eMergy Evaluation: a Multi-Scale Optimum Tool for Visioning Sustainability

1. Shaping a sustainable urban future

Currently, about 49% of the world's population live in urban areas, a figure which is expected to grow to 61% by 2030 (UNEP, 2005). In China, the urbanization rate reached 42%. Only about 2% of the earth's surface is occupied by urban areas, but, as centers of concentrated population, the main resource consumption and wastes generation are taking place here, which brings significant ecological pressures, including water, food, timber and metals; as while exports large quantity of wastes and pollutants, including household and industrial wastes, wastewater and the gases linked with global warming. Cities have become the keystone for people in pursuing sustainable development. Along with the movement of money, resources, pollutants and people themselves, these pressures and pollutants are across different levels, from local to regional and global scales.

Despite the enthusiasm of planners on sustainable urban development, it is still not entirely evident on how to achieve, or even shape the goal. From the view of ecologist, a clear understanding of metabolism within the urban systems, their subsystems and interactions, from the input to the output, is pivotal to ensure what effects specific development strategy will have on the sustainability of these systems.

Beijing, China, like other emerging cities, has been identified uniquely appropriate for study of urban development trajectories and their sustainability implications. They are experiencing rapid growth that is projected to continue to increase in the future and suffering from limited natural resources and air quality problems. Other problem, as the recent desertification of the counties adjacent to Beijing metropolitan area has added more difficulties to the public.

Cities' vision could be various, but Urban SUstainability (USU) is considered as the primary visioning issue to all of the stakeholders throughout the world. By cross-questioning past short-sighted developments, people realize there is a need for an integrated tool to evaluate urban projects comprehensively, especially for their ecological pressures. The key is not only for economic profits, but also for the externalized costs and the gained sustaining capability.

For a planner, achieving USU means by changing cities' structure to make cities better, like promoting economy growth, mitigating pollutants from industries and household and increasing social equality. We need a handy tool to specify the direction and evaluate progress. It's favorable if we can take feedback from our past or current projects' impact regarding to the whole city's sustainability.

2. Compromise among Planning at Different Depths

Planners always work at different scales, or saying depths. At the macro level, spatial configuration and functions are main points, besides the micro level, public spaces, urban cityscape or buildings are more considered. Similarly to the diversity at spatial scales, time scales are also various. We are not only needed to confirm a sustainable future for a city, but also needed to implement it step by step.

On the other way, large amount of urban renewal and construction, occur in Cities in China everywhere. The driven force is seeking economic profit. Through there is the first national policy on circular economy in China, the sum of individual projects are going contrary. One of the reasons why strategy can not achieve visioning, is due to lacking of governance framework and tools, which can be used to remedy the development path at all time. It's important to coordinate plans at different scales, i.e. master plan, transportation plan, zoning plan, aiming at the same target. Emergy theory can provide people necessary information and tools regarding what's the sustainable future in long-term, and monitoring/evaluating the progress within short-time, linking the strategy with practices.

3. Emergy and Urban Systems

Urban systems are complex adaptive systems, which are networks that consist of many nonlinearly interacting elements that can adapt their dynamic behavior to external changes. The challenge of studying urban systems, with a purpose such as sustainable development, is complicated especially by the complexity and unpredictability of the human systems and institutions involved, especially their self-reflexive character. Regardless it is critical to understand these urban dynamics in order to develop and refine our policy and educational tools, which will enable better planning of urban regions and sustainably improve the quality of life of urban inhabitants.

From viewpoint of ecological energetics, ecological and social systems are analogous, the laws describing growth, depreciation, and interaction of ecological systems can be applied to social systems like cities. 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 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. 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.

3.1. Concept

Emergy (spelled with an 'm') is defined as the energy of one type required in transformations to generate a flow and storage[1]. In this account solar emergy is used. Solar emergy of a flow or storage is the solar energy required to generate that flow or storage. Its units are solar emergy emjoules (abbreviation: sej). It evaluates the work previously used up directly and indirectly to make a product or services. The transformity is defined as the amount of emergy of one type required directly and indirectly to generate a unit of energy of another type. It is the emergy per unit energy in units of emjoules per Joule which constitutes the ratio of emergy to available energy. The units of transformity are solar emjoules/Joule, abbreviated sej/J or solar emjoules/g (sej/g). As its name implies, the transformity can be used to transform a given energy into emergy, by multiplying the energy by its transformity. Once transformities are known for a class of item, the total emergy of an item can be expressed as:

emergy = available energy of item × transformity

Emergy Analysis (EMA) has been developed over the past 20 years[1]. Emergy can measure both the work of nature and that of humans in generating products and services, as a science-based evaluation system that represents both natural values and economic values with a simple, universal unit. Emergy provides a tool for different kinds of energy flows and materials in a system.

Emergy theory introduced a general systems energy circuit language which combines open system thermodynamics with system kinetics and represents system hierarchy by positioning components from left to right on diagrams. Urban systems self-organize and develop hierarchical patterns with symbiotic closed feedback loops for structural reinforcement. After data aggregation, emergy flows can be described by certain symbols to help understanding the system. Here are some illuminations.

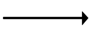
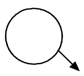
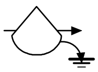
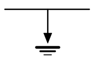
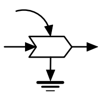
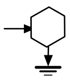
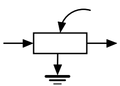
	Energy circuit, a pathway whose flow is proportional to the quantity in the storage or source upstream
	Source: outside source of energy delivering forces according to a program controlled from outside; a forcing function, any input that crosses the system boundary is a source, including pure energy flows, materials and information
	Tank, a compartment of energy storage within the system storing a quantity as the balance of inflows and outflows; a state variable
	Heat sink: dispersion of potential energy into heat that accompanies all real transformation processes and storages; loss of potential energy from further use by the system
	Interaction: interactive intersection of two pathways coupled to produce an outflow in proportion to a function of both; control action of one flow on another; limiting factor action; work gate. The flows that are controlled enter and leave from the sides and the pathways that control the switches are drawn entering from above to the top of the symbol
	Consumer, unit that transforms energy quality, stores it, and feeds it back autocatalytically to improve inflow
	Box: miscellaneous symbol to use for whatever unit or function is labeled

Table 1 emergy language

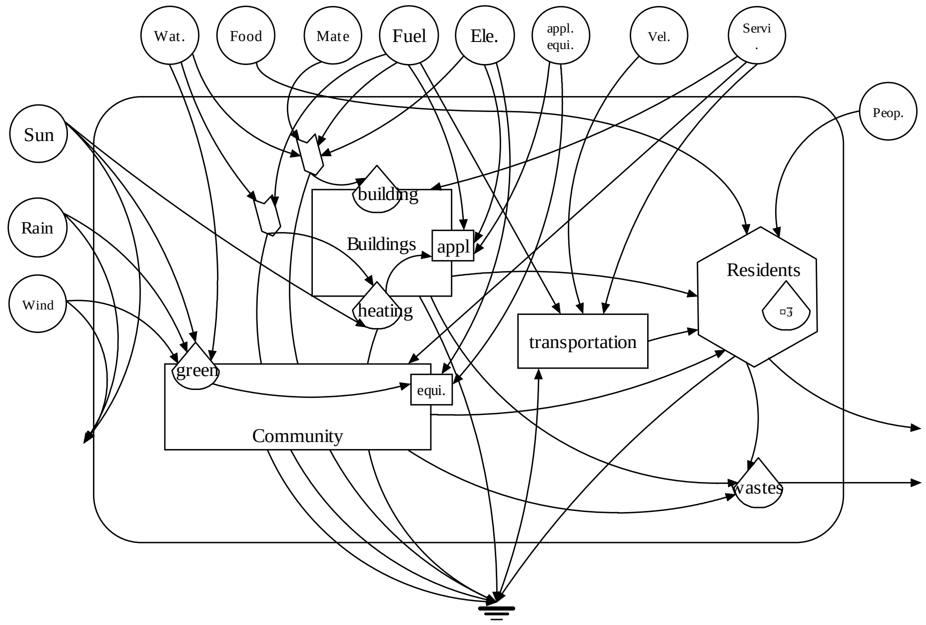


Fig 1 a typical Emergy chart of urban residential zone

Cities are major places for consuming goods and resources for human society, especially in the emerging economies. A great rigid demand for living and working from the mass exists, and increase the resource utilizing and the environmental burdens. The main point to planners, is how to evaluate and be aware of the impacts from social metabolism of resources during urban development. Some researches, like Material Flow Analysis (MFA), Ecological Footprint (EF), green building index, etc, have made efforts in this field. However, the perfection of methodological integrality and comparability among different projects or scales is still not accomplished. EMA is more appropriate for urban system researches.

Methodology	Characters	Shortages
Material Flow Analysis	Using conversed weights to evaluate environmental pressure	Not suit for planners
Ecological footprint	Using conversed land acreage to evaluate environmental pressure	Catalogs incomplete
green building index	Evaluate building’s energy efficiency	Only single building scale
LCA	Environmental impacts during a products’ life-cycle time	Subjectivity results

Table 2 comparison of methodologies to evaluate ecological impacts of urban development

3.2. Maximum Power Principle

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.

Thus, emergy theory is not only an evaluating tool, but also provides energy-based hierarchical picture of self-organizing urban systems and its optimum evolving mechanism is advanced in emergy theory, Maximum Power Principle (MPP). It indicates the whole system will take the predominance by increasing its energy inflows and improving its internal structure, etc.. The more inflows are, the higher development the system is. To ensure the MPP, planners should pay attention to these points during working on a strategy planning.

(1) Designing storage system for high quality resources inflows;
(2) Making positive feedback path for lower supporting systems;
(3) Recycling materials;
(4) Building control system for a city and make it stable;
(5) Exchanging different resources with outside;

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 MPP operates. People also get a clearer view of the good and the bad impacts of urban projects at larger scales and long-term, as the deviation to sustainable visioning, by referring to EMA and MPP.

3.3. Emergy Indicators as meaningful tool

After emergy evaluation tables were completed, indicators can be calculated to check the perspective and aid in decision-making. Several criteria were used to judge projects and make recommendations. Generally, the more emergy contributed to the public and less environmental losses was achieved, the better projects were.

Indicator	Description	Catalog
Emergy Yield Ratio (EYR)	Ratio of output emergy (Y) divided by the input emergy purchased from the economy, shows the relative intensity of a process and its competitive position.	System
Purchased Emergy Ratio	Ratio of purchased emergy (F) to the total used emergy	Input
Renewable Emergy Ratio (ELR)	Ratio of renewable emergy (R) to the total used emergy	Input
Emergy Density	Total emergy used divided by the area	Utilization
Per Capita Emergy Use	Total emergy used divided by the population	utilization
Electricity Emergy Ratio	Ratio of electricity emergy divided by the total used emergy	Carrying capacity
Waste Emergy Ratio	Emergy of waste (W) divided by the total used emergy	Carrying capacity

Table 3 emergy indicators[2]

4. A Case Studies

4.1. Residential zone in Beijing

Tian Tongyuan (TTY) is a high-density residential zone located in the northern suburban of Beijing, which was launched in the last 90s'. TTY contains 8,000,000 m^2, built area is about

5,200,000 m^2. It's divided into four zones. So far, the population is more than 190,000, which was planned 300,000 in future. Due to the fast-increasing prices of flats in the Beijing inner city and less available space for development, more and more residential zones are moving outside, in terms of urban sprawl. Several large zones with more than 100,000 residents are planned and building. Large amount of construction activities, people assembling and commuting reduced the local environment qualities obviously. Emergy analysis (EMA) was chosen as a tool to investigate the impacts of urban residential development.

To prepare the necessary data for emergy analysis, we conducted a survey for the below variables, heating: space, water; cooling: air-conditions; lighting; appliances; cooking; vehicles, etc. The quantities of building materials were estimated according to related literatures[3].

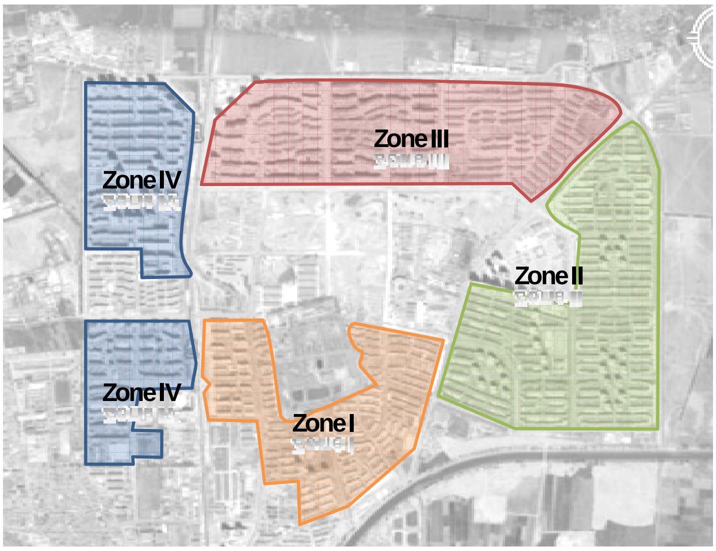


Fig 2 scheme of TTY

Note	Item	Data (units/yr)	Unit	Transformity (sej/unit)[4,5]	Solar Emergy (E15 sej/yr)
RENEWABLE INPUTS					
1	Sunlight	3.95E+16	J	1.00E+00	39
2	Rain	6.50E+12	J	3.02E+04	196
3	Wind	1.82E+14	J	9.83E+02	178
	Sum of renewable Inputs				414.98
PURCHASED INPUTS					
4	Natural Gas	8.39E+14	J	1.11E+05	93034.89
5	Electricity	6.63E+14	J	2.69E+05	178246.93
6	Water	5.26E+13	J	3.00E+05	15788.07
7	Gasoline	1.52E+08	g	4.71E+10	7171.96
8	Construction materials-cement	3.27E+12	g	1.00E+09	3268700.56

9	Construction materials-steel	1.11E+12	g	4.15E+09	4610332.24
10	Construction materials-sand	6.62E+12	g	1.00E+09	6624352.90
11	Construction materials-stone	1.38E+13	g	1.00E+09	13784145.72
12	Construction materials-wood	1.49E+11	g	9.22E+08	137132.11
13	Construction materials-brick	1.60E+11	g	2.20E+09	352383.54
	Sum of Purchased Inputs				3562942.40
Output					
14	Sewage	4.79E+13	J	6.60E+05	31640.07
15	Municipal solid waste	7.67E+10	g	5.00E+09	383414.43
16	Building material waste	8.95E+10	g	4.72E+09	422516.91
	Sum of outputs				837571.41

Table 4 emergy evaluation of TTY

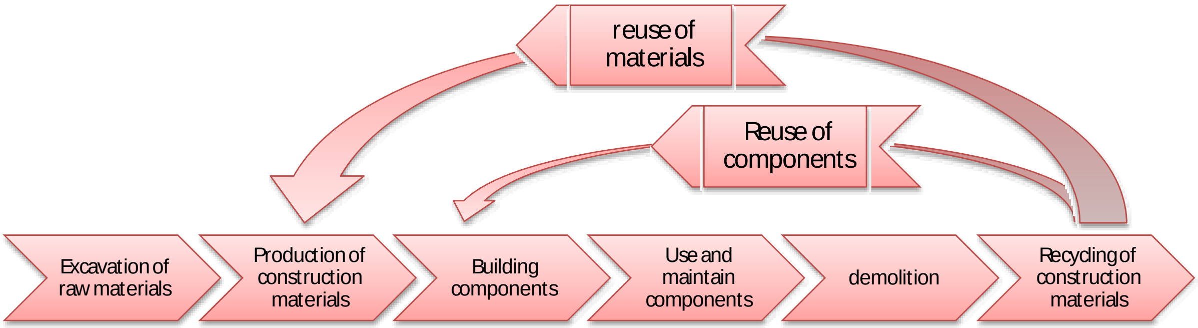


Fig 3 two paths of recycling

From the table above, we can find the emergy density of TTY is 3.57E+15 sej per m^2 and 152.22E+15 sej per person. The major non-renewable input is introduced by construction materials. By establishing a recycle plant, the ecological pressure showing by emergy indicators can be found improved. Hereby, according to the EMA result, a plan of material recycling plant is very helpful to carrying out the city's sustainable vision and circular economy policy.

	Business as usual	Materials reuse*	changes
Emergy Yield Ratio (EYR)	0.03	2.00	++
Purchased Emergy Ratio	98%	96%	-
Renewable Emergy Ratio (ELR)	2%	4%	+
Emergy Density (E+15 sej/m2)	3.57	2.03	-
Per Capita Emergy Use (E+15 sej/p)	152.22	86.36	-
Electricity Emergy Ratio	0.006	0.01	++
Waste Emergy Ratio	0.03	2.00	++

* reuse rate: 50%

Table 5 emergy indicators of TTY

Furthermore, urban renewal progress is also appeared in developing Beijing besides the new residential development. Due to the fast changing social value, the lifespan of structures without cultural value is short because they no longer comply with current expectations (only 20 to 30 years for office blocks and industrial buildings, 50 years for housing and 100 years for infrastructure[6]). The developments result in an increase in the long-distance transportation of raw and waste materials with high specific gravity. All these situations are needed to be evaluated their total impacts, for helping re-think our ways of urban development/renewal.

4.2. Beijing city

As mentioned above, one of the features of emergy evaluation is working across levels. On the other hand, city's assets are important conditional issues for urban development, research on city's assets and development greatly helps planners to understand the complicated mechanisms of their interactions. Here is another example for evaluating the ecological assets and urban development in Beijing by using emergy.

note	Item	Solar Emergy (sej/yr)	Percentage (%)
1	Renewable Resources	3.28E+21	1.08
2	Renewable Products	1.62E+22	5.33
3	Non-Renewable Resources	2.29E+22	7.53
4	Non-Renewable Products	8.88E+22	29.19
5	Purchased Input	1.73E+23	56.87
	Sum of input	**3.04E+23**	100.00
6	Exports	2.34E+23	51.66
7	Wastes	2.19E+23	48.34
	Sum of output	**4.53E+23**	**100.00**

Table 6 Emergy evaluation of Beijing (2000)

Beijing is a large metropolis with a population of 15 million and is undergoing a rapid urban sprawling. This development has several characteristics similar to the other large emerging cities all over the world:

(1) Very fast city economic growth and urban sprawling: its GDP grew from $1295.17 billion US dollars in the year 2000 to $2380.18 billion US dollars in the year 2005, an annual increase rate of 9.5% , and its central area of urban areas is more than 1000km^2. The fast urban development produces huge impacts on its surroundings.

(2) Serious resource shortage: especially for the water. The average water use amount of the city is annually 3.96 billion m^3, and emission of waste water is annually 1.36 billion m^3, but the water shortage is about annually 1.65 billion m^3, in the meantime, the ground water was seriously over-withdrawn. This situation of water shortage is challenging the sustainable development of the city.

(3) Huge immigration from other regions: the large size of population in Beijing has high diversity and its majority immigrated from provinces all over the country.

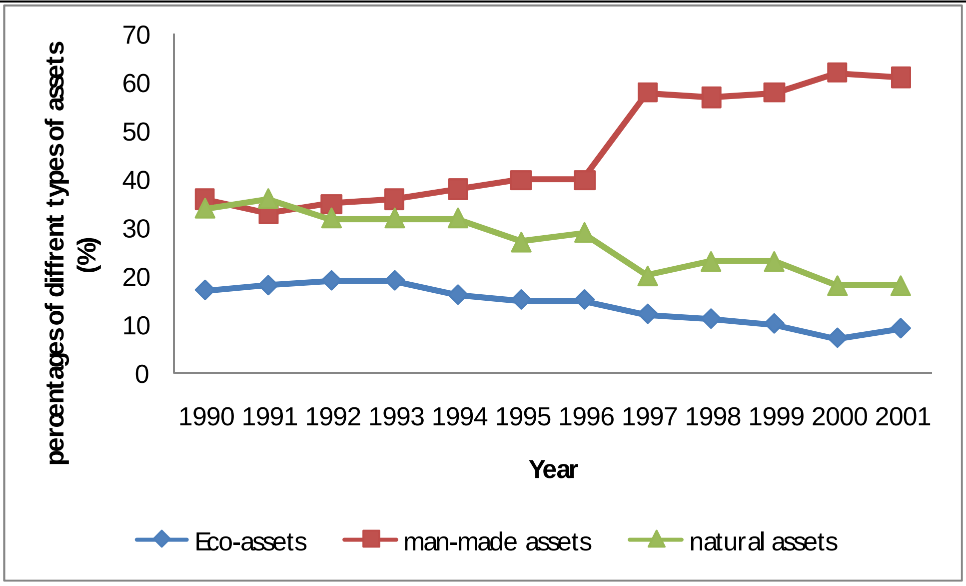


Fig 4 trends of total assets in Beijing[7]

The current and dynamic trends of emergy evaluation result of Beijing. The constitution of gross assets becomes polarized as the city develops, asset browning increases and greening decreases. The ecological assets and natural assets in Beijing are decreasing recently, meanwhile the man-made assets, mainly consuming resources non-renewable resources and products, are increasing observably. Although the regeneration rate of ecological assets in gross assets rose slightly, the size of ecological assets went down slowly.

5. Conclusion

For planers and decision-makers who constituting and implementing plans of urban sustainable vision, the Emergy Analysis (EMA) is constructive from these viewpoints:

(1) Helping understanding system dynamics and assets of cities;
(2) a tool for evaluating different visions of city, by investigate their emergy indicators and characteristics of urban system;
(3) a tracking framework for monitoring the smaller-scale plans in the road to the larger-scale plans;
(4) be awareness of direct and indirect ecological pressures induced from every urban development projects, and seeking alternatives.

6. References

[1] Howard T. Odum, *et al* (2000) series of Handbook of Emergy Evaluation, University of Florida
[2] Zhu, Yanyan (2002) Coordinative Development Assessment of Beijing Eco-economic System Based on Energy -- Emergy Analysis, Institute of Engineering Thermophysics, Chinese Academy of Sciences: Master thesis (in Chinese)
[3] Liu, Tianxing (2005) The Research of Metabolism and Environmental Impact of Urban Residential Building – with the Case of Beijing from 1949 to 2003, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences: Master thesis (in Chinese)
[4] Buranakarn, Vorasun (1998) Evaluation of Recycling and Reuse of Building Materials Using the Emergy Analysis Method, University of Florida: PhD thesis
[5] Huang, Shu-li (2004) Energy Basis for Urban Ecological Economic System, Taipei: Chan's Arch Books Co., Ltd (in Chinese)

[6] JANSSEN, Gabriëlla M T (2007) Reducing Greenhouse Gas Emissions by Megarecycling in Urban Renewal, Enviro Challenge & Delft University of Technology

[7] Hu, Dan (2006) "The Changes of Gross Assets in Beijing Urban Ecosystem and Their Ecological Relations to City Development", Acta Ecologica Sinica, Vol. 26 ,No. 7 (in Chinese)

Author: Li Dong
State Key Lab of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing