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Taking the pulse of urban economy: From the perspective of systems ecology

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ABSTRACT

Pulsing paradigm is regarded general for all scales of ecosystem. The pulsing succession view insists that a resource-dependent system will approach its peak through intensive consumption of resources, then move towards recession and get ready for the next cycle. Urban economy, as an open and resource-dependent subsystem in the whole ecosystem may pulse, and its quantitative growth in physical scale will be limited by the finite ecosystem eventually. This raises one problem: what would be the future of urban economy when it gets to the physical climax under the ecological constraint? Modelling is a feasible approach to simulate and reveal the pulse of a large scale system whose wave length is too long for individuals to witness. In this study, systems ecology-modelling, as a combination of ecological modelling and theories of systems ecology, is applied to take the pulse of urban economy. Cosmic emergy is applied to synthesize the material, energy, information, currency and population flows and stocks, which greatly facilitates and simplifies the simulation. Taking Beijing city as a case, the systems ecology-modelling is carried out, and the pulses of Beijing's economy and its components are partly observed. Suggestions on urban management are proposed accordingly.

1. Introduction

The pulsing succession view insists that global economy, as a typical resource-dependent system, will reach its peak through intensive exploitation of natural resources accumulated in a long time, then move towards recession into a low consumption stage and getting ready for the next cycle (Odum, 1983a,b). This pulsing paradigm is depicted as Fig. 1, from which four main stages of the pulsing cycle can be recognized: (1) Sharp growth of the size of socioeconomic capital based on abundant available resources, with low-efficiency and high-competition; (2) Climax and transition, when the economy reaches the maximum size allowed by the available resources, the efficiency increases, collaborative competition pattern forms, and the information is stored for descent; (3) Descent, as a decrease in the quantitative size of socioeconomic capital but qualitative improvement with adaptations to less available resources; (4) Low resource restoration for a new cycle ahead, in this stage, socioeconomic capital reports no growth, and consumption of resources is smaller than its accumulation (Odum et al., 1995; Odum and Odum, 2001).

With the booming growth of urban economy, people are confronted with increasing ecological crises, such as the drastic decline of natural capital (natural resources inside cities) and the shrinkage of environmental capacities to carry waste emissions (Chen et al., 2006; Chen and Chen, 2006; Ji et al., 2014). As an open and resource-dependent subsystem in the whole ecosystem, the growth of urban economy as a quantitative increase in physical scale will be limited by the finite ecosystem over long periods of time (Daly, 1974, 1990, 1991, 1992). This raises the problems: would urban economy evolves with its pulse from a long time scale? what would be the future of urban economy when it gets to the physical climax under the ecological constraint? Therefore, taking the pulse of urban economy and adjusting its growth pace according to surrounding conditions are of great importance towards sustainable development. Urban economy is a large scale system, and modelling is hence necessary since it is almost impossible for individuals to witness the whole pulse cycle of the urban economy. Decision makers are supposed to alter the planning and management ideas in different pulsing stages and only by adjusting attitude and behaviour according to environmental pulse can we ensure the sustainable development of both the human economy and the environment. The modelling and simulation can safeguard decision makers a better understanding of the evolution mechanism of urban economy and the environment, as well as export a general idea of the current stage at which the urban economy works.

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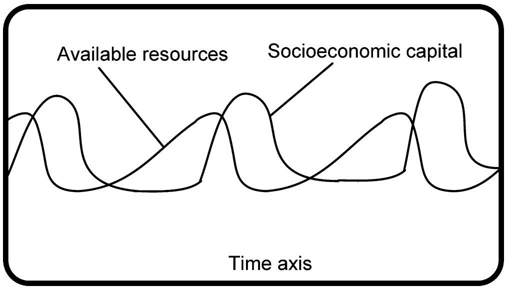

Fig. 1. The pulsing succession of global economy. (Referring to: Odum and Odum, 2001).

The method of ecological modelling is frequently used by planners and decision-makers for management and regulation. The idea of ecological modelling first came out in the 1920s when mathematical models such as Lotka and Volterra's competition and predation model (Lotka, 1922a,b; Volterra, 1926) and Verhust and Pearl's logistic growth model (Pearl and Reed, 1920; Sibly and Hone, 2002) were introduced into ecological fields. The 1970s witnessed the fast development of ecological modelling. The International Ecological Modelling Institute was founded and later became the academic frontier of its field, when ecological problems become unprecedentedly complicated, and the conflicts between human activities and the environment are more prominent (Ji and Chen, 2010). Thus, ecological models are more macroscopic in order to take human society into consideration (Ulgiati and Brown, 1998; Coulter, 2002; Jiang and Chen, 2011; Chen and Yang, 2013), and more and more decision makers are using ecological modelling to better their plans and lower the risks. Since the rapid urbanization challenges facing urban sustainable development all over the world, ecological modelling for urban strategic management has attracted keen interest from a lot of scholars and policy makers' interests (Yuan et al., 2008; Feng et al., 2013), and numerous studies have applied ecological modelling to reveal the metabolism of cities recently (Kennedy et al., 2007, 2011; Churkina, 2008; Chen and Chen, 2012, 2014; Chen et al., 2014).

However, with the development of ecological modelling, associated problems are raised, such as the subjectivity in parameter assessment and the lack of reliable models for either natural or socioeconomic system. Systems ecology brings novel ideas that are effective in building an ecological model. Ecological modelling founding on the theories of the perspective and the theories of systems ecology is entitled as systems ecology-modelling in this study, which is a dynamic integration of systems ecology and ecological modelling. Systems ecology as the application of system theory in ecology (Odum, 1971), mainly focuses on the inter-connection within an ecosystem and the performance of the entire system (Odum, 1971, 1983; Brown and Ulgiati, 2011). As one of the pioneers to study the operating mechanism of ecosystem with the aid of computers, Odum gradually set up a series of Macroscopic Mini-models in the basic framework of systems ecology, and these models are applied in several studies to realize a macroscopic forecasting (Huang, 1998; Huang and Chen, 2005; Jiang and Chen, 2011). This study would like to further strength the intrinsic laws of ecology and eco-thermodynamics embedded in these models, especially the maximum empower principle which is regarded widely existing in ecosystems (Odum, 1989; Odum and Odum, 1989; Kleidon, 2009a,b). Based on the maximum empower principle, the systems ecology-modelling is able to use the simplest method to highly integrate and generalize the dynamic mechanism of complex systems on a large scale. Such models aim at conceptualizing the development trend of a system rather than giving an accurate prediction (Odum, 1989), which is more feasible to get a general idea of the functional dynamic mechanism of a system. Compared with conventional ecological modelling, systems ecology-modelling follows the intrinsic designs and laws of ecosystem, and thus avoids complex explanation of mathematic methods, lowers the subjectivity and uncertainty rooted in the parameters assessment, and brings the model closer to reality (Kangas, 1995).

Urban economy emerges with complicated structure of diverse ecological stocks of natural resources, suburban agricultural capitals, urban centre capitals, population, as well as culture and information capitals, and various ecological flows of material, energy, currency, population, and information. The diversity of stocks and flows leaves the modelling of an urban economy great complexity and uncertainty. This study combines systems ecology-modelling and the theory of cosmic emergy to dissolve the complexity instigated by the diversity of ecological stocks and flows in urban economy. Cosmic emergy, as a combination of cosmic exergy and the existing solar emergy, is proposed by Chen (2005, 2006) to construct a biophysical evaluation paradigm from the perspective of systems ecology. Cosmic exergy is defined as the maximum work that the thermodynamic system of earth can perform when the thermodynamic equilibrium is achieved between solar radiation as a hot thermal reservoir and cosmic background as a cold thermal reservoir (Chen, 2005, 2006). Cosmic emergy as embodied cosmic exergy, refers to the cosmic exergy consumed directly or indirectly in making or sustaining a general product or service. The theory of cosmic emergy proves that cosmic exergy is the primary driving force of the earth system to revitalize the metrological system, feed the hydrological system, renovate the biosphere and make all other natural and anthropogenic phenomena possible (Chen, 2005, 2006).

As the real wealth of the ecosphere and the human society, cosmic exergy is proved scarce related to the scale of human activities (Ji, 2011). Being characterized universal, scarce and exclusive, cosmic exergy as the primary driving force of the biophysical world, is proved qualified as the fundamental metric of ecological stocks and flows, no matter those are natural and manmade. Therefore, the diverse ecological stocks and flows of material, energy, information, currency and population in urban economy are able to be integrated into cosmic emergy, which largely safeguards the briefness of the model and preserves the accurate information.

In the author's doctoral dissertation, cosmic emergy based ecological accounting and modelling are systematically discussed and applied in the evaluation of urban economy of Beijing (Ji, 2008), with the main results primarily reported in Chen et al. (2010). Based on the doctoral dissertation, the theory of cosmic exergy as the primary driving force of the biophysical world and as the fundamental metric of ecological value of both natural and man-made resources was discussed, and the method of cosmic emergy as an alternative to conventional monetary based accounting and evaluation of urban economy is illustrated in Ji (2011). To move a further step to those mentioned studies, this study brings more comprehensive views on the pulse paradigm, and aims at taking the pulse of urban economy by modelling. On the basis of the accounting results displayed in Ji (2011), the evolution trends of Beijing's economy and its component stocks of natural resources, agricultural capitals, urban capitals, population, as well as the culture and information capitals are simulated. Policy suggestions on the urban management of Beijing City are proposed accordingly.

The remainder of this paper will be structured as follows: part 2 illustrates the theoretical basis of the superiority of systems ecology-modelling which follows the intrinsic design and laws of ecosystem. Several systems ecology theories of autocatalysis feedback design, maximum power principle, pulsing paradigm and hierarchy are discussed and necessarily updated according to the theory of cosmic emergy. Then, part 3 takes Beijing City as a case to display how to get the pulse of an urban economy by systems ecology-modelling. A toy model is established to understand the evolution mechanism and the development trend of Beijing's economy. Part 4, the results and discussion part, illustrates the pulse of Beijing's economy and its component stocks like environmental capital, suburban agricultural capital, urban centre capital, financial capital, population capital, culture and information capital. The pulsing paradigm embedded in the results of the toy model is discussed. Part 5 makes summary and puts forward targeted policy proposals towards a prosperous way down of Beijing's economy.

2. Theories

2.1. Autocatalysis feedback design and maximum power principle

In the process of self-organizing, there can be two basic system designs, non-feedback design and the autocatalysis feedback design (Odum, 1995), as shown in Fig. 2.

For a simple non-feedback design (no. 1), the growth dynamic equation for its stock Q_1 is

$$\frac{dQ_1}{dt} = k_{11} \times S - Q_1 - k_{13} \times Q_1. \quad (1)$$

where S is the inflow of low-quality energy, and k_{11}, k_{12}, and k_{13} are the coefficients of each flow. For an autocatalysis feedback design (no. 2), through the conversion path a great number of low-quality energy enters the production processes from the left, accumulated as a high-quality product stock. A small amount of high quality feedback flows in the opposite way from product stock into the production process, in order to increase the capability to obtain energy of the stocks. Stock Q_2's growth dynamic equation is

$$\frac{dQ_2}{dt} = k_{21} \times S \times Q_2 - k_{22} \times Q_2 - k_{23} \times S \times Q_2 - k_{24} \times Q_2. \quad (2)$$

Similarly, k_{21}, k_{22}, k_{23}, and k_{24} are also marked as the coefficients of each flow. Within an energy transformation network, non-feedback design systems can only develop when there exists low density energy that is not enough to support autocatalysis feedback designs (Odum, 1995). Otherwise, the autocatalysis feedback designs will compete with the non-feedback design for energy with an absolute advantage.

Lotka (1922a,b) defined the autocatalysis feedback design principle as the maximum empower principle, and regarded it as the fourth law of thermodynamics, following which, the design that can obtain the maximum power (that is, maximize of energy transformation within a given time) wins. In an ecological network, when there's limited energy, self-organizing system tries all kinds of designs to achieve the maximum energy transformation. In the competition, only the maximum power design survives eventually. In sum, the maximum empower principle explains why some designs are lasting while others are fleeting, and why successful systems have similar structures.

The maximum empower principle has been proven a general rule in different fields. For Earth system processes like atmospheric circulation, hydrothermal conversion and etc., many studies indicate that power generation and transfer is maximized during these processes (Lorenz, 1960; Paltridge, 1979; Kleidon, 2010a). In biospheric evolution, life is observed to evolve to maximize power generation and consumption (Kleidon, 2009a), and according to Kleidon (2010b) there are abundant cases in environmental system and ecosystem as well.

As an important progress of systems ecology, Odum proposed the maximum empower principle of emergy (Odum, 1996) based on the maximum empower principal, indicating that system designs which can transmit and transform the maximum amount of emergy within a given time prevails. Considering cosmic exergy as the resources supporting biosphere and human social activities, the maximum empower principle could be applicable to indicate that within an ecological network, only the design that obtains the maximum cosmic emergy power will survive in the end. According to Fig. 2 (no. 2), in ecological network, autocatalysis feedback design doesn't take in outside cosmic exergy flow (low quality energy S, as Fig. 2 depicted) passively, instead they actively return part of their stock as the investment to itself and other systems to grow together in the long-run. Similar design exists widely in both ecosystem and human socioeconomic systems.

2.2. Pulse paradigm and hierarchy

Pulse is regarded as a general paradigm of all the scales of nature from tiny fast systems of biochemistry to the largest galaxies of the cosmos (Odum et al., 1995). As observed, nearly all ecosystems pulse (Odum, 1989, 1995). Human economies as compound ecosystems pulse as well, and the idea that economic evolution is subject to cyclical fluctuation has been around for more than a century (King, 1993). Berry's book organized the wide discussion on the topic of economic long waves, and he investigated the relationship between economic growth and urban-ward migration, and concluded a phenomena of half-century long wave's (Berry, 1991). Kondratiev once put forwarded the theory of long economic cycle (also called Kondratiev waves, or *K*-waves), indicating that the modern capitalist world economy evolves with sinusoidal-like cycles averaging fifty and ranging from approximately forty to sixty years in length, and consisting of successive phases of over-expansion and collapse (Kondratiev and Konjunktury, 1925). Although the long economic cycle is not completely accepted by current mainstream economics, and maybe average fifty years-length is not a typical wave length for real economy, the pulses of human economy and civilization are indeed observed from historical records.

Urban economy, as a self-organizing, resources-dependent, and energy-open system, driven by pulsing energy inputs as well as oscillating components within its own network, must pulse in the long term. Abundant historical records show that the lifecycle of many ancient city–state civilizations followed the pulsing style, for example, the ancient Maya, the ancient Greek, the Sumerian Civilization, and some Chinese ancient cities, typically, Chang'an and Luoyang, which used to serve as the imperial capitals of many dynasties in ancient China. Many scholars believe that fluctuation of the environment has exerted an indispensable influence on the rise and fall of city–state civilizations (Wang, 2002; Gill et al., 2007; Yaeger and Hodell, 2008; Glaeser, 2011; Turner and Sabloff, 2012).

As depicted in Fig. 1, there is a reciprocal relationship between natural capital and socioeconomic capital for an economy, just like that "growth of one part of nature consumes and pulls down another part of nature" (Odum et al., 1995). Urban economy is constantly receiving available energy which is transformed and embodied in natural capital after a slow and long process. The socioeconomic capital reports a weak growth during this storage stage, while it rises rapidly and natural capital goes down sharply when urban economy goes through an intense exploitation of resources.

It appears to be a general principle that the self-organizing pulsing succession systems prevail in the long run (Holling, 1986; Odum et al., 1995), since the pulsing succession system with the autocatalysis feedback design can transmit more power than any other systems (Ulgiati et al., 2007). In addition, the autocatalysis feedback design aims at long-run profits. Taking the traditional fallow farming as an example, fallow farming allows lands to rest and soil fertility will be renewed by adding farm manure. Thanks to the fallow form, China's agricultural civilization has sustained for more than five thousand years, and we still learn and benefit from this ancient wisdom (Gong et al., 2003). But modern intensive

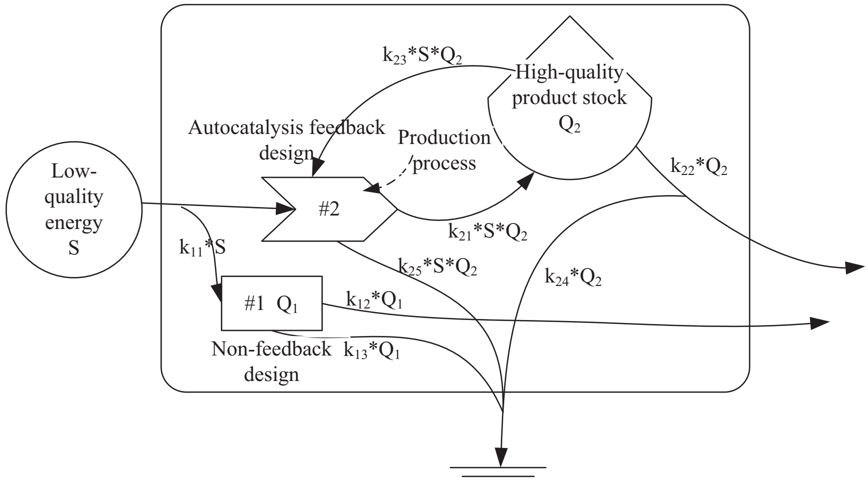

Fig. 2. Two basic designs in self-organizing process. (Referring to: Odum, 1995).

farming pursues high production growth without fallow, which makes soil overwhelmed. In order to ensure the soil fertility, increasing chemical fertilizer that could rapidly fertilize soil is used, resulting in serious soil erosion and soil harden deterioration (Zhang et al., 2010).

Earth system is hierarchical (Kleidon, 2010a), and pulsing paradigm exists in different hierarchies. As another crucial progress of systems ecology, Odum brought forward the concept of energy hierarchy and indicated that all energy transformations of the geo-biosphere can be arranged in order to form an energy hierarchy (Brown and Ulgiati, 2004a,b; Ulgiati and Brown, 2009).

Fig. 3a sketches the hierarchical network of complex ecological–economic systems, with many small and fast turnover stocks on the left and *f* and comparative fewer stocks of larger concentration and control power on the right. During the transformation, energy flow decreases, while concentration of the stocks, territories of support, intervals between feedback pulses to lower levels, and intensity of episodes of mass and energy recycles all increase. Hierarchy means that units at lower levels contribute to fewer units at a higher level, and units in the higher level in turn control those at the lower levels to maintain and reinforce the hierarchy structure.

As shown in Fig. 3a, there are lots of parallel processes occurring in the same hierarchy. When given an overall view of a large ecological–economic system, for example, a city, the linear hierarchies of cities can be simplified as Fig. 3b with five hierarchies of primary production, agricultural production, urban production, population production, and culture and information production processes. As the results of energy transformations in ecological–economic networks, population and information stocks at the highest hierarchies of cities own the largest amplifier control effect on the whole urban economy.

As shown in Fig. 4, pulse exists and differs in different hierarchies of ecosystem.

Due to the fact that systems disconnect among different hierarchies, therefore their pulses influence each other. The large-scale systems in upper hierarchy have strong anti-interference power, and fluctuation in the systems in lower hierarchy exerts weak and lagging influence on them. However, fluctuation of the systems in upper hierarchy often causes serious destruction or might even lead to collapse of the systems in lower hierarchy with small scale (Odum and Odum, 2001). Systems with more stocks can tolerate more serious fluctuation. For example, some small economies break down in global financial crisis while large economies are still robust.

There is an optimal pulse frequency for systems in any hierarchy of any scale (Odum, 1983a,b), and the system can reach its balanced accumulation and consumption status at such frequency. In nature, many organisms achieve sustainable development by changing its pulse to match that of the environment. For example, herbivores have learned to adjust their reproduction time according to the growing cycle of plants to avoid shortage of food. Traditional migrating agriculture and nomads also adjust their ways of farming and grazing according to the pulse of the environment.

Human economy and the environment are large-scale systems, and for each of us it is almost impossible to witness their full pulse cycle. However, it is possible to rely on common patterns of self-organizing systems and the historical and present situation of the economy and the environment to simulate the cycles.

3. Method: Taking the pulse of Beijing's economy

3.1. The hierarchy of the ecological network of Beijing's economy

Rooted deeply in its long history and central political and cultural position, Beijing is one of the most attractive cities in China. Distinct spatial expansion has been witnessed during recent decades coupled with enormous economic growth, which almost results in the deficit of ecological carrying capacity of local ecosystem. Like other metropolises in developing countries, Beijing is facing the dilemma of growth of economic capital versus stagnation of ecological capital. Located in the Hai River Basin, where the environment is deteriorating during fast urbanization, Beijing is frequently threatened by soil erosion, sandstorms and some other natural disasters.

Based on the understanding of the action of ecosystem and related theories discussed in Section 2, and by using the energy circuit language developed by Odum (1967, 1972a,b) (see Appendix A), the ecological network of Beijing's economy is sketched as Fig. 5. From this Figure, it can be recognized that urban economy of Beijing is described hierarchically, and five hierarchies of natural environment, suburban agriculture, urban centre, population, culture and information from bottom to top are sketched. The stocks in each hierarchy are, respectively, depicted as autocatalysis feedback design following the maximum empower principle that is approved as a universal laws of all scales of nature. The stocks in each hierarchy and the disconnected ecological flows make up the whole ecological network of Beijing's economy. The letters W, TS and F&O in Fig. 5 in the natural environment hierarchy refer to the stocks of water, topsoil as well as fuel and ore, respectively, and ACs and UCs indicate agricultural capitals and urban capitals, respectively. P refers to population, and CI expresses culture and information.

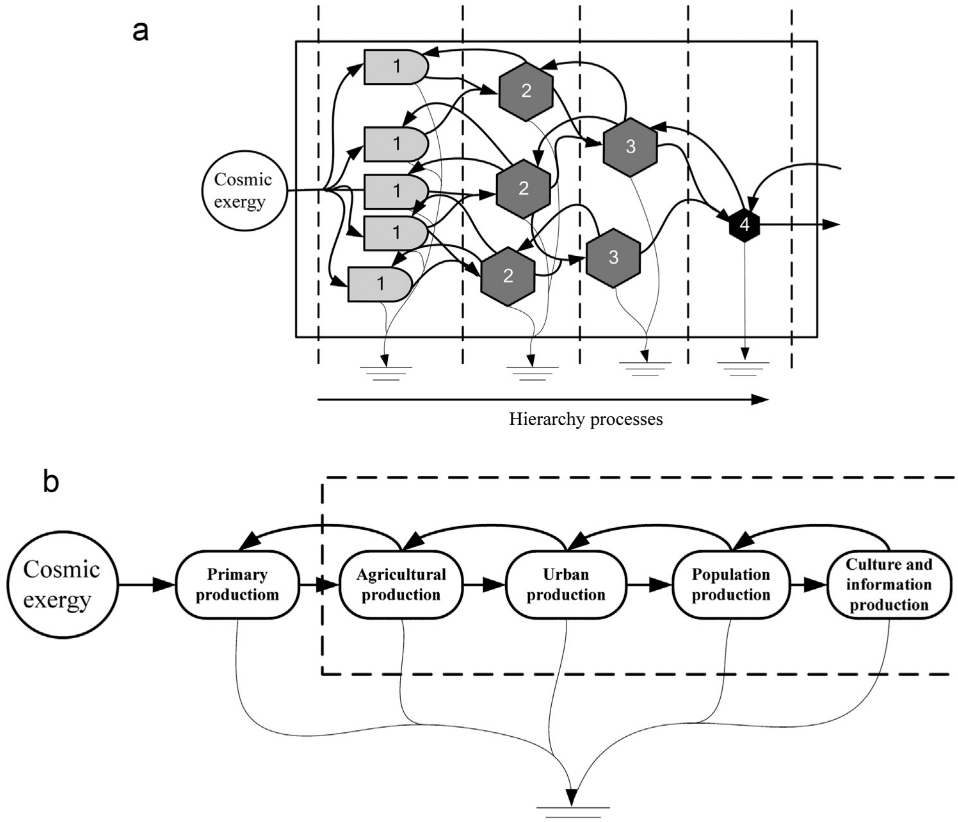

Fig. 3. (a) Hierarchies of the network of ecological–economic systems. (Referring to: Ulgiati and Brown, 2009). (b) Simplified hierarchies of urban economy.

As shown in Fig. 5, part of the local free natural resources RS (such as solar radiation, wind, rain and so forth) and imported natural flows IF (for example, immigrating river) enter the stocks in natural environment first from the very bottom. Some of the local free natural resources enter the suburban agriculture hierarchy together with water and soil in natural environment. The suburban agriculture in Beijing requires a large amount of fuel, especially electricity, to power the equipment for production and transportation. The fuel and electricity resources required are either from local mines or purchased from outside. Agriculture provides food and raw material to urban centre. The production in urban centre at the top of the ecological network is superior to aggregate resources. Population growth as well as culture and information are the terminal products of the interaction between energy, material and products from different hierarchies in the natural environment, suburban agriculture and urban centre, with the highest controlling ability, and can provide influential feedbacks to all levels in the ecological network. Besides, land stocks including urban land (UAr), agricultural land (AAr) and natural land (NAr), financial capitals (FCs), and wastes stock (EI, refers to environmental impact) are directly and indirectly connected to each hierarchy. Ecological flows in or out of these stocks make all the components of this ecological network an organic whole. From Fig. 5, the stocks in each hierarchy follow the autocatalysis feedback design.

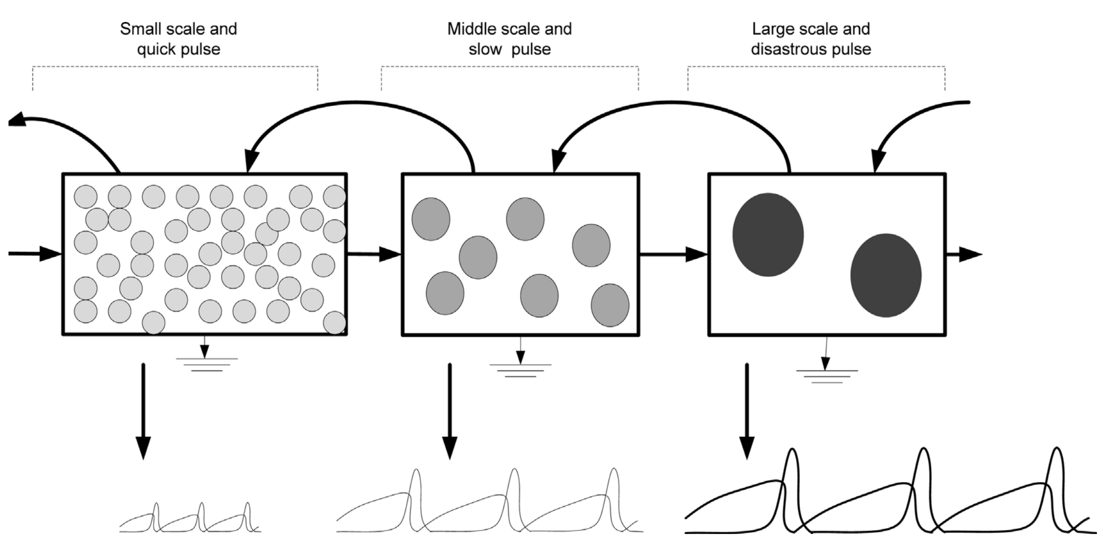

Fig. 4. Pulse in different hierarchies of ecosystem. (From: Odum and Odum, 2001).

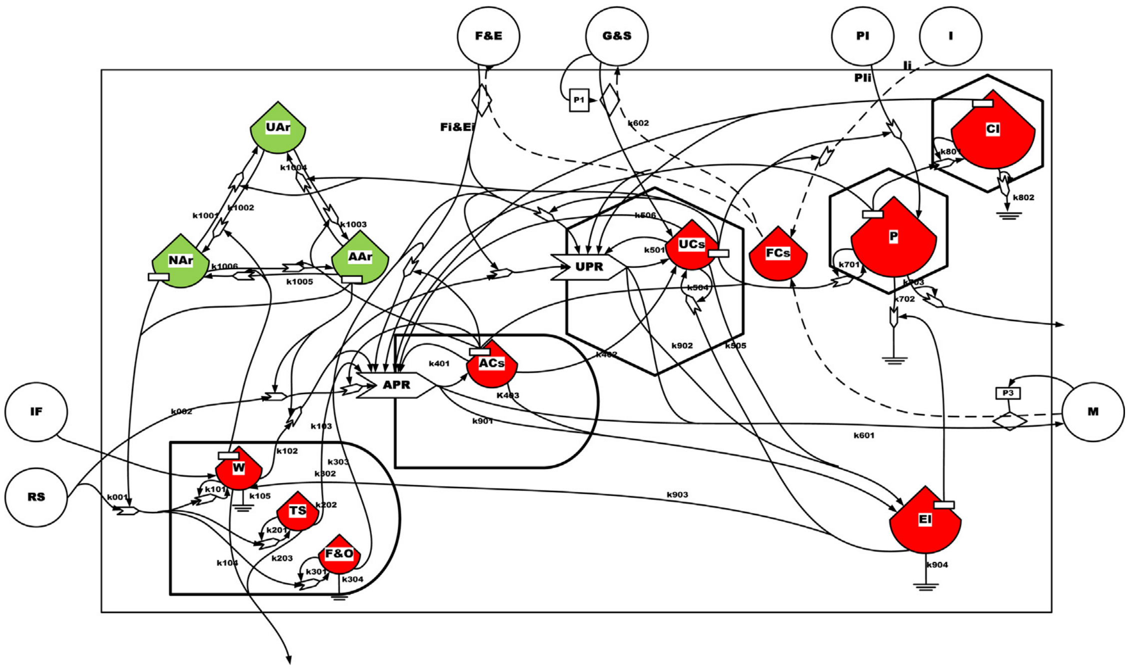

Fig. 5. The ecological network of Beijing's economy.

3.2. *Systems ecology-modelling of Beijing's economy*

Followed the insights of the ecological network of Beijing, systems ecology-modelling of Beijing's economy is carried out. It is a toy model, designed to stimulate the pulsing paradigm and development trend of Beijing's economy, rather than to give an accurate prediction. The systems ecology-modelling on the theoretical basis of autocatalysis feedback design and maximum power principle is easier to integrate and generalize the dynamic mechanism of such a complex and compound ecological–economic system, and could avoid subjectivity and uncertainty as far as possible compared with conventional ecological modelling.

Taking the stocks as the state variables, there are 12 state variables in this model: W (water), TS (topsoil), F&O (fuel and ore), ACs (agricultural capitals), UCs (urban capitals), FCs (financial capitals), P (population) and CI (culture and information), EI (potential environmental impact), UAr (urban land), AAr (agricultural land), and NAr (natural land). Also, there are almost 80 flow rate variables and other auxiliary variables. The explanation, equation, and initials values of the variables in this model are listed in Table 1.

The initial value of all the variables and parameters are calculated according to the economic, social and environmental data of Beijing in the year 2000, which is derived from Beijing General Urban Planning (2004–2020) (BGUP, 2005), China Statistical Yearbook (CSY, 1992–2007), the Almanac of China's Cities (ACC, 1992–2007), China Agriculture Yearbook (CAY, 1992–2007), China Rural Statistical Yearbook (CRSY, 1996–2007), China City Statistical Yearbook (CCSY, 2001–2006), Beijing Area Statistical Yearbook (BASY, 1996–2007), Beijing Industry Yearbook (BIY, 1996–2007), and other published databases. Detailed calculation is presented in my previous published paper (Ji, 2011). Politically the year 2000 is the first year of a new "Five Year Plan" in China. Historical data shows that from 2000 Beijing experienced a stable development, implying low possibility of system-fluctuation due to radical change of social, economic, or political factors in the future. Therefore, in either long or short run the situation in 2000 reflects the general prospect in policy making, and taking the data of the year 2000 as initial data is reasonable for prediction of Beijing's development trend.

The dynamic equations (listed in Table 2) of state variables indicating the stocks with autocatalysis feedback design are mostly based on the theory of maximum power principle.

Starting from the year 2000, the model spans over 100 year. The results from 2000 to 2005 predicted by the model match the real data very well, proving the effectiveness and authenticity of the model.

4. Results and discussion

4.1. *Results*

The results of the main stocks in each hierarchy of Beijing's economy are illustrated in Figs. 6–9. Shown in Fig. 6 are the modelling results of natural environmental capital, suburban agricultural capital, urban centre capital, financial capital, population, culture and information capital which are the representative stocks in the five hierarchies of natural environment, suburban agriculture, urban centre, population, culture and information. 100-year time series seem short compared with the long history of city's civilization, and the modelling results only show part of the pulsing cycle of the urban economy of Beijing, nevertheless, the structure succession of the urban economy as well as the pulse of its component stocks can be observed.

4.1.1. *Natural environmental capital*

The natural environmental capital in the lowest hierarchy of the whole economy here is an integration of renewable water resources and nonrenewable soil, fuel and ore resources. Since water makes little difference in the natural environmental capital, the pulsing cycle of natural environmental capital represents mainly the situation of nonrenewable resources. Nonrenewable resources are accumulated in a long period of time, and then consumed in a short time. From Fig. 6, the natural environmental capital is observed under its descent phase currently and the low restoration for a new cycle will begin during the next decades. That means, Beijing's economy is facing the sharp decrease of natural environmental capital currently, and not until the high cost of the resources forces humans to stop overuse can these resources start to accumulated again.

Table 1
The parameters of the model of Beijing's economy.

Item		Variables	Equations	Initial values	Unit	k
Inward	Flows					
	Free natural resources	RS		17.3	PJc/yr	
	Input flows	IF		2.23	PJc/yr	
	Fuel and electricity	F&E	Fi&Ei × (ACs + UCs)	2.13E + 04	PJc/yr	
	Products and service	G&S	k_{602} × FCs × H/p1	7.79E + 04	PJc/yr	6.27E − 03
	Immigration population	PI	PI_i × UCs	8.20E + 02	PJc/yr	
	Investments	I	I_i × UCs	2.21E + 01	Billion yuan/yr	
Internal flows						
1	W-related flows					
	Local free renewable resources	J101	k_{101} × RS × (NAr + AAr) × W	4.30	PJc	3.46E − 04
	Input flows	J002	IF	2.23	PJc	
	Diverted water	J003	CW × X	0.00	PJc	
	Waste water recovery	J104	k_{903} × EI × W	1.00	PJc	6.75E − 06
	Water consumed in agricultural production	J105	k_{102} × W × Aar	2.17	PJc	3.62E − 03
	Water consumed in urban production	J106	k_{103} × W × UCs	3.78	PJc	1.99E − 06
	Output flows	J107	k_{104} × W	2.43	PJc	4.61E − 01
	Losses	J108	k_{105} × W	0.10	PJc	1.89E − 02
2	TS-related flows					
	Local free renewable resources	J201	k_{201} × RS × (NAr + AAr) × TS	1.73E − 04	PJc	1.34E − 12
	The fertilizer embodied in top soil	J202	k_{202} × TS	7.95E + 02	PJc	1.45E − 02
	Losses	J203	k_{203} × TS	5.80E + 02	PJc	1.06E − 02
3	F&O-related flows					
	Local free renewable resources	J301	k_{301} × RS × (NAr + AAr) × F&O	1.73E − 06	PJc	1.55E − 15
	F&O consumed in agricultural production	J302	k_{302} × F&O × ACs	3.08E + 03	PJc	2.65E − 07
	F&O consumed urban production	J303	k_{303} × F&O × UCs	8.92E + 03	PJc	2.29E − 07
	Losses	J304	k_{304} × F&O	5.00E + 02	PJc	1.05E − 02
4	ACs-related flows					
	Net agricultural production	J401	k_{401} × RS × AAr × W × TS × (F&O + Fi&Ei × ACs) × P × CI × ACs × UCs × Aar	4.78E + 03	PJc	8.77E − 38
	ACs Transformed to UCs	J402	k_{402} × ACs	2.00E + 03	PJc	8.70E − 02
	Discarded ACs	J403	k_{403} × ACs	3.91E + 02	PJc	1.70E − 02
5	UCs-related flows					
	Net urban production	J501	$k_{501} \times W \times (F\&O + F_i\&E_i \times \text{UCs}) \times \text{UCs} \times P \times \text{CI}$	1.81E + 04	PJc	1.64E − 29
	UCs transformed to ACs	J402	k_{402} × ACs	2.00E + 03	PJc	8.70E − 02
	Products and service from outside	J005	k_{602} × FCs/p_1	7.79E + 03	PJc	6.24E − 03
	Wastes recovery	J502	k_{504} × EI × UCs	1.98E + 03	PJc	5.91E − 07
	Feedback to agricultural production	J503	k_{506} × UCs	4.00E + 03	PJc	1.11E − 02
	Discarded UCs	J504	k_{505} × UCs	8.51E + 03	PJc	2.36E − 02
6	FCs-related flows					
	Revenue	J601	(AO + PO) × p3	1.19E + 02	Billion yuan	
	Investments	J602	UCs × I_i	2.21E + 01	Billion yuan	
	Expenditure for fuels and electricity	J603	F&E × p2	2.79E + 01	Billion yuan	
	Expenditure for Products and service	J604	k_{602} × FCs	1.01E + 01	Billion yuan	6.27E − 03
7	P-related flows					
	Births	J701	k_{701} × (ACs + UCs) × P	1.59E + 02	PJc	6.21E − 09
	Deaths	J702	k_{702} × P × EI	2.89E + 02	PJc	1.54E − 03
	Immigrants	J703	PI_i × UCs	8.20E + 02	PJc	
	Migrants	J704	k_{703} × P × P	2.68E + 02	PJc	6.06E − 08
8	CI-related flows					
	Cultural products	J801	k_{801} × P × CI	3.95E + 04	PJc	4.21E − 06
	Losses	J802	k_{802} × CI × CI	1.29E + 04	PJc	1.66E − 06
9	EI-related flows					
	Agricultural pollutants	J901	k_{901} × AO + k_{403} × ACs	1.77E + 03	PJc	1.23E − 02
	Urban pollutants	J902	k_{902} × UO + k_{505} × UCs	8.21E + 03	PJc	5.10E − 03
	Solid wastes recovery	J104	k_{504} × UCs × EI	1.98E + 03	PJc	5.91E − 07
	Waste water recovery	J503	k_{903} × EI × W	1.00	PJc	6.75E − 06
	Losses	J903	k_{904} × EI	2.98E + 03	PJc	1.06E − 01

Table 1 (*Continued*)

Item		Variables	Equations	Initial values	Unit	*k*
10	Land-related flows					
	NAr transformed to UAr	J1001	$k_{1001} \times$ NAr $\times$ UCs	7.00E − 01	Thousand hectares	8.53E − 09
	NAr transformed to Aar	J1006	$k_{1006} \times$ NAr $\times$ ACs	1.00E + 01	Thousand hectares	1.91E − 06
	UAr transformed to Nar	J1002	$k_{1002} \times$ UAr $\times$ W	0.00E + 01	Thousand hectares	0
	UAr transformed to Aar	J1003	$k_{1003} \times$ UAr $\times$ ACs	0.00E + 01	Thousand hectares	0
	AAr transformed to Nar	J1005	$k_{1005} \times$ AAr $\times$ W	3.00E + 00	Thousand hectares	5.01E − 04
	AAr transformed to UAr	J1004	$k_{1004} \times$ AAr $\times$ UCs	1.00E + 01	Thousand hectares	2.45E − 08
Stocks	Water	W		5.28	PJc	
	Fuels and ore	F&O		4.75E + 05	PJc	
	Topsoil	TS		5.47E + 04	PJc	
	Agricultural capital stock	ACs		2.45E + 04	PJc	
	Urban capital stock	UCs		3.61E + 05	PJc	
	Financial capital stock	FCs		1.61E + 03	Billion yuan	
	Population	P		6.66E + 04	PJc	
	Cultural and information	CI		1.41E + 05	PJc	
	Potential environmental impact	EI		2.77E + 04	PJc	
	Ecological land area	NAr		2.28E + 02	Thousand hectares	
	Agricultural land area	AAr		1.13E + 03	Thousand hectares	
	Urban land area	UAr		2.80E + 02	Thousand hectares	
Others	Agricultural output	AO	$k_{601} \times (\text{RS} \times \text{AAr}^2) \times (\text{W} \times \text{TS}) \times (\text{F\&O} + F_i\&E_i) \times \text{ACs}^2 \times P \times \text{CI} \times \text{UCs}$	1.93E + 03	PJc	6.49E − 38
	Urban centre output	UO	$k_{605} \times (\text{W} \times \text{UCs}) \times (\text{F\&O} + \text{Fi\&Ei}) \times \text{UCs} \times \text{UCs} \times P \times \text{CI}$	7.76E + 04	PJc	1.46E − 28
	The average price of goods and service	p1		3.39E − 02		
	The average price of fuel and electricity	p2		1.32E − 03	Yuan/Billion Jc	
	The average market price	p3	$\text{p3} \times (1 + \text{p3i})^{(n-2000)}$ (*n* is the year)	1.49E − 03	Yuan/Billion Jc	
	The index of market price	p3i		5.00E − 02		
	The ratio of cosmic emergy and currency	H		2.61E + 08	Jc/Yuan	

The modelling results of water, soil, as well as fuel and ore resources are illuminated in Figs. 7–9, respectively. Water resource in Beijing is constantly decreasing in the following years. Although water is renewable, the demand from urban economy outgrows the supply of water from rainfalls and immigrating flows. Therefore, Beijing is faced with serious water shortage currently. In addition, water resource in Beijing would take especially long time to accumulate according to the trend shown in the model, therefore in a fairly long period of time, Beijing will be lack of water. The only solution is to adjust the economic activities accordingly.

Soil resource in this study refers to the fertility (including organic matters, N, P and K) of topsoil. Soil should be renewable, but only with slower rotations rather than operated by our present economy. Land structure change, intensive agricultural cultivation and soil erosion are the primary reasons for the decrease of soil resource. The recovery of soil fertility due to plant and animal decomposing is comparatively a slow process and even can be ignored in this modelling. From the modelling results (Fig. 8), soil resource is constantly decreasing.

Fuel and ore resources are nonrenewable. Although Beijing highly depends on outside resources, it still consumes a fairly great

Table 2
Dynamic equations of Beijing's economy.

$d\text{W}/dt = k_{101} \times \text{RS} \times (\text{NAr} + \text{AAr}) \times \text{W} + \text{IF} + \text{CW} \times \text{X} + k_{903} \times \text{EI} \times \text{W} - k_{102} \times \text{W} \times \text{ACs} - k_{103} \times \text{W} \times \text{UCs} - k_{104} \times \text{W} - k_{105} \times \text{W}$
$d\text{F\&O}/dt = k_{301} \times \text{RS} \times (\text{NAr} + \text{AAr}) \times \text{F\&O} - k_{302} \times \text{F\&O} \times \text{ACs} - k_{303} \times \text{F\&O} \times \text{UCs} - k_{304} \times \text{F\&O}$
$d\text{TS}/dt = k_{201} \times \text{RS} \times (\text{NAr} + \text{Aar}) \times \text{TS} - k_{202} \times \text{TS} - k_{203} \times \text{TS}$
$d\text{ACs}/dt = k_{401} \times \text{AO}/k_{601} - k_{402} \times \text{ACs} \times \text{UCs} - k_{403} \times \text{ACs} - k_{404} \times \text{ACs} \times \text{P}$
$d\text{UCs}/dt = k_{501} \times \text{UO}/k_{605} + k_{402} \times \text{ACs} + k_{602} \times \text{FCs}/\text{p1} + k_{504} \times \text{EI} \times \text{UCs} - k_{506} \times \text{UCs} - k_{505} \times \text{UCs} - k_{603} \times \text{P} \times \text{UCs} \times \text{CI}$
$d\text{FCs}/dt = (\text{AO} + \text{UO}) \times \text{P3} + \text{UCs} \times \text{Ii} - \text{FI\&UI} \times \text{UCs} \times \text{P1} - k_{602} \times \text{FCs}$
$d\text{P}/dt = k_{701} \times (\text{ACs} + \text{UCs}) \times \text{P} + \text{PIi} \times \text{UCs} - k_{702} \times \text{P} - k_{703} \times \text{P} \times \text{P}$
$d\text{CI}/dt = k_{801} \times \text{P} \times \text{CI} - k_{802} \times \text{CI}^2$
$d\text{EI}/dt = k_{901} \times \text{AO} + k_{403} \times \text{ACs} + k_{902} \times \text{UO} + k_{505} \times \text{UCs} - k_{504} \times \text{UCs} \times \text{EI} - k_{903} \times \text{EI} - k_{904} \times \text{EI}$
$\text{NAr} = 164.1 - \text{AAr} - \text{UUr}$
$d\text{AAr}/dt = k_{1006} \times \text{NAr} \times \text{ACs} + k_{1003} \times \text{UAr} \times \text{ACs} - k_{1005} \times \text{AAr} \times \text{W} - k_{1004} \times \text{AAr} \times \text{UCs}$
$d\text{UUr}/dt = k_{1001} \times \text{NAr} \times \text{UCs} + k_{1004} \times \text{AAr} \times \text{UCs} - k_{1002} \times \text{UAr} \times (\text{W} + \text{TS}) - k_{1003} \times \text{UAr} \times \text{ACs}$

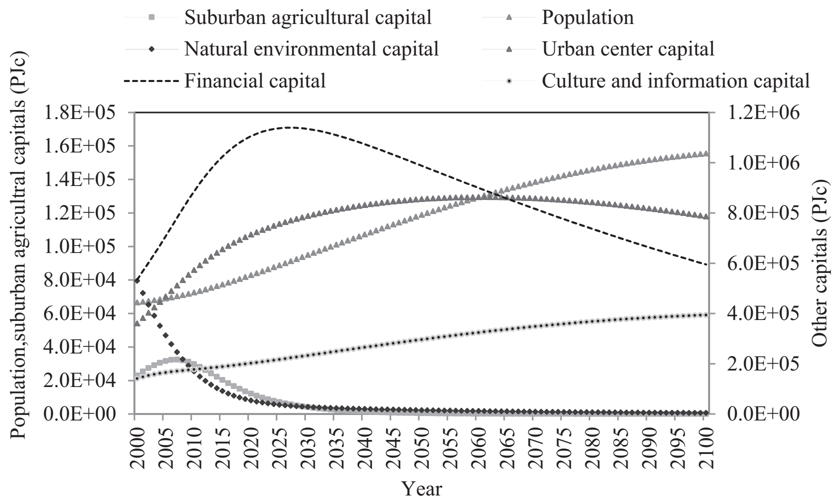

Fig. 6. The pulse of the components in the ecological network of Beijing economy.

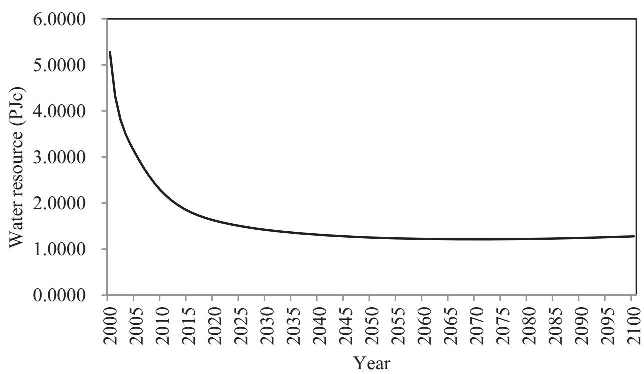

Fig. 7. The modelling result of water resource in Beijing.

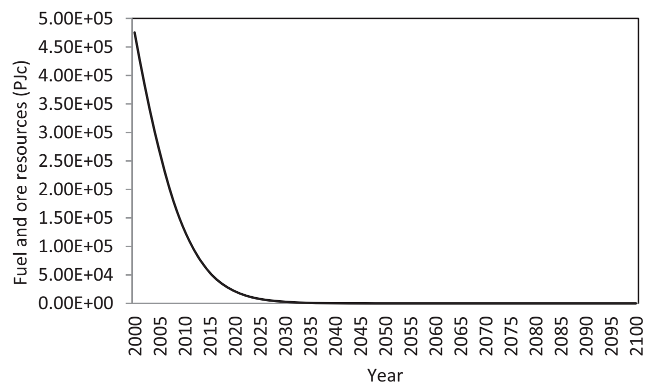

Fig. 9. The modelling result of fuel and ore resources in Beijing.

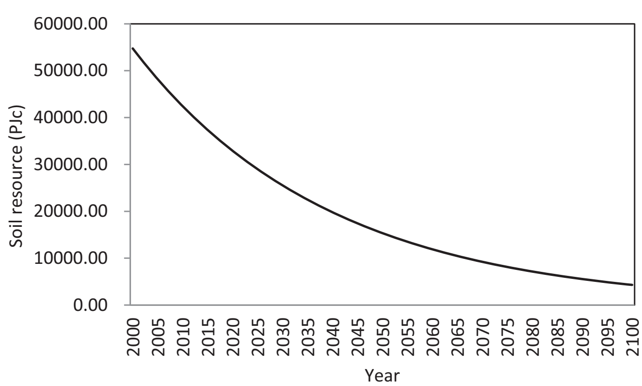

Fig. 8. The modelling result of soil resource in Beijing.

quantity of local resources. The modelling results (Fig. 9) show that the local mines will run out in decades and later Beijing will totally reply on outside supply if it cannot find substitutes inside the city.

4.1.2. *Suburban agricultural capital*

Compared with the higher level stocks like urban centre capital, population as well as culture and information stocks, the agricultural capital in the lower hierarchy of urban economy is relative small in scale and has comparatively short pulsing wave length and quick pulsing frequency.

From the modelling results shown in Fig. 6, suburban agricultural capital has already experienced a complete pulse cycle from growth to maturity, then to recession and finally to slow restoration within the 100 years. Experienced with growth and accumulation, agricultural capital has reached its climax currently, and descent is expected in the flowing years. Suburban agricultural capital includes all plant stocks and animal stocks. Although modern agriculture is able to increase production efficiency through mechanization and utilization of fertilizers, the increase is temporal and will stop when it hits the limit set by the amount of resources.

4.1.3. *Financial capital and urban centre capital*

Financial capital and urban centre capital will reach their climax around the year of 2030 and 2050, respectively, and then plunge into transition and recession stage.

Financial capital here refers money supply. Monetary stock is a symbol of wealth rather than genuine wealth, thus it is the only stock in this model without biophysical base. Nevertheless, discarding inflation, the financial stock pulses under the effects of other pulsing stocks. Urban centre capital contains mainly the urban infrastructures, such as buildings, equipments, vehicles, roads and other supporting facilities. Urban centre capital is the main component of urban economy, and urban centre production is the primary activity of urban economy with the highest resources consumption. As the local natural resources (especially water resources) decrease, the urban production slows down.

4.1.4. *Population and culture and information capital*

Population capital here implies both the quantity and quality of the population, and the latter is the most important factor to urban economy's development. Culture and information capital consists of two parts: one is the historical legacy, and the other is the art, science and technology information embedded in books, papers, and audio and video products.

Population, as well as culture and information capital among the highest hierarchies of the whole economy, has the longest pulsing cycle. Among the simulated 100-year horizon, only the growth stage is demonstrated for these two capitals.

At the very top of the ecological network of urban economy, population as well as cultural and information as the production of the coupling of all other energy flows are with the most controlling power. The cultural and information stock is the result of a long accumulation process of human civilization. Therefore they are the strongest in defending outside environmental changes, and their recession comes later than that of suburban agricultural and urban centre capitals. The modelling results show that Beijing's population will continue growing and then stagnate after 100 years when the scale of urban production becomes stable and the environmental carrying capacity cannot hold any more. Cultural information stock will nearly stop increasing once the population stock stops rising.

4.2. Discussion

This is a toy model which is conducted to reveal the pulse paradigm of an urban economy rather than to give an accurate quantitative forecast, thus the discussion will mainly focus on the pulsing rules indicated by the modelling results. From the results, we can conclude that:

First, pulse paradigm does exist in Beijing's economy. As a self-organizing, resources-dependent, and energy-open system, Beijing's economy pulses, which is the result of its pulsing components of natural environmental capital, suburban agricultural capital, financial capital, urban centre capital, population capital and culture and information capital.

Second, different pulsing cycles are observed for stocks in different hierarchies, and it is unambiguous that small scale stocks pulse with quicker frequency while large scale ones have longer pulsing wave length. Agricultural capital in the lower level of urban ecological system has comparatively shorter pulsing wave length. While higher level stocks like urban centre capital, population as well as culture and information stocks have longer pulsing wave length, which is only partly visualized in the 100-year simulation.

Third, a reciprocal relationship between the natural capitals as producers and socioeconomic capitals as consumers are observed, and the growth of socioeconomic capitals such as urban centre capital and population capital consume and pull down the natural environmental capital.

Fourth, the anti-interference ability for stocks differs in different hierarchies. According to the simulation, less availability of water is the largest interference confronted with Beijing. Water shortage and its rising costs cause the low level agricultural capital contract firstly. Urban centre capital will recess decades later. The influence of less available water resources on population stock and culture and information stock is much delayed.

In addition, it is observed that the accumulation and growth of local natural resources including water, soil, fuel and ore already end, and Beijing is currently in the natural resources recession, while the scale of Beijing's economy remains increasing. Beijing highly depends on outside resources, and it is too large to be supported by its outskirts. In other words, the size of Beijing's economy is beyond the local carrying capacity. As water and fuels become scarce and expensive, Beijing has to get smaller to an optimal size that is compatible with the carrying capacity. According to the trend in the modelling, Beijing will reach its climax and then encounter its contract and recession eventually. It is worth mentioning that decrease or recession do not mean collapse. As strengthened by the Odum and Odum (2001), decisive changes in attitudes and practices can stop a destructive collapse and instead result in a prosperous way down.

5. Conclusions

Urban economy and its component stocks are typical self organizing and autocatalysis feedback designs. Although urban economy is comparatively large in scale whose pulsing cycle is too long for us to witness, by systems ecology-modelling based on the theory of cosmic emergy, the pulse is partly observed for the whole urban economy and its component stocks in this study.

As the improvement and advancement of ecological modelling, systems ecology-modelling applies the basic theories and principle of systems ecology in general ecological modelling. Compared with general ecological modelling, systems ecology-modelling tries the best to follow the design principle and rules of ecosystem (especially the autocatalysis feedback design and the maximum power principle of cosmic emergy), which lowers the subjectivity and uncertainty to a large degree during the modelling. The combination of systems ecology-modelling and the theory of cosmic emergy integrates the material flows, energy flows, population flows and information flows into emergy flow, greatly simplifying the model but preserving the essential information of the system. In addition, the systems ecology-modelling based on the theory of cosmic emergy achieves the visualization and dynamic accounting of emergy flow, and the quantification also describes the dynamics mechanism of ecosystem and provides a foundation for macro regulation of the system.

The toy model has revealed the pulse paradigm and the structure evolution of Beijing's urban economy. From the modelling results, we can recognize that: Pulse paradigm does exist in Beijing's economy; Different hierarchies have different cycles, and small scale stocks like natural environmental capital and suburban agricultural capital pulse more quickly while large scale ones such as financial capital, urban centre capital, population capital, as well as culture and information capital have longer pulsing wave length; A reciprocal relationship between the natural environmental and suburban agricultural capitals as producers and financial, urban centre, population, culture and information capitals as consumers are observed; The anti-interference ability for suburban agricultural stock which is in low hierarchy is much lower than those stocks in the higher hierarchies. Last but not least, the size of Beijing's economy is beyond the local carrying capacity. According to the trend revealed in the toy model, Beijing will reach its climax and then encounter its contract and recession eventually.

The simulation of Beijing's economy facilitates taking its pulse and recognizing the part of the pulse cycle the city is current in. The development of the city is now facing the restriction derived from natural resources shortage. To face the forthcoming changes, much experience from other resources-dependent species is useful. The production and consumption mode under abundant resources should be discarded. Governments should question the GDP oriented growth mode, especially the investment-dominated mode. All citizens should stop over-consuming. This may help contribute to less-intensive fuel consumption, less transportation, less advertising, longer life of building and infrastructure, and a more efficient spatial pattern. Quantitative growth will give way to qualitative development, which will lead better recycle of materials between the city and its environmental surroundings, an efficient transmission of energy in a way that minimizes losses, a reasonable production and consumption mode without extravagance and waste, as well as compact urban morphology. In sum, to stop a destructive collapse and instead toward a prosperous way down, decisive changes in attitudes and practices should be strengthened.

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Appendix A. The energy circuit language

Appendix A of the energy circuit language is necessary to help understanding Fig. 5 in Section 3.1. Based on traditional electrical circuit language, Odum developed a set of energy circuit language. This set of circuit language is able to match all elements of

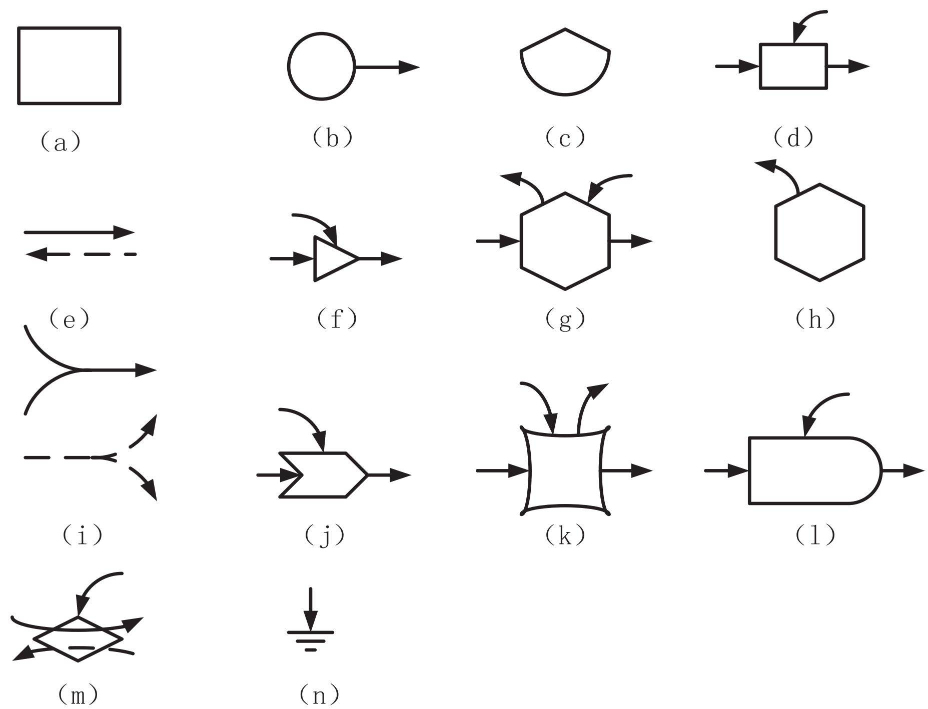

Fig. A.1. Symbols in energy circuit language.

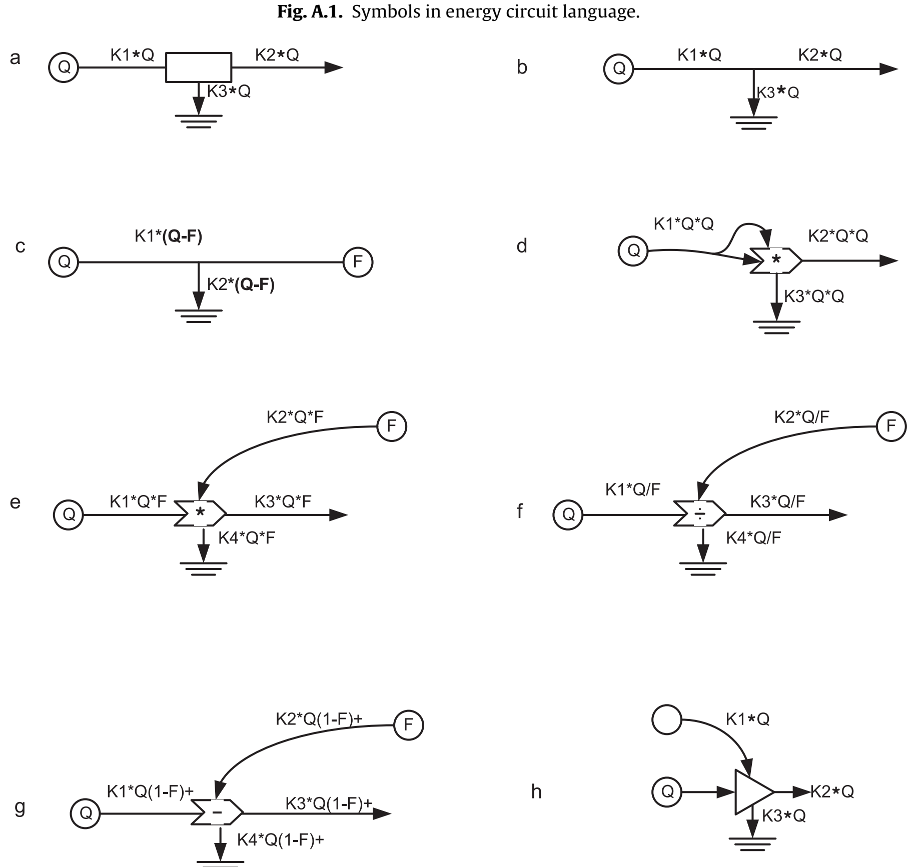

Fig. A.2. Quantitative expression of the flows in systems ecology-modelling.

ecosystem and describe the energy-network of ecosystem. Energy circuit language is designed to model the process of energy transmission, transformation as well as accumulation.

Specific items and descriptions are shown in Fig. A.1.

The descriptions of the symbols listed in Fig. A.1 are as follows:

(a) System boundary;
(b) source: exergy sources from outside;
(c) stock: a compartment of exergy storage within the system as the balance of in-flows and out-flows;
(d) box: a symbol to stand for any subsystems labelled;
(e) circuit: the solid line stands for a material or energy flow, and the dashed line indicates a currency flow;
(f) amplifiers: gain the flow from left side, and output the flow according to the control signal from the top;
(g) consumer: a unit that receives exergy flows from producers and feed flows back autocatalytically;
(h) feedback: interactions among different compartments;
(i) combination and divaricating of flows: the combination of flows shows these flows will work together, and the divaricating of flows shows a flow will be distributed to work on different units;
(j) interaction: interactive intersection of two pathways coupled to produce an outflow;
(k) switch action: on-off processes;
(l) producer: a unit that collects and transforms low-quality exergy carriers and output high-quality exergy carrier flows;
(m) transaction: a unit that indicates the exchange of goods or services (solid line) and money (dashed line);
(n) waste heat dissipation.

Fig. A.2 shows the mathematical expressions for some common pathways of systems ecology models, of which (a) expresses linear transformation; (b) linear frictional process; (c) reversible linear flow with back-force; (d) quadratic flow; (e) product interaction; (f) driving interaction; (g) subtracting interaction; (h) constant gain amplifier (gain = K2).

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