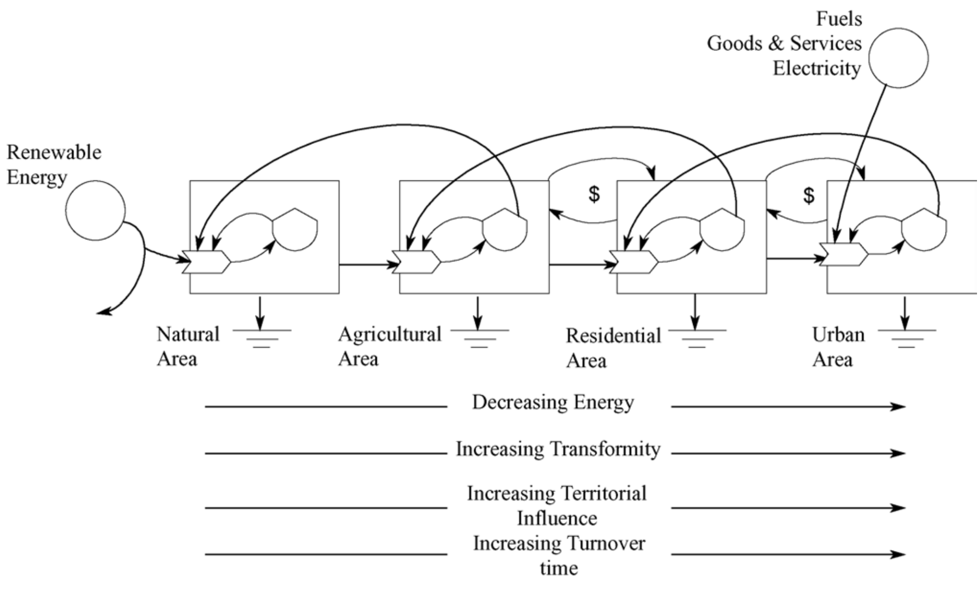


Fig. 10. Energy hierarchy of urban system.

Hierarchy theory allows for the creation of a new level of organization out of the interaction of a number of different parts. The study of ecosystems suggests principles by which energy flows generate hierarchies in all systems. Energy hierarchy, represented by energy transformation chains, develop a special kind of division of labor to reinforce the system's power and efficiency (Odum, 1988, 1996). From a viewpoint of ecological energetics, urban systems represent the highest level of the ecosystem hierarchy. The energy chain in Fig. 10 shows the way the energy decreases through successive levels, while the transformities of the products, territorial influence, and turnover time increase.

Urbanization results in an increased demand for energy to satisfy the needs of the growing urban metabolism. As Fig. 11 shows, the empower density in Taipei area has increased sharply during the past 60 years exhibiting a leveling trend in recent years, and the transformity, the index of energy hierarchy, of each administrative district in Taipei area is highly correlated to the empower density (Fig. 12). The areas with higher empower densities have higher energy transformity. Furthermore, not only does urbanization increase demand for energy, it also increases the demand for land. As urban emergy budgets have increased, cities have expanded their boundaries, pushing back the countryside and expanding the city's emergy footprint. The areas with higher energy hierarchy in Taipei areas have higher emergy footprint, which is expressed as the amount of land required to sustain its emergy inflows (Fig. 13). As a result of increasing the import of fossil fuels, goods and services from outside the system, the emergy investment ratio in Taipei area has also increased rapidly over the past decades (see Fig. 14).

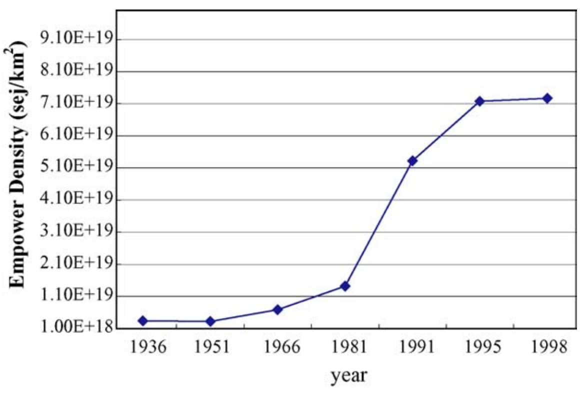


Fig. 11. Empower density of Taipei area.

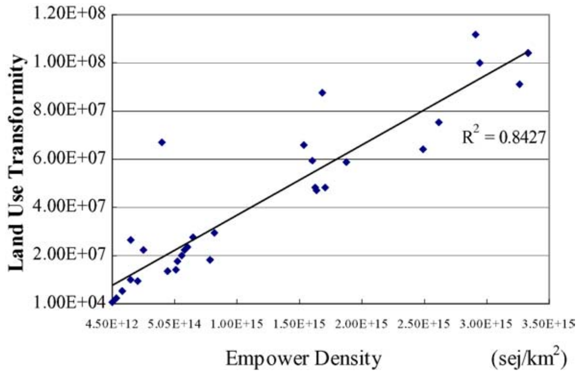


Fig. 12. Empower density and land use transformity of each administrative district in Taipei area.

5.4. *Emergy and money flows*

The development of early cities was closely associated with the emergence of civilization itself. Over the last two centuries, urban growth has enabled countries to capitalize on the economies of scale through transformation and convergence of energy, which is inherent in industrial processes. The flow and transformation of energy through the environment and within the urban system makes possible the circulation of money.

The emergy/money ratio is an index of the average buying power of the currency in an economy. In less developed rural areas, since many environ-

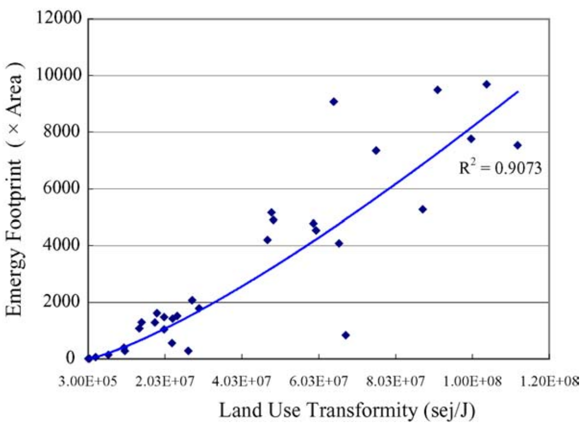


Fig. 13. Emergy footprint and land use transformity of Taipei area.

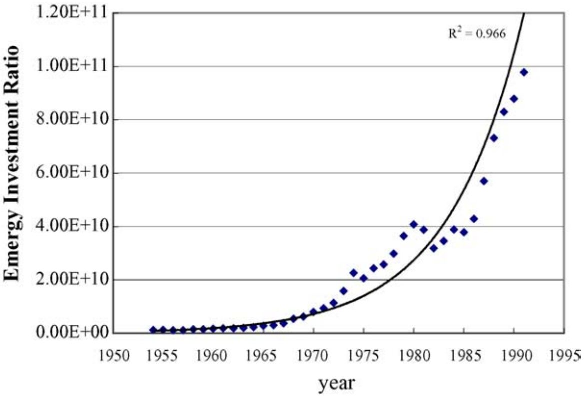


Fig. 14. Emergy investment ratio of Taipei area.

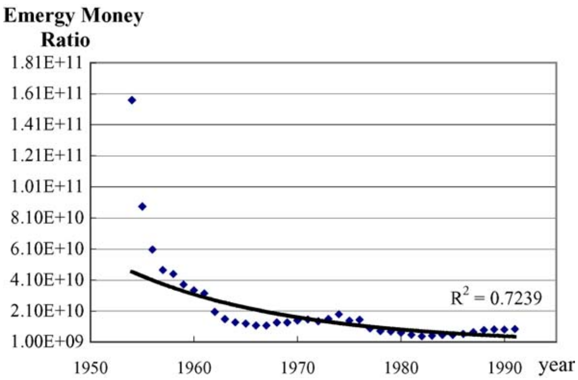


Fig. 15. Emergy/money ratio of Taipei area.

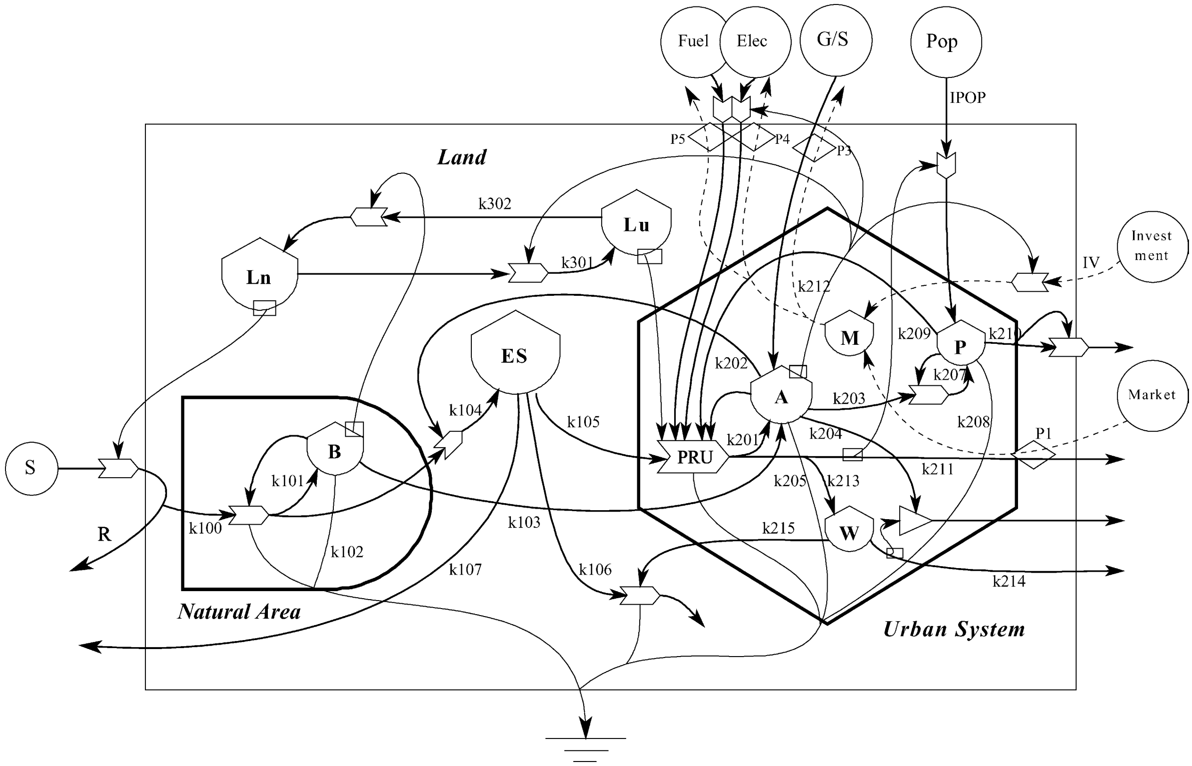
mental resources can be used without purchasing, the emergy/money ratio is highest. The more urbanized an economy the more it relies on purchased emergy and the lower its emergy/money ratio. In other words, money has higher emergy purchasing power in rural areas, meaning that it can buy more real wealth. Fig. 15 indicates that the emergy/money ratio in Taipei area has decreased during its urbanization process. In an urban center like Taipei, nearly all human necessities have to be purchased and brought in from farther areas, money buys less because payment is required.

6. System model of urban energetics

In order to further investigate the mechanisms of energy flows on urban development, one needs to employ ideas of General System Theory (GST) and techniques of energetic analysis for the simulation of urban ecological economics. In this section, a macro model of an urban ecological economic system will be presented for describing system components and interactions of flows and storages for investigating the mechanism of energy flows on urban development (Fig. 16).

An ecosystem is characterized by storage of biomass with inflows and outflows of imports, feeding, maintenance, exports, etc. In an urban system, similarly, storages of structure, population, land, etc., and flows of energy, goods and services, can be identified. Energy can be considered as a common denominator for all processes in the ecosystem, including human economic system. The model developed in this paper comprises subsystems of natural area and urban area. In all, there are eight state variables in the modeled system: biomass (*B*), environmental storage (ES), natural area (Ln), urban area (Lu), urban assets (*A*), money supply (*M*), population (*P*), and waste (*W*); they are interconnected by energy flows marked with coefficients (*k*100, . . ., *k*215). All symbols used in the model diagram were designed by Odum in the development of his energy language, which has been used for analysis, synthesis and simulation of ecological systems since 1960s. Odum's energy symbols have rigorous energetic and kinetic definitions so that they can also represent open-system thermodynamics and the equations for its simulation. The completed diagram of the urban ecological economic system is a rigorous representation of the differential equations and they may be written by translating the energy symbols into mathematical relations (see Fig. 16). A description, explanation, and mathematical representation of these symbols can be found in Odum (1971, 1983, 1996).

The production of biomass (*B*) relies mainly on the flow-limited renewable energies (*R*). The finite flow of renewable sources is represented by an equation of Michaelis–Menten type, $R = S \times \mathrm{Ln}/(1 + k100 \times B)$, which imposes a limit to growth. The accumulated storage in biomass *B* feedbacks to increase biomass production ($k101 \times B$) and converges to support a storage at a higher hierarchy level ($k103 \times B$). In addition, the accumulated storage of biomass *B* affects the conversion of urban land into natural area ($k302 \times B \times \mathrm{Lu}$). Changes in the area of natural system affects the amount of renewable energy ($S \times \mathrm{Ln}$) captured by the



B：Biomass

$dB/dt = k101*B*R - k102*B - k103*B$

R：Environmental remainder

$R = S*Ln - k100*R*B$

$R = S*Ln / (1+k100*B)$

ES：Environmental storage

$dES/dt = k104*R*B*A - k105*PRU - k106*ES*W - k107*ES$

PRU：Urban production

$PRU = ES*Lu*A*P*Fuel*Elec$

$Elec = A*EI$

$Fuel = A*FI$

W：Waste

$dW/dt = k213*PRU - k214*W - k215*W*ES$

A：Urban Assets

$dA/dt = k103*B + k201*PRU + k212*M/P3 - k202*A*R*B - k203*A*P - k204*W - k205*A$

M：Money supply

$dM/dt = k211*PRU*P1 + A*IV - k212*M - Elec*P4 - Fuel*P5$

P：Population

$dP/dt = k207*A*P - k208*P - k209*PRU - k210*P*P + k211*PRU*IPop$

Lu：Urban area

$dLu/dt = k301*A*Ln - k302*Lu*B$

Ln：Natural area

$Ln = L - Lu$

Fig. 16. Energy diagram and system equations of urban ecological economic system.

natural system itself. In addition to biomass, the model also includes an environmental storage (ES), which functions as life-support sources for urban system. The production of environmental storage (ES) is function of renewable energy flow (R), biomass (B), and feedback from urban asset (A) and can be represented as ($k104 \times R \times B \times A$). The amount of environmental storage provided to support urban area is function of urban productivity (PRU), which is represented as a multiplier of environmental storage (ES), urban area (LU), urban assets (A), population (P), and inflows of fuel (Fuel) and electricity (Elec).

The production of urban assets (A) is generated by an autocatalytic interaction (PRU). The addition of urban assets via inflow of goods and services is purchased from external economic system, the amount of which is proportional to the storage of money supply ($k212 \times M/P3$). $P3$ is the price of goods and services. In addition to the feedback of urban assets to reinforce the production of environmental storage ES, and its depreciation ($k205 \times A$), the urban asset also contribute to the treatment of urban waste ($k204 \times W$). The accumulated urban assets will affect the amount of land converted from natural area to urban area ($k301 \times A \times \mathrm{Ln}$), inflow of fuel ($A \times \mathrm{FI}$) and electricity ($A \times \mathrm{EI}$), and investment from outside ($A \times \mathrm{IV}$).

Population (P) is also a storage by an autocatalytic production pattern. The death rate is calculated as a proportion of population ($k208 \times P$). Migration of population also occurs as a crowding effect ($k210 \times P \times P$). Another inflow to urban areas which has profound effects is the immigration of people, resulting from the attraction of urban activities. The higher the urban productivity, the greater the amount of people attracted from outside ($k211 \times \mathrm{PRU} \times \mathrm{IPop}$). The accumulation of money supply (M) in urban systems is mainly due to the exchange of urban product with external economic system ($k211 \times P1 \times \mathrm{PRU}$); $P1$ is the price of general goods. The purchasing of fuel and electricity to power urban production depend on the demand of fuel and electricity and their respective prices ($\mathrm{Elec} \times P4$, $\mathrm{Fuel} \times P5$). The generation of waste W is associated with urban production; the untreated waste is likely to deteriorate the environmental storage ($k106 \times \mathrm{ES} \times W$). The heat sink at the bottom of Fig. 16 represents the dispersion of potential energy into heat, as described by the second law of thermodynamics, which accompanied all real transformation processes and depreciation of storage (for example, $k205 \times A$).

Using Odum's energy circuit language, we described the overview aspect of an urban ecological economic system within the framework of GST by using equations expressing the interactions of system components. The system equations express the interdependence of components within system, and these nonlinearities result in the self-organization of the urban ecological economic system. The evolutionary changes of an urban system depend strongly on the exogenous energetic inputs and the internally self-organized behavior.

7. Simulation results

7.1. A macro-view of the development of urban ecological economic system

In this section, the evolution of urban ecological economic system is described through simulation runs; Taipei metropolitan region is used as a case study to provide numerical data to run this simulation model. After preliminary collection and estimation of data, the coefficients for each pathway in the model diagram (see Fig. 16) can be estimated. Tables 3 and 4 summarize the values of storages and values of assumed flows of the urban ecological economic model. The data of year 2000 were used as basis for estimation and the assumed flows are consistent with known turnover times when inflows and outflows are equal and storage is maximum. Coefficients of equations of the system model can be calibrated from the assumed flows.

Table 3
Storage values for calibrating coefficients

Storage	Name and values	Basis
L	Total area	1.90×10^3 km^2
Ln	Natural area	1.20×10^3 km^2
Lu	Urban area	0.70×10^3 km^2
B	Biomass of natural area	8.53×10^{12} g (forest area 0.853×10^3 km^2 $\times 1 \times 10^{10}$ g km^{-2})
ES	Environmental storage	20.51×10^8 m^3 (total volume of reservoirs)
A	Urban assets	1.05×10^3 km^2 (floor area of urban structure = 150% of urban area)
M	Money supply	8.80×10^{12} TW$ (total saving)
P	Population	5.50×10^6 people (maximum population)
W	Waste	2.09×10^6 t (1 kg person^{-1} day^{-1} $\times$ population)

Table 4
Flow values of Taipei's urban ecological economic system

Flow name	Mathematical expression	Value and basis
Env input	S	3×10^6 m^3 km^{-2} yr^{-1} (rain = 3000 mm yr^{-1} × 10^{-3} m mm^{-1} × 10^6 m^2 km^{-2})
Fuel inflow	FI	1.14×10^{15} J km^{-2} (fuel consumption density of urban floor area)
Electricity inflow	EI	2.54×10^{17} KWH km^{-2} (electricity consumption density of urban floor area)
Population immigration	IPop	37.3×10^3 people 10^{-12} TW$ (ratio of immigration and urban GDP)
Investment	IV	6.54×10^8 TW$ km^{-1} (ratio of investment and urban floor area)
Exchange price of urban output	$P1$	0.294 TW$ TW$$^{-1}$ (assumed ratio of urban productivity)
Price of goods and services	$P3$	0.126×10^{12} TW$ km^{-1}
Price of electricity	$P4$	3 TW$ KWH^{-1}
Price of fuel	$P5$	1.12×10^{-7} TW$/J
Env use by national area	$k100 \times B \times R$	25.2×10^8 m^3 yr^{-1} (70% of Env input = 0.7 × 3 × 10^6 m^3 km^{-2} × 12 × 10^2 km^2)
Env remainder	$R = S \times \text{Ln} - k100 \times B \times R$	10.8×10^9 m^3 yr^{-1} (30% of Env input = 0.3 × 3 × 10^6 m^3 km^2 × 12 × 10^{12} km^2)
Biomass production	$k101 \times B \times R$	1.71×10^{11} g yr^{-1} (based on a growth rate of 0.02)
Biomass depreciation	$k102 \times B$	0.427×10^{11} g yr^{-1} (based on a turnover period of 200 yr)
Biomass use by urban system	$k103 \times B$	1.28×10^{11} g yr^{-1} (assumed to be 1.5% of biomass)
Production of Env storage	$k104 \times B \times R \times A$	2.3×10^9 m^3 yr^{-1} (annual stream inflow to reservoir)
Use of Env storage for urban production	$k105 \times \text{PRU}$	900×10^6 m^3 yr^{-1} (annual water consumption)
Outflow of Env storage	$k106 \times \text{ES}$	1.22×10^9 m^3 yr^{-1} (annual stream outflow)
Production of urban assets	$k201 \times A$	0.21×10^2 km^2 yr^{-1} (assumed growth rate of 2%)
Urban assets contributed to produce Env storage	$k202 \times A \times R \times B$	5.25×10^{-2} km^2 yr^{-1} (assumed to be 0.5% of urban assets)
Urban assets consumed by people	$k203 \times A \times P$	0.149×10^2 km^2 yr^{-1} (assumed to be 15% of urban assets)
Urban assets used for waste treatment	$k204 \times W$	3.15×10^{-2} km^2 yr^{-1} (assumed to be 0.3% of urban assets)
Depreciation of urban assets	$k205 \times A$	0.21×10^2 km^2 yr^{-1} (based on a turnover period of 50 yrs)
Growth of population	$k207 \times A \times P$	0.22×10^6 pop yr^{-1} (based on a 4% growth rate)
Death of population	$k208 \times P$	0.0825×10^6 pop yr^{-1} (based on 1.5% death rate)
Labor contribution to urban production	$k209 \times \text{PRU}$	0.303×10^6 pop yr^{-1} (assumed to be 5.5% of population)
Population immigration	$k210 \times P \times P$	0.11×10^6 pop yr^{-1} (assumed to be 2% of population)
Urban production	$k211 \times \text{PRU}$	7.37×10^2 TW$ yr^{-1} (GDP)
Expenditure for purchasing goods and services	$k212 \times M$	2.64×10^{12} TW$ yr^{-1} (assumed 30% of Money supply)
Generation of waste	$k213 \times \text{PRU}$	2.087×10^6 t yr^{-1} (1.04 kg per capita per day)
Waste treatment	$k214 \times W$	1.88×10^6 t yr^{-1} (90% treatment rate)
Untreated waste	$k215 \times W$	0.209×10^6 t yr^{-1} (10% of waste)
Change of natural area to urban area	$k301 \times \text{Ln} \times A$	0.14×10^2 km^2 (assumed to be 2% of urban area)
Change of urban area to natural area	$k302 \times \text{Ln} \times B$	0.14×10^2 km^2 (assumed to be 2% of urban area)

PRU = Es × Lu × A × P × Fuel × Elec.

Fig. 17 gives the simulation results of the evolution of Taipei's urban ecological economic system. The natural area (Ln), which has been converted to developed land (Lu) decreased gradually over time. With the accumulation of biomass (*B*) and the feedback from urban asset (*A*), the storage of environmental resource (ES) increase rapidly in the early stage and levels off due to the flow-limited characteristics of renewable sources. The supply of environmental resources, together with the inflows of fuels and goods and services from outside the system, enhance the growth and prosperity of the urban system of Taipei. As urban assets (*A*) accumulated, the population (*P*) and money supply (*M*) also increased (Fig. 17B). The increase of urban assets levels off eventually due to the carrying capacity of the natural system.

In order to further explore the effects of change of a specific flow rate on the system as a whole, sensitivity analysis is performed to simulate the change of coefficients (*k*) on system variables (Table 5). As a result, the increased conversion of natural land into developed land ($k103 \times \mathrm{Ln} \times A$) tends to decrease the storage of

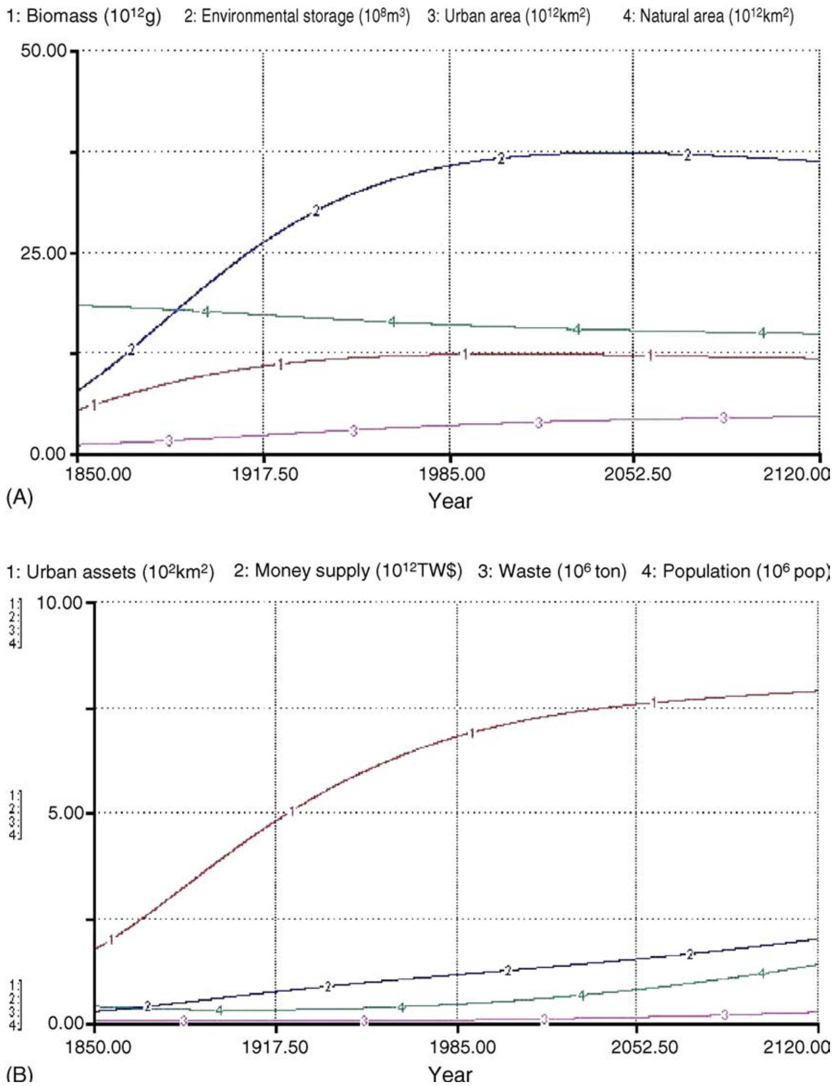


Fig. 17. Simulation results of the evolution of Taipei's ecological economic system.

Table 5
Effects of change of flow rates on storages of urban ecological economic system

Flow	Storage					
	Biomass	Environmental storage	Urban area	Urban assets	Money supply	Population
Increase inflow of fuel, FI	0	0	0	+	−/+	0
Increase inflow of electricity, EI	0	0	0	+	−/+	0
Decrease price of goods and services, *P*3	−	+	+	++	++	+
Increase population immigration, IPop	0	−	0	+	++	++
Increase inflow of investment, IV	−	+	+	++	++	+
Increase production of environmental storage, *k*104	0	++	+	++	++	0
Increase conversion from national area to urban area, *k*301	−−	−−	++	−	−	−

+: increase; ++: significantly increase; −: decrease; −−: significantly decrease; −/+: decrease first then increase; +/−: increase first then decrease; 0: no significant effect.

biomass (*B*). In addition, the inflows of investment (IV) and the decrease in the exchange price (*P*3) for more inflows of goods and services (GS) also decrease the biomass storage (*B*). On the contrary, the increase in the flows of IV and GS translates into an increase of the accumulation of environmental resources (ES). The increase of population inflow (IPop) consumes and eventually decreases environmental resource. The storages of urban assets (*A*) and money supply (*M*) are enhanced by the increase of all other inflows (fuel, electricity, goods and services, population, investment, etc.) to the urban system. The increase in the inflows of fuels (FI) and electricity (EI) first decreases the storage of money supply, then increases it again due to the higher urban productivity. The increase of population is primarily due to the increase of inflows of investment (IV) and goods and services (GS).

7.2. *Energetic characteristics and mechanisms of urban system*

For the purpose of exploring the change of urban energetics during its evolutionary process, emergy and emergy indices are incorporated into the urban ecological economic model for simulation as indicated in Fig. 18. The equations for simulating emergy flows to study the characteristics of urban energetics are summarized in Table 6. The results of simulation indicate that the emergy self-sufficiency of the urban system decreased during the process of urban development and the diversity of emergy sources increased as a result of increasing inflows of emergy from outside the system (Fig. 19A). The *P*/*R* ratio increases rapidly in the early stage of urban development, but is anticipated to level off as the urban system reaches its steady state. Although the urban structure increases, represented by the accumulation or urban assets, the ratio of *P*/*S* also increases due to the accelerated growth of urban productivity. As for the indices of energy hier-

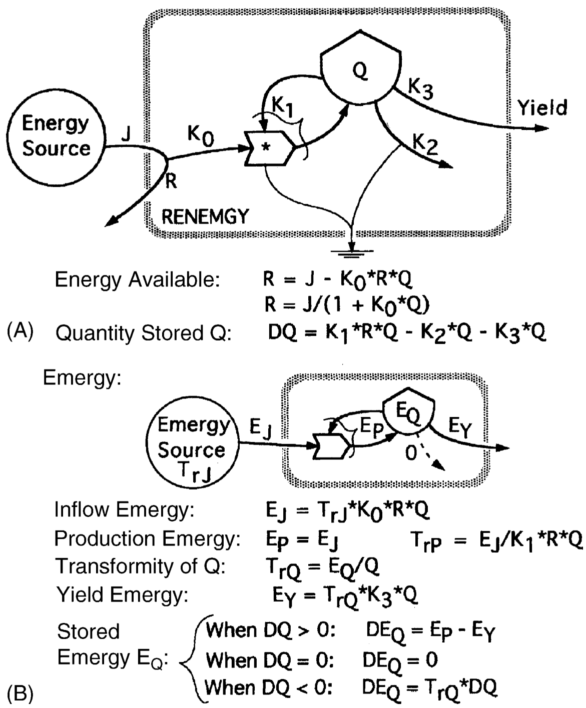


Fig. 18. Energy system diagram and equations for simulating transformity and emergy (redraw after Odum and Odum, 2000).

Table 6
Equations for simulating emergy flows to represent urban energetics

Urban energetics	Equation
Emergy sources	
Diversity (H)	$(-1)\times[(\mathrm{Tr}\,S\times \mathrm{k}100\times S\times \mathrm{Ln})\times \log_e(\mathrm{Tr}\,S\times k100\times S\times \mathrm{Ln}/U)+(\mathrm{Tr\,Fuel}\times \mathrm{Fuel})\times \log_e(\mathrm{Tr\,Fuel}\times \mathrm{Fuel}/U)+(\mathrm{Tr\,Elec}\times \mathrm{Elec})\times \log_e(\mathrm{Tr\,Elec}\times \mathrm{Elec}/U)+(\mathrm{EMR}\times k212\times M)\times \log_e(\mathrm{EMR}\times k212\times M/U)+(\mathrm{EMR}\times \mathrm{IV}\times A)\times \log_e(\mathrm{EMR}\times \mathrm{IV}\times A/U)$
Self-sufficiency ($S\times U$)	$\mathrm{Tr}\,S\times k100\times S\times \mathrm{Ln}/U$
Urban metabolism	
Urban structure (S)	EmA
Ratio of production and structure (P/S)	$(k211\times \mathrm{PRU}\times \mathrm{EMR})/\mathrm{Em}\,A$
Ratio of production and consumption (P/R)	$(k211\times \mathrm{PRU}\times \mathrm{EMR})/[(k202\times A\times B\times R+k203\times A\times P+k204\times W)\times \mathrm{Tr}\,A]$
Entropy	$k213\times \mathrm{PRU}$
Energy hierarchy	
Total emergy used (U)	$\mathrm{Tr}\,S\times k100\times S\times \mathrm{Ln}+\mathrm{Tr\,Fuel}\times \mathrm{Fuel}+\mathrm{Tr\,Elec}\times \mathrm{Elec}+\mathrm{EMR}\times k212\times M+\mathrm{EMR}\times \mathrm{IV}\times A$
Empower density (UD)	U/L
Emergy footprint (EF)	$U/\mathrm{Tr}\,S\times k100\times S\times \mathrm{Ln}$
Emergy investment ratio (EIR)	$(\mathrm{Tr\,Elec}\times \mathrm{Elec}+\mathrm{Tr\,Fuel}\times \mathrm{Fuel})/\mathrm{Tr}\,S\times k100\times S\times \mathrm{Ln}$
Emergy and money flow	
Emergy/money ratio (EMR)	$U/(\mathrm{A}\times \mathrm{IV}+k211\times \mathrm{PRU}\times P1+k212\times M+P4\times \mathrm{Elec}+P5\times \mathrm{Fuel})$

archy, the emergy investment ratio (EIR) increases as a result of urban system's increasing dependence on emergy flows from economic sectors (Fig. 19B). The increase of empower density (UD) and emergy footprint (EF) represents the intense energy flows in the urban ecological economic system over time. Due to the ever decreasing emergy/money ratio, which results from the heavy reliance on imports of external emergy flows, the purchasing power of money in urban system also decreases. Therefore, the emergy value of inflowing goods and services and investment also decrease, which results in the decreasing empower density after year 2000.

According to the simulation results of the urban ecological economic system described in this section, the mechanisms of urban energetics during its evolutionary process can be summarized as follows:

(1) *Energy convergence.* Renewable energy is absorbed and transformed into biomass, which enhances the generation of environmental storage. The convergence of energy from the life support natural system toward the urban consumer center provides the primary driving force for urban development at the early stage, which is also vitally important for a developed urban system.
(2) *Urban-subsidized environmental flows.* The conversion of natural land into urban land decreases the production and accumulation of environmental storage. In order to increase inflows from natural system, the urban system has to feedback energy from urban assets to reinforce environmental flows.
(3) *External-dependency development.* In addition to renewable emergy, the urban system has to rely on fuel, goods and services, and even investment from the external economic system. The increase in the inflows of emergy from external economic system will decrease its emergy self-sufficiency. The economic-environment ratio, represented as emergy investment ratio in this paper, tends to increase and results into a decrease of the purchasing power of money in the urban system.
(4) *Maximum power system.* In order to prosper, the urban system has to increase its inflows of emergy for urban production and for the accumulation of urban assets. The inflow of emergy from external economic system is maximized through the autocatalytic feedback of emergy from urban assets. Therefore, the increase of urban structure, empower density, and diversity of emergy sources characterize a maximizing power urban system.

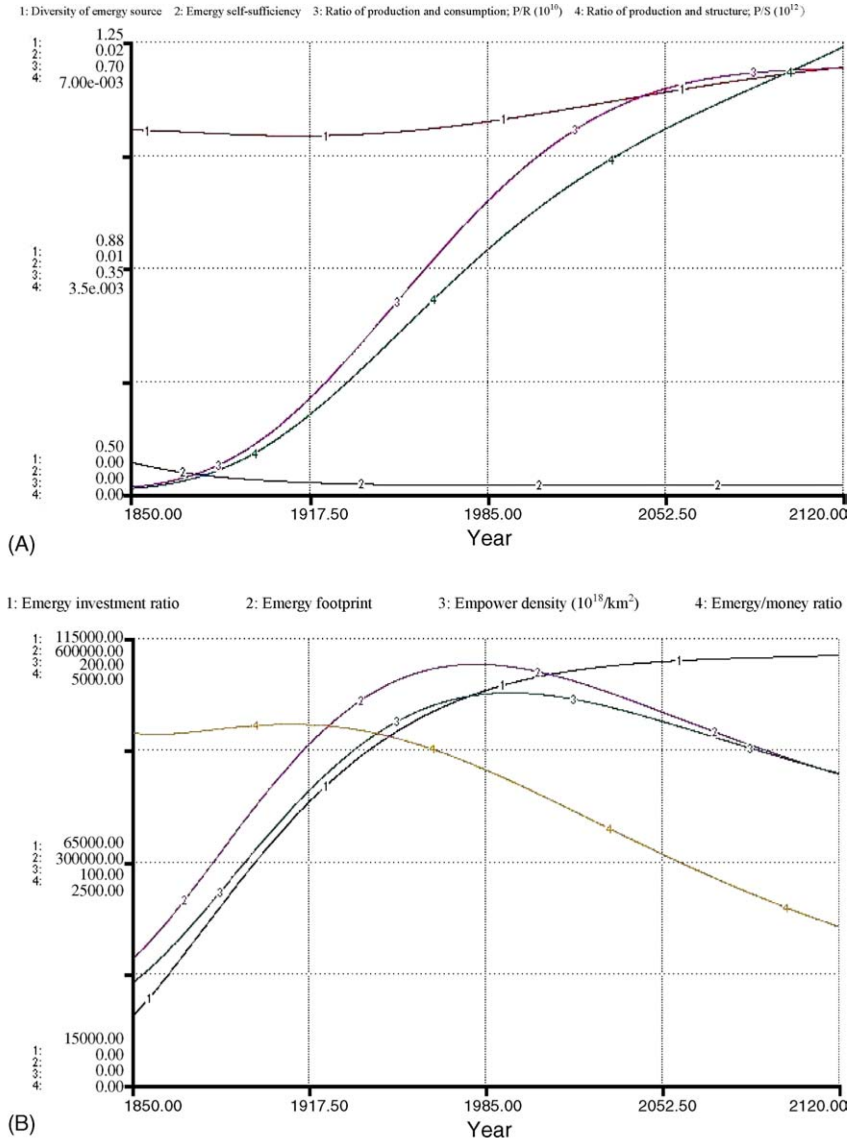


Fig. 19. Simulation results of Taipei's urban energetics.

8. Concluding remarks

The evolution of urban systems exhibits a self-organization dynamics which planners must take into account. When compared to ecosystems, analogies can be made between the stages of urban development and the development stages of ecosystems. In the early stages of development, urban systems exhibit early successional characteristics of rapid growth and inefficient use of resources. As they mature, urban systems generate more structure; higher empower density, greater entropy production and larger information flows. Past research on urban system has studied urban change in many parts of the world, but most of the emphasis to date has been on the socio-economic aspects such as demography or land use change; only recently have energetic aspects also been considered (see Laconte et al., 1982). This paper presents a mixture of quantitative

Table 7
Summary of temporal changes in characteristics of urban development from early development to later stages of development

Characteristics	Trend in urban development
Emergy sources (early stage → urbanized)	
Diversity	Increases at first, then decreases
Self-sufficiency	Decreases
Urban metabolism (early stage → urbanized)	
Urban structure (*S*)	Increases
Ratio of production and structure (*P*/*S*)	Decreases
Ratio of production and consumption (*P*/*R*)	Increases → stabilized
Entropy	Increases
Information	Increases
Energy hierarchy (early stage → urbanized)	
Empower density	Increases
Transformity	Increases
Emergy footprint	Increases
Emergy investment ratio	Increases
Emergy and money flows (early stage → urbanized)	
Emergy/money ratio	Decreases

and theoretical results for understanding the energetics of the development of urban ecological economic system. A summary of changes of the characteristics of energy flows in urban system that are to be expected during the process of urban development is given in Tables 7 and 8. Trends from early stages of development to more mature stages are given in Table 7, while spatial trends along the gradient from the urban center to the rural fringes are given in Table 8. The data presented in the series of graphs show the increasing concentration of energy and material resources and the circulation of money in the central city where energy sources are primarily non-renewable. A greater percentage of total emergy is from renewable sources in rural areas where money has greater overall buying power. The empower density of urban systems varies from 4.50×10^{12} sej/yr/km^2 in the rural fringes to about 3.50×10^{15} sej/yr/km^2. The result of simulation not only describes the evolving urban system in Taipei, but also reveals the change of urban energetics over time.

The system simulation approach adopted in this paper advocates models capable of taking complex growth into account, while retaining extreme simplic-

Table 8
Summary of spatial changes in characteristics of developed lands from the Central city to the rural fringe

Characteristics	Spatial trend from fringes inward
Spatial hierarchy (urban center → rural)	
Fuel use	Decreases
Environmental input	Increases
Diversity of emergy sources	Decreases
Empower density	Decreases
Transformity	Decreases
Emergy investment ratio	Decreases
Emergy/money ratio	Increases
Entropy	Decreases
Urban fragmentation (urban center → rural)	
Fractal dimension	Decreases
Measures of energy hierarchy (transformity, source diversity, empower density, entropy, emergy investment ratio	Decreases

ity in the model structure. This is the key feature of the general system theory of dynamic model. Although energetics approaches are powerful in studying macro patterns and mechanisms in ecological systems, alternative approaches to modelling ecological systems also exist. For example, individual-based models (IBMs) emphasize individual (or agent) behavior and interactions, and were developed at the end of the 1980s. These were followed by multi-agent simulations (MASs) (Bousquet and Le Page, 2004). While these different modelling approaches provide useful insights for different aspects of ecological complexity, systems modelling still remains a powerful tool to understand the "whole" of an ecosystem (Wu and Marceau, 2002).

Although the items listed in Table 7 was tested using data for Taiwan cities, they still must be considered provisional or hypothetical; they should be further verified with more cases and with longer spans of data. While most of the trends outlined in Tables 7 and 8 should be further explored and elaborated, the "how" and "why" remain as matter of debate about different approaches to self-organization of cities as in Portugali (1997). One hypothesis of self-organization of cities relies on the concept of dissipative structure as the inherent capacity of moving far-from-equilibrium. Odum (1988) contended that during self-organization, system designs develop and prevail with strategies of maximizing power intake, energy transformation and those uses that reinforce production and efficiency. Many urban scientists, even ecologists, might not accept this hypothesis. Much depends on the outcome of the current debate about mechanisms of evolutionary change. This paper is not concerned with debating the actual mechanisms of the evolutionary process in urban ecological systems, but rather the way in which system level responses can be explained by the interactions and feedback of components in an evolutionary dynamic.

The system model developed in this paper uses Taipei as an example of urban development for discussion of urban energetics. It is somewhat restricted to the urban setting itself. The model of urban ecological economic system could be further expanded to include interactions with external system under the impact of globalization. For example, the city not only attracts investment from outside, but socio-economic resources have also been attracted by the external mega system. In another words, the energy of an urban system converges toward another higher hierarchy level in the global setting of the planetary economy. Although the system modelling approach continues to dominate the simulation of energy and material flows in various ecosystems, spatial modelling seems to have taken over the central place of ecological modelling since the 1990s (Wu and Marceau, 2002). There have been many efforts to extend ecosystem models to spatial simulations, for example, the Patuxent Landscape Model (Costanza et al., 1990; Binder et al., 2003), LANDIS (Scheller and Mladenoff, 2004) and Ecospace (Christensen and Walters, 2004). In order to explore the hypothesis of spatial energetic hierarchy of urban system, the next logical progression is the application of a GIS-based simulation model for the representation of spatial development of urban ecological economic system in the context of energy flows. It is hoped that this paper and the concepts in it may further our understanding of the urban ecological economic system and stimulate further ideas and research need for exploring the mechanisms of energetic flows in the urban system.

Acknowledgements

I would especially like to thank Mark Brown for his thorough review and comments on the manuscript. Financial support for this research was provided by the National Science Council, Executive Yuan of Taiwan (Grant nos. NSC90-2415-H- 305-005 and NSC91-2411-H-305-003).

References

Binder, C., Boumans, R.M., Costanza, R., 2003. Applying the patuxent landscape unit model to human dominated ecosystems: the case of agriculture. Ecol. Model. 159, 161–177.

Bousquet, F., Le Page, C., 2004. Multi-agent simulations and ecosystem management: a review. Ecol. Model. 176, 313–332.

Brown, M.T., Ulgiati, S., 2004. Emergy and environmental accounting. In: Cleveland, C. (Ed.), Encyclopedia of Energy, vol. 2. Elsevier, pp. 329–353.

Christensen, V., Walters, C.J., 2004. Ecopath with ecosim: methods, capabilities and limitations. Ecol. Model. 172, 109–139.

Christaller, W., 2004. Central Places in Southern Germany. Prentice-Hall, New Jersey (translated by Baskin, C.W., 1966).

Costanza, R., Skalar, F.H., White, M.L., 1990. Modeling coastal landscape dynamics. BioScience 40, 91–107.

Douglas, I., 1983. The Urban Environment. Edward Arnold, London.

Geddes, P., 1915. City in Evolution. Williams and Norgate Ltd., London.

Girardet, H., 1996. The Gaia Atlas of Cities. Gaia Book Ltd., London.

Haines, V., 1986. Energy and urban form: a human ecological critique. Urban Affairs Quart. 21, 337–353.

Huang, S.-L., 1998a. Urban ecosystems, energetic hierarchies, and ecological economics of Taipei metropolis. J. Environ. Manage. 52, 39–51.

Huang, S.-L., 1998b. Ecological energetics, hierarchy, and urban form: A system modeling approach to the evolution of urban zonation. Environ. Plan. B: Plan. Design 25, 391–410.

Huang, S.-L., Lai, H.-Y., Lee, C.-L., 2001. Energy hierarchy and urban landscape system. Landscape Urban Plan. 53, 145–161.

Huang, S.-L., Odum, H.T., Chang, S.-L., 1996. Ecological Energetic Evolution of Urban System, A Report to the Chiang Ching-Kuo International Scholar Exchange Foundation (RG008-D-'92). Graduate Institute of Urban Planning, National Chung-Hsing University, Taipei, Taiwan (in Chinese).

Jaakson, R., 1977. Urbanization and natural environments: a position paper. Urban Ecol. 2, 245–257.

Laconte, P., Gibson, J., Rapoport, A. (Eds.), 1982. Human and Energy Factors in Urban Planning: A Systems Approach. Martinus Nijhoff, The Hague.

Martinez-Alier, J., 1987. Ecological Economics. Blackwell, Oxford.

Odum, H.T., 1971. Environment, Power, and Society. Wiley, New York.

Odum, H.T., 1995. Self-organization and maximum power. In: Hall, C.A.S. (Ed.), Maximum Power: The Ideas and Applications of H.T. Odum. University Press of Colorado, Niwot, CO, pp. 311–330.

Odum, H.T., 1988. Self-organization, transformity, and information. Science 242, 1132–1139.

Odum, H.T., 1996. Environmental Accounting: Emergy and Environmental Decision Making. Wiley, New York.

Odum, H.T., Odum, E.C., 1981. Energy Basis for Man and Nature, 2nd ed. McGraw-Hill, New York.

Odum, H.T., 1983. Systems Ecology. Wiley, New York.

Odum, H.T., Odum, E.C., 2000. Modeling for All Scales. Academic Press, San Diego.

Odum, H.T., Odum, E.C., 2001. A Prosperous Way Down. University Press of Colorado, Boulder, CO.

Odum, H.T., Peterson, L.L., 1972. Relationship of energy and complexity in planning. Archit. Design 43, 624–629.

Portugali, J., 1997. Self-organizing cities. Future 29, 353–380.

Prigogine, P., Allen, P.M., Herman, R., 1977. The evolution of complexity and the laws of nature. In: Laszlo, E., Bierman, J. (Eds.), Goals for a Global Community. Pergamon, Oxford.

Scheller, R., Mladenoff, D., 2004. A forest growth and biomass module for a landscape simulation model, LANDIS: design, validation, and application. Ecol. Model. 180, 211–229.

von Bertalanffy, 1968. General System Theory. George Braziller, New York.

Wolman, A., 1965. The Metabolism of City. Scientific American, pp. 179–188.

Wu, J., Marceau, D., 2002. Modeling complex ecological systems: an introduction. Ecol. Model. 153, 1–6.