Ecological evaluation of Zhoushan economy based on emergy indices

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Abstract. Cities economy is an important pattern for the region to realize the transition of sustainable development. Scientific evaluation of the development of economy is the decision-making foundation to further promote sustainable development. This paper provides an integrated study on the ecological account of Zhoushan city economy with the data from 1995 to 2010 based on emergy synthesis theory. Through evaluating environment and economic inputs within and outside the Zhoushan economy, the Zhoushan's resource structure, economics situation and trade status and its sustainability are discussed based on a series of emergy indicators. In this study we used five types of emergy indicators or ratios to assess the sustainability of system, Emergy Intensity (EIs), Economic Efficiency, Environmental Efficiency, Emergy Sustainability Index and Source Diversity. The energy value per unit area of Zhoushan City increased from 4.51E+11 sej/m² in 1995 to 1.46E+12 sej/m² in 2010, with an average annual growth rate of 12%, which was 3.2 times that of 1995. During the 12-year study period, the per capita emergy value in Zhoushan increased from 1.02E+16 sej/person in 1995 to 3.36E+16 sej/person in 2010, which was 3.29 times that of 1995. Zhoushan’s emergy currency ratio dropped from 1.13E+21 sej/ $ in 1995 to 3.41E+20 sej/ $ in 2010. The emergy output rate of Zhoushan City dropped from 14.18 in 1995 to 12.99 in 2010, indicating that the economic system needs more emergy flows to provide enough goods and services for the society. The Environmental Loading Ratio (ELR) increased rapidly from 0.10 in 1995 to 1.80 in 2010. The emergy sustainability index (ESI) of Zhoushan was declined from 145.11 in 1995 to 7.23 in 2010. The source diversity of Zhoushan was increased during the period 1995-2010, with the highest value of 0.7284 in 2007 and lowest of 0.5114 in 2000. These emergy based indexes are calculated here in order to provide a deeper understanding of complexity growth or decline in Zhoushan city.

1. Introduction
In an increasingly urbanized world, city has become centre of population, economic production and consumption. This economic and ecological system plays a driving role in the development of regional and is connected by the throughput of energy and matter from natural ecosystems and other economic systems those supporting its activity. In order to accurately account the supporting functions of other systems, analysis of the inflows and outflows of energy, materials, and information between urban system and other systems has emerged as a complement to economic accounting [1][2]. In the past 30 years, H.T. Odum and his colleagues have used emergy theory to explain natural and economic systems.

Emergy refers to "available solar energy directly or indirectly used to provide services or products" [3]. This concept, which embodied 30s years of the late H.T. Odum’s energy and ecology work,
considers a system to be a network of energy, mass and information flows in each of the components of the network. Emergy analysis (EA) is an ecological accounting method that uses similar emergy units [4] to comprehensively and adequately account for all human inputs, including energies, natural resources consumption and financial payments. Once the system is quantified as an emergy unit, a series of emergy indicators and ratios can be used for analysis. It has been widely used to analyze many different systems, such as ecological, industrial, economic and astronomical processes [5-11]. The development and use of EA and emergy indicators and ratios [12-14] have proven to be an effective tool for evaluating the resource flow of natural and economic systems, and can provide a useful method for measuring the sustainability of the system.

In this paper, we propose a method for environmental accounting by using emergy indicators and emergy ratios, and applies them to the environmental and economic sustainability evaluation of the Zhoushan urban system from 1995 to 2010, with a view to assessing the environmental and economic aspects of the Zhoushan urban system. Sustainability conducts a comprehensive and objective analysis.

2. Method

Odum (1983, 1988, 1996) used energy system theory to develop a comprehensive ecological economic evaluation method (i.e., emergy analysis), which evaluates different energy, material and currency flows from the perspective of emergy. Emergy, especially solar emergy, refers to "available solar energy directly or indirectly used to make a service or product." Its unit is solar emjoules (abbreviated seJ) [3]. Odum (1996) defines the degree of integration (also named Unit Emergy Value, UEV) as: "Integration degree refers to the energy value required to complete one joule of service or product." Its unit is solar joule per joule (seJ/J). A solar transformity of a product is its solar emergy divided by its energy. The units of transformity are solar emjoules/joule, abbreviated seJ/J or solar emjoules/gram (seJ/g). As its name implies, once transformities are known for a class of item, the total emergy of an item can be expressed as: Emergy = available energy or mass of item × transformity.

The development and use of EA and emergy indicators and ratios [15-18] have proven to be an effective tool for evaluating the resource flow of natural and economic systems, and can provide a useful method for measuring the sustainability of the system. There are three main steps in carrying out an EA. First, an energy systems diagram is completed to identify the system’s flows. The second step is to use the transformity to estimate the emergy value of the flow. Third, use emergy indicators to assess the sustainability of the system. Once the emergy amount of each flows have been calculated, it can be analyzed easily through a number of emergy related indicators and ratios, which are meaningful to evaluate the condition of the concerned system. These indicators and ratios indicate different performance features of the system in terms of efficiency and sustainability. In this study we used five types of emergy indicators or ratios to assess the sustainability of system, Emergy Intensity (EIs), Economic Efficiency, Environmental Efficiency, Emergy Sustainability Index and Source Diversity.

2.1. Emergy intensity

The amount of emergy required to make one unit of service or product is called emergy intensity and is measured in seJ/unit. Emergy intensity is a measure of efficiency, involving the conversion of necessary environmental inputs into final outputs. It has also been defined by Brown et al. (2009) as "It is evaluated as a factor that divides the total emergy required for a product or service by the available energy of the product (leading to a transformity) or by the quality of the product (leading to a specific emergy)". Three indicators are used to describe the Emergy Intensity in our study. Emergy density (ED) is calculated through the division of total annual emergy use by the area of the region under the study. The per capita emergy is calculated by dividing the total annual emergy flow by the population of the study area, which is seJ person-1 unit. It can be used to measure the potential average living standard of the population. The emergy-to-money ratio is calculated by dividing the total emergy of a country or region to drive the economy by the Gross Domestic Product (GDP) of the country or region. This index indicates how much work has been done in a country or region in relation to the money flow in the country or region. This number becomes smaller as the economy
becomes more developed and more dependent on purchased goods and services from outside. It also tells us the purchasing power of the currency. A higher number means more emergy use per unit of currency [19].

2.2. Economic efficiency
In economics, the economic efficiency refers to the use of resources to maximize the production of goods and services. If an economic system can provide society with more goods and services without consuming more resources, it will be more efficient than another (relatively speaking) economic system.

True economic efficiency means that all resources that affect sustainable human welfare are included in the distribution system, not just the goods and services sold. Our current market distribution system excludes most non-market natural and social capital assets and services, and these assets and services make an important contribution to human well-being. The current economic model ignores this point and therefore cannot achieve true economic efficiency. A new and sustainable ecological economy model will measure and include the contributions of natural capital and social capital, and can better approximate real economic efficiency.

2.3. Environmental efficiency
In this paper two indicators will be given to assess the environmental efficiency: the environmental loading ratio (ELR) and Ratio of waste to renewable emergy (W/R). The ELR is an indicator that reflects the pressure of production activities on the local environment. It is the ratio of economic input and non-renewable emergy to free environmental emergy, reflecting the pressure of human activities on the environment. Waste is a by-product of human activities and has the most significantly impact on the environment. In this analysis, the emergy of wastes we analyzed includes wastewater and solid waste.

2.4. Emergy sustainability index
The goal of sustainable development is focused on getting the higher yield ratio versus the lower environmental loading. In this study we used the emergy sustainability index (ESI) to assess the sustainability of the economic system evaluated. The ESI is the ratio of the emergy output ratio to the environmental loading ratio and provides a sustainability index that captures the production capacity of the system and its burden on the environment, that is, a high ESI indicates high yield per unit environmental stress [17]. According to Brown et al (2009), the ESI inventories the essential respects of sustainable development: yield, renewability, and loading on the environment.

2.5. Source diversity
The complexity of a system requires a significant improvement of the analysis tools and indicators. Brown et al and Ulgiati et al (2011) developed a complexity index based on the diversity of energy and resource uses by a system. The index is a complex index based on emergy. It is developed by adapting the Shannon information formula, and uses emergy inflow to provide a quantitative assessment of source diversity. They presented a quality-adjusted Shannon diversity, where the probability of each individual or species is replaced by an emergy importance value of sources (EIVS): 

\[ EIVS_{i} = \frac{U_i}{\sum U_i} \]  

(1)

Where \( U_i \) = emergy used = (amount of i-th flow; J or g) × (emergy intensity of the i-th flow; Sej/J or Sej/g). The measure of source diversity is obtained: 

\[ SD = - \sum (EIVS \times \log_{10} EIVS) \]  

(2)

The maximum possible value (SDmax) for this index occurs when each component’s EIVSi have the equal value. In addition, a diversity ratio was defined as \( \triangle SD = 100 \times (SD/SDmax) \). According to Ulgiati et al. (2011), a SD closer to SDmax (and therefore a ratio \( \triangle SD \) closer to 1) suggests higher system resilience.
3. Results and discussion

3.1. Study area
Zhoushan City is located in the Zhoushan Islands in the northeastern part of Zhejiang Province. It is the only prefecture-level city established on an island in China. It is located at the intersection of the Yangtze River, Qiantang River, and Yongjiang River. In total, Zhoushan has an administrative area of 22,240 km², of which 1,440.12 km² of land is composed of 1,390 islands. There are 103 inhabited islands, making it the fourth largest island in China. The principal island has an area of 503 km², a population of 970,000, and a population density of 672 people per km². During the eleventh five-year period, the average growth of Zhoushan national economic is 15%; the GDP per person is about 10,000 USD in 2010.

3.2. Emergy analysis of Zhoushan’s economy from 1995 to 2010
We used the data of material, energy and currency flows from 1995 to 2010 to evaluate the changes in the development status of the Zhoushan urban system. The main data used in our analysis comes from the Zhoushan Statistical Office. The primary emergy flows for Zhoushan are listed in Figure 1. In this analysis, we adopted the 9.26E+24 sej planetary baseline for annual emergy input. Only the largest emergy inflow to marine and land area is included. Therefore, the rain chemical and wave were selected as an indicator of the renewable emergy resources received by the Zhoushan system, thereby minimizing the double-counting.

3.3. Emergy analysis of Zhoushan’s economy from 1995 to 2010
As mentioned in section 2.1, emergy intensity can be defined as either area-based, per capita-based, or currency-based. The following situation of Zhoushan economy illustrates some of the consequences of the use of emergy in the regional economy.
Emergy per area represents the level of development pressure an economy exerts on the environment. The higher value, the more emergy is consumed to support economy development. Zhoushan’s Emergy per area has increased from 4.51E+11 sej/m² in 1995 to 1.46E+12 sej/m² in 2010, with an average annual growth rate of 12%, which was 3.2 times that of 1995 throughout the study.

Figure 1. Summary diagram for the main emergy flows in Zhoushan urban system.
period. The results show that Zhoushan’s economic pressure on environment increased continuously (Table 1).

As shown in Table 1, another measure of emergy intensity for Zhoushan, that emergy per capita is an index of residents' happiness. During the 12-year study period, Zhoushan’s emergy per capita increased from 1.02E+16 sej/person in 1995 to 3.36E+16 sej/person in 2010, which represents 3.29 times the 1995 value.

The emergy money ratio represents the relationship between economic and emergy flow. A high value indicates that more natural resources are consumed to produce the same GDP. Zhoushan’s emergy money ratio decreased from 1.13E+21 sej/$ in 1995 to 3.41E+20 sej/$ in 2010 (Table 1).

Table 1. Emergy indicators and ratios for the Zhoushan from 1995 to 2010.

| Energy indicators | 1995     | 2000     | 2001     | 2002     | 2003     | 2004     | 2005     | 2006     | 2007     | 2008     | 2009     | 2010     |
|-------------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| The total emergy use (U) | 1.00E+22 | 1.43E+22 | 1.45E+22 | 1.54E+22 | 1.87E+22 | 1.82E+22 | 2.12E+22 | 2.39E+22 | 3.28E+22 | 3.28E+22 | 3.25E+22 |
| Emergy density (ED) | 4.51E+11 | 6.43E+11 | 6.61E+11 | 6.51E+11 | 6.92E+11 | 8.39E+11 | 8.16E+11 | 9.54E+11 | 1.08E+11 | 1.47E+11 | 1.47E+11 | 1.46E+11 |
| Emergy per capita (EP) | 1.02E+16 | 1.45E+16 | 1.50E+16 | 1.48E+16 | 1.59E+16 | 1.93E+16 | 1.88E+16 | 2.20E+16 | 2.48E+16 | 3.39E+16 | 3.39E+16 | 3.36E+16 |
| Emergy money ratio | 1.13E+21 | 9.73E+20 | 9.06E+20 | 7.62E+20 | 6.83E+20 | 6.68E+20 | 5.27E+20 | 4.96E+20 | 4.35E+20 | 4.47E+20 | 4.19E+20 | 3.41E+20 |

3.4. Economic efficiency

An indicator of Zhoushan's economic efficiency is the percentage of renewable energy in total energy use. Zhoushan's %R value dropped from 91.1% in 1995 to 35.75% in 2010. This means that the development of Zhoushan's economic system is increasingly dependent on non-renewable resources (Figure 2).

The import-export ratio reflects the dependence and exploitation of different countries and regions. In all systems where transactions are fair, the exchanged energy will be roughly equal. Zhoushan’s import/export ratio decreased from 174.71% in 2000 to 35.27% in 2010 (Figure 2). Zhoushan export more emergy in products and services than it imports. The emergy ratio of imports and exports shows that the emergy value of exports leaving the city in 2010 was almost twice that of imports, which shows that the actual wealth exchange with other countries or regions is imbalanced.

A third index of economic efficiency is the emergy yield ratio (EYR) defined as the ratio of total emergy used and exploited by the process (U) to the emergy invested from outside the system. It can be a measure of the ability of a process to exploit and make local resources available by investing in outside resources. The higher the value of emergy ratio index, the greater the return of unit emergy investment. The emergy output rate of Zhoushan City decreased from 14.18 in 1995 to 12.99 in 2010 (Figure 3), indicating that the economic system needs more emergy flow to provide sufficient goods and services for the society.
3.5. Environmental efficiency
The value of environmental load rate (ELR) can be calculated from 2.3 Environmental Efficiency. This ratio increased rapidly from 0.10 (1995) to 1.80 (2010) (Figure 3). The ELR ratio has been increasing year by year, indicating that the pressure on local environmental resources is increasing. However, there was some decline in 2010 (Figure 3). The small decline in 2010 may be due to fluctuations in growth trends on the one hand, and may also be due to the global financial crisis in 2008.

The rapid economic growth in the last decades improves the quality of living standard, and brings great environmental impacts in Zhoushan city which can be measured by the emergy indicators of waste to renewable emergy use ratio. In addition to reflecting the environmental efficiency of resources, the ELR ratio also indicates the pressure of local environment. The higher the ELR ratio is, the larger the pressure on environmental resources and the higher the pressure on local natural environment. The ratio of waste to renewable emergy use reveals the environmental pressure, which increased slowly from 4.50% in 1995 to 8.49% in 2010 as shown in Table 1, but decline obviously in 2010 maybe be owing to the global financial crisis in 2008.

3.6. Emergy sustainability index
According to the definition of 2.4 Emergy Sustainability Index, ESI index is rapidly decreasing year by year, which indicates that the long-term life support capacity of renewable resources is declining. When ESI < 1 indicates that the current economy is dominated by consumption, conversely, ESI > 1 represents an economy dominated by processes and products that currently provide net contributions to society. A high ESI index (ESI > 10) indicates that the current society is an "underdeveloped" economy [6]. The ESI of Zhoushan was declined from 145.11 in 1995 to 7.23 in 2010 (Figure 4). Although per capital GDP of Zhoushan was almost 10,000 $ in 2010, an ESI (7.23) of Zhoushan is more than that of the other cities in China, indicating that the sustainability of Zhoushan City and the emergy output rate under unit environmental pressure are quite high, which is questionable.

3.7. Source diversity
The emergy characteristics of Zhoushan in 2010 are highly dependent on seafood and energy imports, energy and service sources (Figure 5). The application of equation (2) is derived from the data of Zhoushan in 2010 and converted into emergy index and sustainability index of Zhoushan (1995-2010) as shown in Table 1. As shown in Table 1, the source diversity of Zhoushan was increased during the period 1995-2010, with the highest value of 0.7284 in 2007 and lowest of 0.5114 in 2000. The results showed that \( \Delta \ SD(\%) \) increased from 36.93% (1995) to 48.61% (2010) (Figure 6), with the highest value of 50.89% (2007) and the lowest value of 36.14% (2000). The relatively low source diversity and \( \Delta \ SD(\%) \) of Zhoushan City indicate that the city's economy is facing the risk of limited resource supply and highly dependent on seafood and imported resources. This indicates that the complexity of
sources has increased slightly, which may be attributed to the increase of imported resources. It can be seen that the total energy consumption maintained a steady growth, but the source diversity and $\Delta SD$ (%) did not increase significantly during this period, and the oscillation was about 0.7 and 50% respectively. We observe that Zhoushan's economy is developing at 50% of its maximum potential diversity.

**Figure 5.** Emergy signature of Zhoushan in 2010 (expressed in emergy unit, sej/year).

**Figure 6.** Trend of Zhoushan source diversit and $\Delta SD$ index from 1995 to 2010.

### 4. Conclusions
This research is based on emergy analysis to study the economic system of Zhoushan City. From a historical perspective, this paper analyzes the detailed structure of the resource base and emergy indicators of the modern urban system in Zhoushan from 1995 to 2010. Our results showed that there was a close relationship between the resource base and economic structure. From 1995 to 2010, the emergy intensity of Zhoushan City (except for the authorized market value) had been steadily increasing, which had promoted the continuous development of seafood. This had brought about an improvement in living standards in many ways, but it had led to one of the most serious problems, an increase in environmental load. At the same time, the decline in the ratio of emergy imports and exports indicated that Zhoushan was facing the risk of resource shortages and increasing dependence on external resources, which posed hidden dangers to Zhoushan's sustainable development. Some emergy indicators data of the years 2008 to 2010 reflected the impact of global financial crisis on Zhoushan economy. Although efficiency had increased and improved, Zhoushan's economic structure was still insufficient at the end of the study due to excessive reliance on marine biological resources and imported resources obtained from outside. Therefore, Zhoushan's economic system was clearly still a resource consumption type, and its economic development was increasingly dependent on natural resources and external resources.

The emergy analysis of Zhoushan used in this article provided an effective method for measuring the urban ecological and economic status, because these emergy indicators could effectively reflect the energy flow and efficiency, and thus could evaluate the environmental impact. This study conducted a comprehensive analysis of flux, efficiency and pressure from the environmental and economic perspectives, conducted a direct ecological and economic assessment of Zhoushan, and provided valuable insights for the utilization of the city's natural resources. The results showed that it was very helpful for city governments to improve their sustainable development decisions.

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References

[1] Huang S L 1998 Urban ecosystems, energetic hierarchies, and ecological economics of Taipei metropolis Journal of Environmental Management 52(1) 39-51

[2] Campbell D E, Brandt-Williams S L, Meisch M E A 2005 Environmental Accounting Using Emergy: Evaluation of the State of West Virginia [R]. EPA/600/R-02/011. USEPA, Office of Research and Development, Washington, DC, pp. 116

[3] Odum H T 1996 Environment Accounting : Emergy and Environment Decision Making. John Wiley, New York

[4] Higgins J B 2003 Emergy analysis of the Oak Openings region Ecological Engineering 21(1) 75-109

[5] Giannetti B F, Barrella F A, Almeida C M V B 2006 A combined tool for environmental scientists and decision-makers: Ternary diagrams and energy accounting Journal of Cleaner Production 14(2) 201-210

[6] Lei K, Wang Z, Ton S 2008 Holistic energy analysis of Macao. Ecological Engineering 32(1) 30-43

[7] Meillaud F, Gay J B, Brown M T 2005 Evaluation of a building using the emergy method Solar Energy 79(2) 204-212

[8] Odum H T, Odum E P 2000 The Energetic Basis for Valuation of Ecosystem Services Ecosystems 3 21-23

[9] Pulselli R M, Pulselli F M, Rustici M 2008 Emergy accounting of the Province of Siena: Towards a thermodynamic geography for regional studies Journal of Environmental Management 86(2) 342-353

[10] Rydberg T, Haden A C 2006 Emergy evaluations of Denmark and Danish agriculture: Assessing the influence of changing resource availability on the organization of agriculture and society Agriculture, Ecosystems & Environment 117(2-3) 145-158

[11] Tilley D R, Swank W T 2003 EMERGY-based environmental systems assessment of a multi-purpose temperate mixed-forest watershed of the southern Appalachian Mountains, USA Journal of Environmental Management 69(3) 213-227

[12] Brown M T, Ulgiati S 1997 Emergy-based indices and ratios to evaluate sustainability: Monitoring economies and technology toward environmentally sound innovation Ecological. Engineering 9 51-69

[13] Brown M T, Ulgiati S 2001 Emergy measures of carrying capacity to evaluate economic investments Population Environment 22 471-501

[14] Brown M T, Ulgiati S 2004 Energy quality, emergy, and transformity: H.T Odum’s contributions to quantifying and understanding systems Ecological Modelling 178 201-213

[15] Ulgiati S, Brown M T, Bastianoni S, Marchettini N 1995 Emergy-based indices and ratios to evaluate the sustainable use of resources Ecological Engineering 5 519-531

[16] Ulgiati S, Brown M T 1998 Monitoring patterns of sustainability in natural and man-made ecosystems Ecological Modelling 108 23-36

[17] Ulgiati S, Brown M T 2009 Emergy and ecosystem complexity Communications in Nonlinear Science and Numerical Simulation 14 310-321

[18] Brown M T, Cohen M J, Sweeney S 2009 Predicting national sustainability: The convergence of energetic, economic and environmental realities Ecological Modelling 220(23) 3424-3438

[19] Brown M T, Ulgiati S 1999 Emergy evaluation of the biosphere and natural capital Ambio 28 486-493