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Holistic emergy analysis of Macao

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ARTICLE INFO

Article history:
Received 17 October 2006
Received in revised form
11 August 2007
Accepted 30 August 2007

Keywords:
Emergy
Tourism
Net emergy
Net emergy ratio
Macao
Sustainability

ABSTRACT

Cities rely on ecosystems beyond their limits to provide natural resources that are unavailable within their boundaries, and this reliance increases as cities grow. With its development, Macao is changing from a city based primarily on consumption of natural resources to one supported mainly by the gambling and tourism industry. As a result, Macao has recently experienced an economic boom and rapid social development. This paper adopts the emergy analysis method to evaluate the sustainability of Macao's exchange processes in 2004 with respect to the life-support systems outside the city, tourism, and waste treatment processes. Tourism emergy was estimated using the proportional approach, waste emergy synthesis was expanded to include labor and waste treatment services, and Macao's trading partners were divided into China and "other regions" to produce more accurate results. In 2004, imported emergy equaled 241.95×10^{20} sej, versus exported production equaling 137.23×10^{20} sej and service exports equaling 42.70×10^{20} sej. The gambling and tourism industry earned US$ 8.10 billion in 2004, and with a purchasing power of 211.53×10^{20} sej, it is the largest source for sustaining Macao's dissipative structure. Since sustainability combines social, economic, and ecological factors, a single emergy index cannot measure sustainability adequately. By expanding Odum and Brown's net emergy surplus concept, we developed two aggregated emergy-based indicators: net emergy (NE) and the net emergy ratio (NER). These indicators more accurately reflect the development condition of the city. In addition, we used published data to compare Macao's emergy-based indices with those of four selected cities.

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1. Introduction

Human society is becoming increasingly urbanized, but continues to rely on nature for its resource intake and waste disposal. As cities draw more and more resources from distant areas, they also accumulate large amounts of materials within themselves (Huang and Hsu, 2003), including discharged wastes. As a result of these phenomena, two of the most serious ecological problems associated with urban development are the loss of life-support environments (e.g., prime agricultural land) due to its conversion into urban infrastructure (buildings, roads, etc.), and waste generation, particularly when wastes are discarded instead of recycled for productive purposes (Huang, 1998).

Emergy analysis considers all systems to be networks of energy flows, and determines the emergy values of the streams of materials and the systems involved in these flows. Since the early 1980s, emergy and emergy analysis have been widely used to analyze systems as diverse as ecological, industrial, economic, and astronomical processes. The development and use of emergy-based indicators (Ulgiati et al., 1995; Odum, 1996; Brown and Ulgiati, 1997; Ulgiati and Brown,

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doi:10.1016/j.ecoleng.2007.08.008

1998) has provided useful tools to judge the sustainability of a development pattern.

Colonized by Portugal in the 16th century, Macao was the first European settlement in the Far East. Located on the western side of the Pearl River estuary in southeastern China, Macao is characterized by more than 400 years of cultural mixture between the Western world and China. Pursuant to an agreement signed by China and Portugal on 13 April 1987, Macao became a Special Administrative Region (SAR) of China on 20 December 1999. Macao is a free port where people, cargo and capital are generally allowed to flow freely. Macao and mainland China have long maintained mutually beneficial and co-operative economic and commercial relationships that remain an important part of the city's emergy system. The city of Macao possesses a number of unique attractions, including treasured historical heritage sites, that make tourism another major part of its emergy system. Since 2005, Macao has been officially listed as a World Cultural Heritage Site (ICGRAEM, 2006).

In total, Macao covers an area of 27.5 km^2 (The Statistics and Census Service, 2005). With a population of 465,333, Macao is thought to be one of the most densely populated regions in the world, with 16,921 people per square km (Maritime Administration, 2005).

Macao's industry has changed rapidly since the 1980s. Agriculture disappeared in the mid-1990s (Wu and Ieong, 2006), fishing is dwindling as marine resources decline, and the manufacturing industry has declined in the face of competition from mainland China. However, the gambling and tourism industry (henceforth, "tourism"), has developed to compensate for these losses, and has been the core industry responsible for sustaining Macao's economy (Maritime Administration, 2005). The gross domestic product of Macao was US$ 1.03 billion in 2004, and the number of visitor arrivals was about 35.8 times the local population. In Macao, tourism thus makes a highly significant contribution to Macao's overall economic development. For example, in 2004, gambling tax revenues accounted for 77.8% of the total revenues of Macao's government, and about one-third of the total labor force was employed in the tourism sector (The Statistics and Census Service, 2005).

The study described in this paper uses emergy analysis to evaluate Macao's environmental and economic sustainability in 2004 so as to provide a more comprehensive and objective analysis than has previously been available. We define the concepts of net emergy and net emergy ratio, and use these indicators to assess the real wealth of the city, then compare the emergy results with those for Taipei (in 2002), Zhongshan (in 2000), Miami (in 1990), and San Juan (in 1992). The overall purpose of this research is to use the insights provided by emergy analysis to provide a holistic view of a complex urban ecosystem.

2. Emergy and sustainability evaluation methodology

In addition to the conventional methods for calculating emergy of a city (Odum, 1996; Huang, 1998; Huang and Chen, 2005), we attempted to develop indicators that would provide a more exact accounting of emergy flows and thereby produce more holistic results.

2.1. *The use of emergy/US$ ratios in the accounting for trading flows*

As a typical urban ecosystem, Macao receives inflows of fuels, raw materials, goods, and water from its supporting regions, and produces outflows of finished products, services, and byproduct wastes. To better account for the scale and function of China, Macao's largest trading partner, we divided Macao's trade activities into two groups: China and "other regions". In the emergy accounting for trade, we computed the emergy flows using detailed emergy/US$ ratios rather than simply adopting world values for these ratios, as world values cannot adequately reflect the unique characteristics of a given city. In our research, we used emergy/US$ values of 2.89×10^{12} sej/US$ for China (estimated from China's Emergy/US$ value of 2000, and calibrated to account for the increased GDP of China during the study period) and 1.66×10^{12} sej/US$ for all other regions combined (M.T. Brown, University of Florida, 2005, personal communication).

2.2. *Net emergy and net emergy ratio*

The concept of net emergy (net energy embodied in a process) was first proposed by Ulgiati et al. (1995), and was comprehensively summarized by Odum (1996), among others. Net emergy was defined as the emergy yield of a process minus feedback input, and the emergy yield ratio was defined as the emergy yield divided by the emergy input (Odum, 1996).

Based on previous research (Ulgiati et al., 1995), Brown and Ulgiati (1997) developed emergy-based indices that could be used to judge the sustainable development of a narrowly defined process, and estimated that the sustainability of the system should include the net emergy yield of the system (the total of renewable and nonrenewable resources plus purchased inputs from outside the system), its environmental load, and its use of nonrenewable resources (Fig. 1). They demonstrated that the emergy sustainability index (ESI) can be used to indicate the sustainability of the system (ESI = EYR/ELR), where EYR represents the ratio of the emergy yield ratio (the sum of the output production and services divided by the purchased emergy from outside the system), and ELR (the ratio of emergy inputs from outside the system divided by the renewable emergy) represents the environmental load ratio (the sum of local and external nonrenewable resources, divided by the local renewable resources). Bakshi (2000) and Yang et al. (2003) further developed this concept to include the emergy of wastes (W) and the emergy of waste treatment (F').

At a country-level or a city-level scale, which includes many processes not included in this analysis, this approach seems to be unsuitable, and the emergy yield (Y) usually does not equal the emergy import (Huang and Odum, 1991, 1996; Odum, 1996; Ulgiati et al., 1995; Lan et al., 2002). Brown and Ulgiati (2001) found that long-term sustainable development can be achieved by balancing the exchange of emergy between exports and imports. In order to elucidate the net emergy, we have proposed a modified emergy framework (Fig. 2) that

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