ECOLOGICAL ENGINEERING 32 (2008) 30–43

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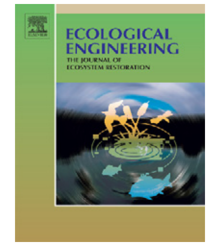

Holistic emergy analysis of Macao

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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.

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

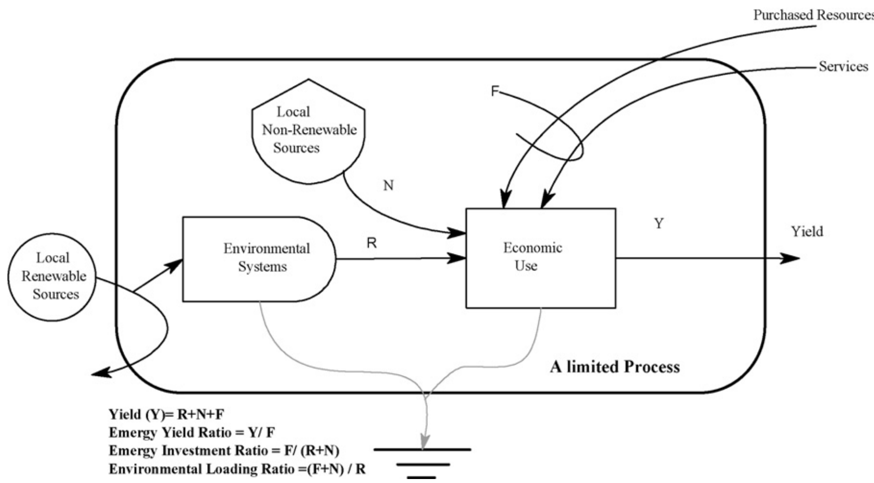

Fig. 1 – Diagram of emergy flows between a system and its external environment. Based on these flows, emergy-based indices can be developed that account for locally available renewable emergy inputs (*R*), locally available nonrenewable inputs (*N*), and inputs purchased from outside the system (*F*). Diagram based on Brown and Ulgiati (1997).

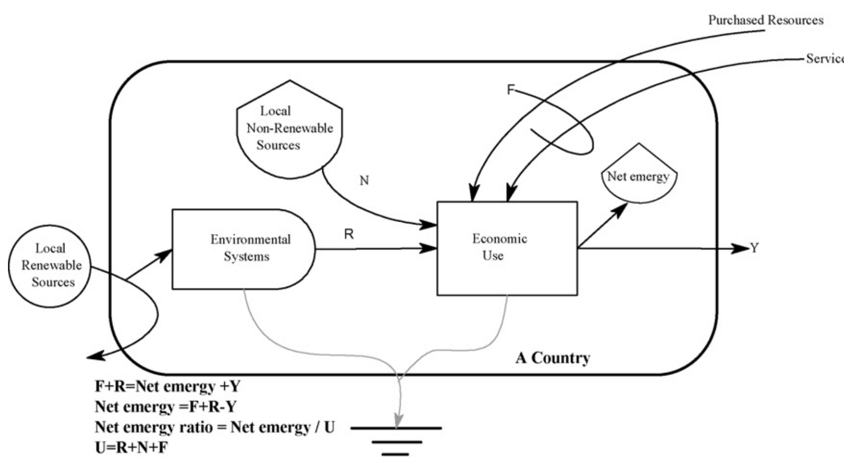

Fig. 2 – A modified diagram showing emergy-based indices at the scale of a country. In this revised version of Fig. 1, net emergy storage has been added at the right side of the system.

reflects holistic processes at the level of a whole country, and have added a "net emergy" frame. The net emergy (Lei and Wang, in press) can be calculated as follows:

$$\text{Net emergy (NE)} = F + R - Y \quad (1)$$

$$\text{Net emergy ratio (NER)} = \frac{\text{NE}}{\text{emergy used}} \quad (2)$$

where *F* represents the resources and services purchased from outside the system, *R* represents the locally available renewable resources, and *Y* represents the emergy yield defined earlier in this section.

2.3. Emergy analysis of tourism and service exports

In order to analyze the emergy consumption that results from the tremendous influx of visitors to Macao, we have proposed a holistic approach to measuring the emergy flows involved in tourism (Fig. 3). In this model, the purchasing power (Odum, 1996) of visitors (T_m), which represents an input into the system, differs from consumption by visitors (service exports, abbreviated as M_t), which represents an output flow. Since a tourism-oriented city like Macao is shared by local residents and visitors, we employed a proportional approach (Eqs. (3) and (4)) to calculate the proportion of total service exports accounted for by visitors (Lei and Wang, in press), which dif-

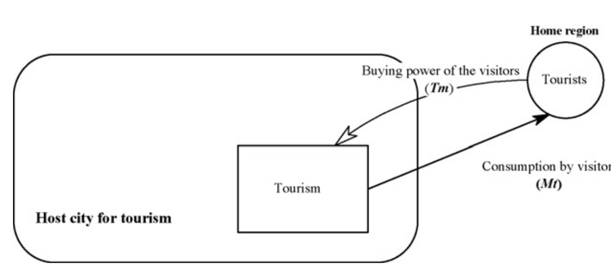

Fig. 3 – A concise diagram illustrating the emergy inputs and outputs that result from tourism and tourists.

fers from the simpler calculation of "P_1E_3" (Odum, 1996). In our analysis, the emergy input resulting from resource consumption by visitors can be defined as follows:

$$R_t = \frac{Tdr}{Tdr + 365P} \quad (3)$$

where R_t is the ratio of visitor-consumed emergy to total emergy used (U); T the total number of tourists; d the average duration of a visitor stay; P the population of Macao; r is the tourist's consumption factor (i.e., the ratio of emergy consumption by a tourist to emergy consumption by a native of Macao). In 2004, r was estimated to be 1.9, which means that a tourist consumes nearly twice as many resources as a local citizen (Lei et al., 2006).

Similarly, emergy export resulting from consumption by visitors can be defined as:

$$M_t = UR_t \quad (4)$$

For a tourism-driven city such as Macao, the contributions and impacts of tourism should be calculated (Lei and Wang, in press). The ratio of emergy contribution to impacts can be thought of as equivalent to an emergy exchange ratio (EER). This parameter is calculated as follows:

$$\text{EER of tourism} = \frac{\text{emergy input into the system}}{\text{emergy output from the system}} = \frac{T_m}{M_t} \quad (5)$$

2.4. Emergy analysis of wastes

Since the 2000s, the emergy analysis framework has been used to analyze the emergy involved in the management of wastes, including municipal solid waste (Luchi and Ulgiati, 2002; Brown and Buranakarn, 2003; Huang and Hsu, 2003; Niccolucci et al., 2003; Yang et al., 2003) and municipal wastewater treatment (Björklund et al., 2001).

By tracking the waste production process, we can calculate details of the emergy of wastes in Macao. In this analysis, the emergy of wastes that we analyzed did not include emissions into the atmosphere; although these are critical components of the overall waste flow, we were not able to analyze them because of a lack of reliable data. Instead, we focused on emergy embodied in the wastes, and the emergy of labor and services used in their treatment processes. This contrasts with the conventional method, which only accounts for the relative emergy of the wastes. Specifically, we focused on two wastes and their associated emergies:

1. Sewage: (a) the embodied emergy in sewage, (b) the labor and services used in wastewater treatment plants, and (c) depreciation of the plants and their equipment.
2. Solid waste: (a) the embodied emergy in solid wastes, (b) the labor and services used to collect this waste, (c) the labor and services used in incinerator plants, (d) depreciation of the incinerator plant and its equipment, and (e) the costs of landfill management.

3. Results and discussion

The data used to calculate the main emergy flows for Macao are listed in Supplementary tables, and are summarized in Fig. 4. In this analysis, we adopted the 9.26×10^{24} sej planetary baseline for annual emergy input (Campbell et al., 2004). The primary data used in our emergy calculations were provided by The Statistics and Census Service (2005) of the Macao SAR. Table 1 summarizes the material trade between Macao and its two categories of trading partners. Table 2 summarizes Macao's imports and exports of resources and services in 2004. Fig. 5 summarizes the emergy flows in these tables, and the associated dollar values per year for exported production (B) and exported services.

3.1. Detailed emergy synthesis for Macao

Based on the data in Table 2, renewable environmental resources (R) accounted for 0.13% of the emergy used by Macao in 2004. Non-renewable environmental resources (N), mainly composed of mined marble (3.53×10^{20} sej), accounted for about 1.44% of the emergy used by Macao in 2004. Imported emergy (F) equaled 241.95×10^{20} sej, which accounted for 98.43% of the total emergy used (i.e., 245.80×10^{20} sej); 58.0% of the imported emergy came from China (Table 1). Service exports (M_t) amounted to 42.70×10^{20} sej (Table 2), versus 137.02×10^{20} sej for exported production (B), and the purchasing power of visitors (T_m, tourism income) was 211.53×10^{20} sej (equivalent to roughly US$ 8.1 billion). The results clearly show how strongly Macao depended on external emergy inputs, as well as the enormous income derived from tourism as a result of providing visitors with services and goods.

Macao exported 74.3% more emergy than it imported in 2004, and exported production (B) accounted for about 56.6% of the imported emergy (F). Textiles are the main exported products, and account for about 86.0% of the total exported production. Fig. 6a depicts the material imports from China and other regions. All the drinking water and electricity, most of the minerals (73.3%) and raw and processed materials (66.6%), and about half of the food (48.2%), fuels (49.9%), and goods (42.2%) were imported from China. Emergy exports (Fig. 6b) amounted to 69.9% of the emergy imports in 2004. Fig. 6b shows that the main components of the exports were raw and processed materials (88.4%) and goods (10.7%), of which 39.4% were exported to China. Fig. 6c shows that 63.5% of service imports and 85.6% of service exports occurred between Macao and China; clearly, China is Macao's largest labor and services trading partner.

To more accurately describe the emergy imports and exports by Macao, we divided these factors among two primary groups of trading partners: China and other regions. This allowed us to use a different emergy/US$ ratio for each group, leading to a more comprehensive emergy analysis. The difference between this approach and using a single overall ratio is summarized in Table 3, and although the difference was generally small, some calculated parameters differed by a considerable margin. We detected differences in the two calculation processes mainly in the trade of raw and processed materials imported from China, which increased the

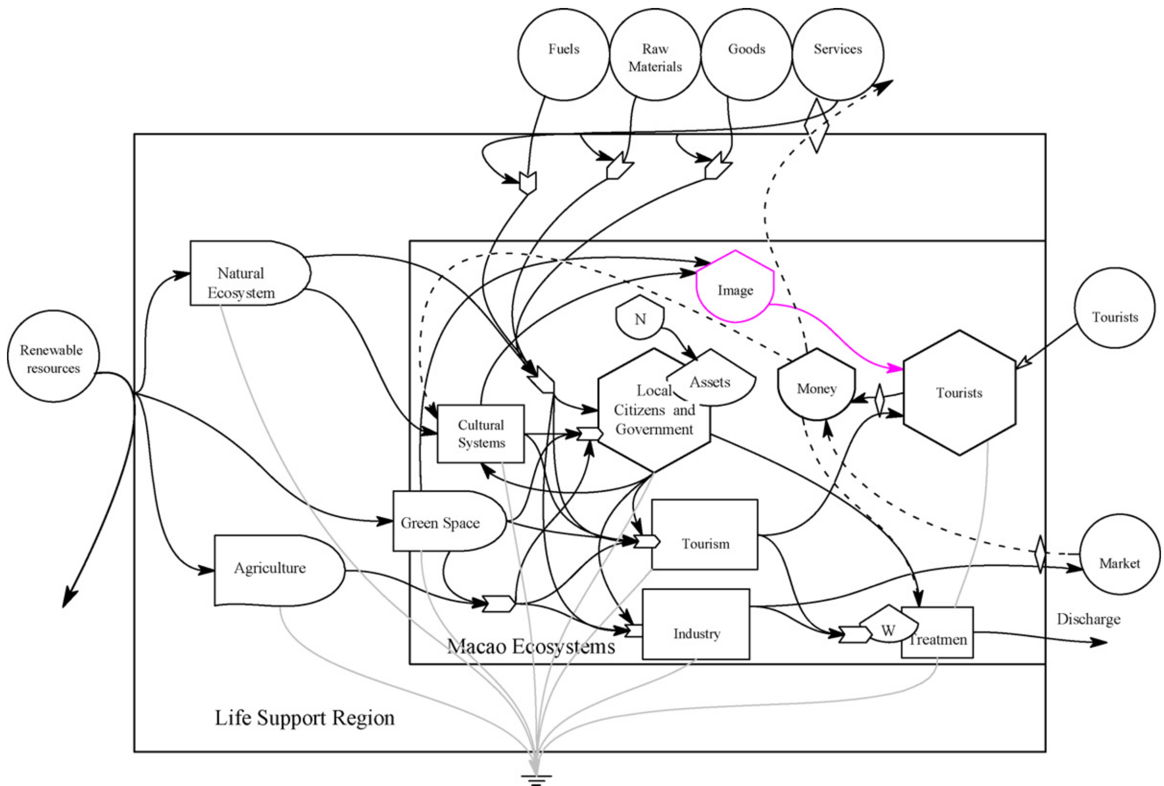

Fig. 4 – Detailed diagram of the emergy flows within Macao and between Macao and its life-support systems. (Modified from Huang, 1998).

Table 1a – The emergy trade between Macao and its two major categories of trading partner in 2004: China and Other Regions

Item	China			Other Regions			Total
	Units	Value (US$)	Emergy (sej)	Units (kg)	Value (US$)	Emergy (sej)	Emergy (sej)
Material imports		157.58×10^7	119.76×10^{20}		260.51×10^7	76.7×10^{20}	196.43×10^{20}
1. Food	1.77×10^{11} g	12.58×10^7	8.73×10^{20}	1.59×10^8	29.49×10^7	9.39×10^{20}	18.12×10^{20}
2. Drinking water	588.49×10^{11} g	0.68×10^7	0.46×10^{20}	0.00	0.00	0.00	0.46×10^{20}
3. Electricity	151.3 GW-h	1.33×10^7	0.93×10^{20}	0.00	0.00	0.00	0.93×10^{20}
4. Fuels	3.72×10^{11} g	12.89×10^7	8.42×10^{20}	3.74×10^8	13.99×10^7	8.46×10^{20}	16.88×10^{20}
5. Minerals	7.15×10^{11} g	1.21×10^7	9.98×10^{20}	2.35×10^8	0.58×10^7	3.63×10^{20}	13.61×10^{20}
6. Raw materials	5.46×10^{11} g	98.73×10^7	80.43×10^{20}	1.64×10^8	109.98×10^7	40.3×10^{20}	120.77×10^{20}
7. Goods	2.45×10^{11} g	30.15×10^7	10.82×10^{20}	1.58×10^8	106.47×10^7	14.8×10^{20}	25.66×10^{20}
Product exports	78.81×10^7	54.01×10^{20}		253.46×10^7	83.2×10^{20}	137.23×10^{20}	
1. Food	0.01×10^{11} g	0.16×10^7	0.08×10^{20}	0.06×10^8	3.16×10^7	0.8×10^{20}	0.89×10^{20}
2. Fuels	0.0002×10^{11} g	0.002×10^7	0.0004×10^{20}	0.0001×10^8	0.001×10^7	0.0002×10^{20}	0.0006×10^{20}
3. Cement	0.08×10^{11} g	0.04×10^7	0.18×10^{20}	0.04×10^8	0.03×10^7	0.07×10^{20}	0.26×10^{20}
4. Raw materials	1.24×10^{11} g	72.67×10^7	50.37×10^{20}	1.52×10^8	216.40×10^7	71.0×10^{20}	121.36×10^{20}
5. Goods	0.50×10^{11} g	5.93×10^7	3.37×10^{20}	0.34×10^8	33.87×10^7	11.4×10^{20}	14.73×10^{20}

Table 1b – Service imports and exports between Macao and its two major categories of trading partner in 2004: China and Other Regions

Item	China			Other Regions			Total
	Value (US$)	Transformity (sej/US$)	Emergy (sej)	Value (US$)	Transformity (sej/US$)	Emergy (sej)	Emergy (sej)
Service imports	71.54×10^7	2.89×10^{12}	20.66×10^{20}	71.54×10^7	1.66×10^{12}	11.88×10^{21}	32.54×10^{21}
Service exports[a]	627.24×10^7	2.89×10^{12}	181.16×10^{20}	182.79×10^7	1.66×10^{12}	30.36×10^{21}	211.53×10^{22}

[a] The total service exports in 2004 was 810.03×10^7 US$ according to the Statistics and Census Service.

Table 2 – Summary of emergy flows and indicators for Macao in 2004

Parameter	Item	Energy (J), money (US$), or mass (g)	Solar emergy (sej)	Emdollars (em$)
R	Renewable resources	1.11×10^{15}	0.32×10^{20}	0.01×10^{9}
N	Nonrenewable resources	3.62×10^{11}	3.53×10^{20}	0.15×10^{9}
Fuel	Imported fuels, and minerals		31.37×10^{20}	1.89×10^{9}
G	Imported goods and raw materials	6.40×10^{15}	178.04×10^{20}	10.73×10^{9}
P2I	Imported services	1.43×10^{9}	32.54×10^{20}	1.36×10^{9}
B	Exported production	2.41×10^{15}	137.02×10^{20}	5.74×10^{9}
T_m[a]	Service exports (tourism)	8.10×10^{9}	211.53×10^{20}	8.87×10^{9}
M_t[b]	Tourist consumption		42.70×10^{20}	1.79×10^{9}
F	Imported emergy = Fuel + G + P2I	38.20×10^{15}	241.95×10^{20}	13.98×10^{9}
U	Emergy used = R + N + F	39.31×10^{15}	245.80×10^{20}	14.14×10^{9}
Y	Exports = B + M_t		179.72×10^{20}	7.53×10^{9}
W	Waste emergy		29.80×10^{20}	1.25×10^{9}
ELE	Electricity = 1880 GW-h	7.36×10^{15}	12.44×10^{20}	0.52×10^{9}
GDP	GDP (US$)	10.30×10^{9}		
Population		4.65×10^{5}		
Area (m^2)		2.75×10^{7}		
P_1[c] (Macao's emergy/US$ ratio)			2.39×10^{12}	
P_2[d] (The world's emergy/US$ ratio)			1.66×10^{12}	
P_3[e] (China's emergy/US$ ratio)			2.89×10^{12}	

[a] The monetary income from tourism.
[b] The emergy consumed by tourists (Eq. (4)).
[c] the emergy/US$ ratio for Macao (determined by our calculations).
[d] The emergy/US$ ratio of "other regions" comes from M.T. Brown (2004, the University of Florida, personal communication).
[e] The emergy/US$ ratio of China (2.89×10^{12} sej/US$) was estimated by accounting for China's increased GDP and emergy use since the 2000 baseline (when China's emergy/US$ ratio was 4.96×10^{12} sej/US$; Zhao, 2002).

emergy value of the monetary categories when we performed a separate calculation for China. But in other categories, particularly in service imports from other regions, the emergy value decreased when using only a single composite ratio.

3.2. *Comparison of Macao's emergy indicators with those of four other cities*

To illustrate how the emergy analysis for Macao compares with the results for other similar cities, we obtained data for Taipei (Huang and Hsu, 2003), Zhongshan (Zhao, 2002), Miami-Dade County (Woithe, 1995), and San Juan (Doherty, 1995).

Taipei is located in the northern part of Taiwan, and is the island's key urban center. The city has an area of about 2325 km^2, and its total population is approximately 6.2 million, having increased by about 25% during the past decade. On average, approximately 2×10^6 m^2 of building floor area per annum were constructed between 1981 and 1998, mainly in response to the rapid urbanization. During recent decades, Taiwan has experienced rapid economic growth, with asso-

Table 3 – Comparison of the emergy indices for Macao in 2004 based on the use of a single (global) emergy/US$ ratio and the use of two (global and Chinese) emergy/US$ ratios in the calculation processes

No.	Name of index	Expression	Two ratios	A single ratio	% difference[a]
1	Imported emergy	F	2.42×10^{22}	2.41×10^{22}	−0.25
2	Emergy used (*U*)	R + N + F	2.46×10^{22}	2.45×10^{22}	−0.24
3	Exported emergy (*Y*)	P1E + B + N2	1.80×10^{22}	1.78×10^{22}	−0.94
4	Net emergy	R + F − Y	6.26×10^{21}	6.36×10^{21}	1.62
5	NER	(R + F − Y)/U	0.255	0.259	1.87
6	Emergy yield ratio	Y/F	0.743	0.738	−0.69
7	Emergy exchange ratio	F/Y	1.35	1.36	0.69
8	Renewable emergy to emergy used	R/U	1.34×10^{-3}	1.10×10^{-3}	−17.8
9	Ratio of used free emergy to *U*	(R + N0)/U	1.57×10^{-2}	1.58×10^{-2}	0.57
10	Emergy density	U/area (m^2)	8.94×10^{14}	8.92×10^{14}	−0.24
11	Use per person	U/population	5.28×10^{16}	5.27×10^{16}	−0.24
12	*ELR*	(F + N)/R	743	904	21.7
13	Emergy/US$ ratio	U/GNP	2.39×10^{12}	2.38×10^{12}	−0.24
14	% of emergy use accounted for by electricity	(Electricity)/U × 100	5.06	5.91	16.8
15	Fuel use per person	Fuel/population	3.63×10^{15}	3.59×10^{15}	−1.08
16	ESI	EYR/ELR	1.00×10^{-3}	8.16×10^{-4}	−18.4

[a] % difference = (Value with a single ratio − value with two ratios)/value with two ratios ×100%.

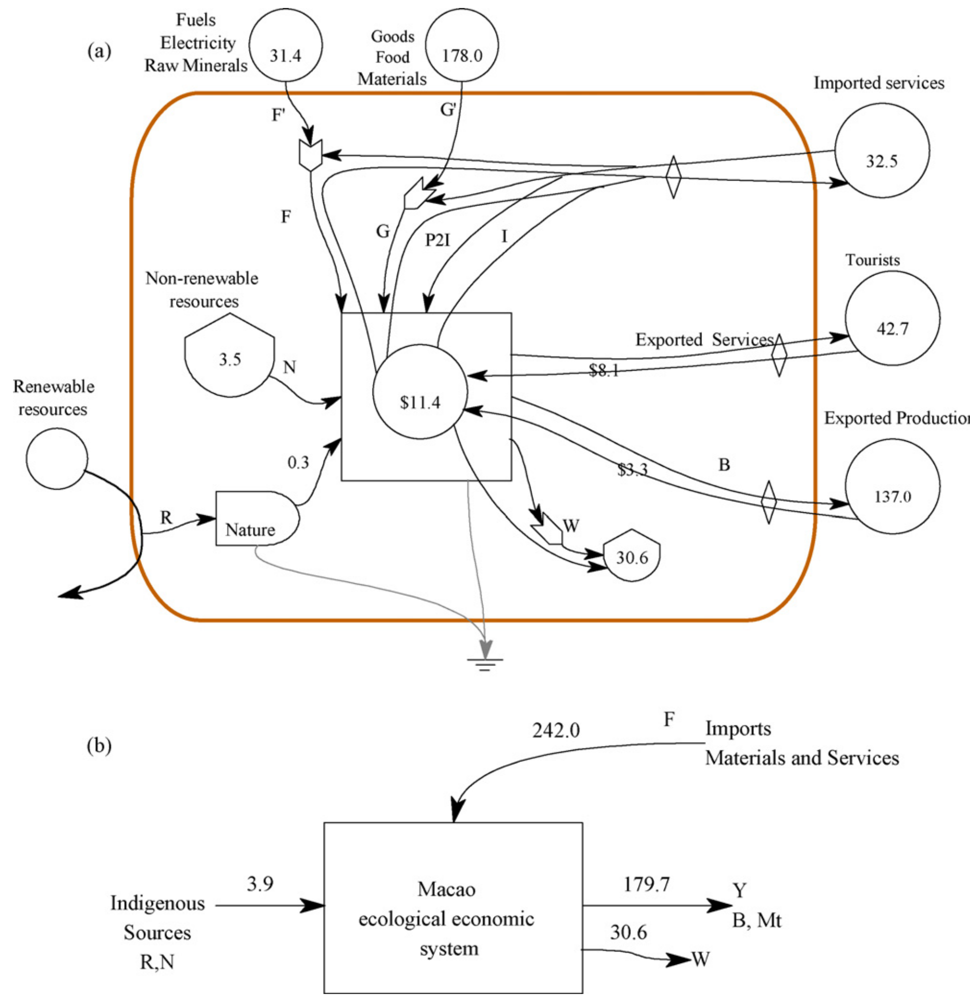

Fig. 5 – Aggregated diagram of emergy flows (Units: Emergy, 10^{20} sej; Money, 10^9 US$) for Macao in 2004. (a) Overall flows. (b) Imports of locally available renewable (*R*) and nonrenewable (*N*) resources and imports of materials and services (*F*) from outside the system. Raw data used to generate the numbers in this figure are reported in Table 2.

ciated expansion of urban areas and high rates of per capita consumption. Its GNP reached 211.21×10^9 US$ in 2002, and its successful economy was called one of the “four little dragons” in Asia. Most of its resources were imported from outside the city and other countries due to a lack of natural resources (Huang and Hsu, 2003).

Zhongshan is located in China’s southern Guangdong province, and is also a newly developing city. The city covers an area of about 1800 km^2, and the total population in 2000 was approximately 2.36 million, of which about 60% live in the city, compared with 18.32% in 1978. During the past 20 years, Zhongshan has experienced a rapid growth in manufacturing, electronics industries, and various types of services, accompanied by rapid expansion of urban areas. Its GDP reached 3.78×10^9 US$ in 2000. Although the region around Zhongshan has an efficient agricultural support system, most of its resources and raw materials were imported from other areas of mainland China and from other countries (Zhao, 2002).

Miami-Dade County is located in the southeastern part of the state of Florida. With a population of 1.94 million in 1990, it was the most populous county in the state. The county seat was Miami, which is located on the southeastern seacoast of Florida, in the northeastern part of the county. Miami-Dade County covers a total area of 6297 km^2. During the 1960s, Miami became a major center of finance and trade with Latin America. The energy maintaining the county’s structure was largely of external origin, being purchased using income obtained from tourism, transfer payments from the U.S. federal government, investment activities, and retirement benefits (Woithe, 1995). We could not find GDP data for 1990, but its GDP had reached 7.15×10^9 US$ in 2003 (The Washington Economics Group Inc., 2004). Miami-Dade County has a large area of wetlands, including Everglades National Park, and has developed extensive agricultural resources and exploitation of rich supplies of minerals. As a highly developed city, Miami-Dade County imported most of its life-support materials, and exported mainly services and technology.

San Juan is the capital of Puerto Rico, and the nation’s largest city. As of the 1992 census, it had a population of 1.71 million living in an area of 537 km^2. The dense city serves as a location for many historical buildings and other tourism resources. Today, San Juan serves as one of Puerto Rico’s most important seaports, and is the island’s manufacturing, financial, cultural, and tourist center. We could not find GDP data

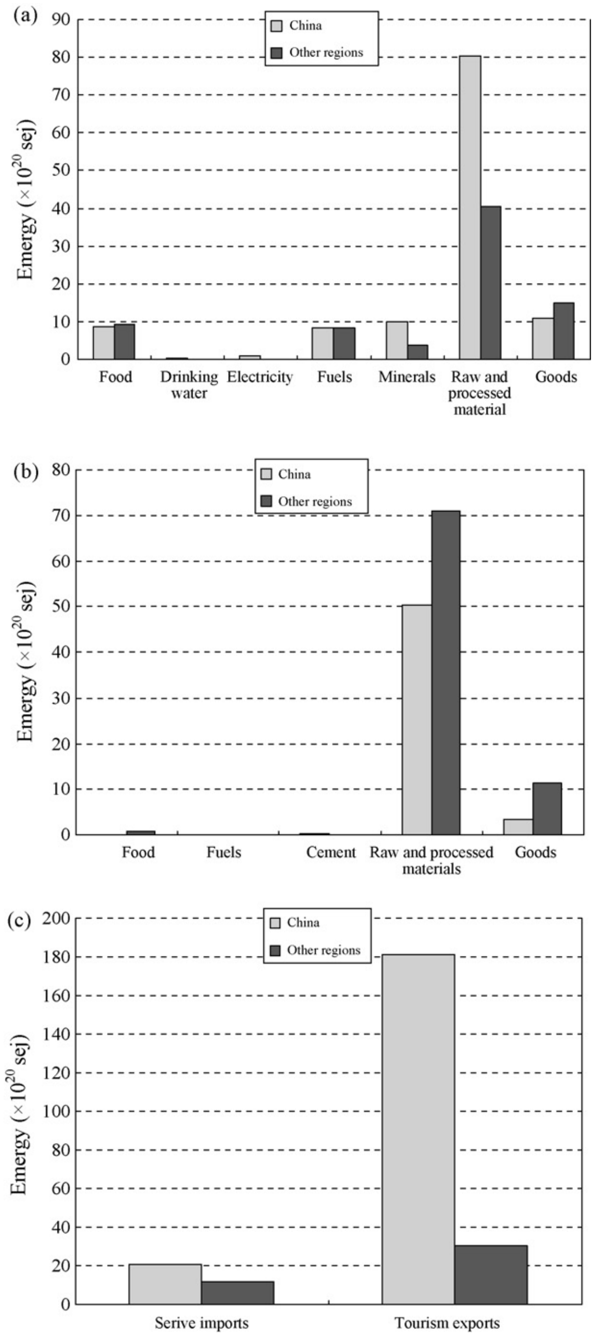

Fig. 6 – Imports and exports of emergy and services between Macao and its two major trading partners in 2004: China and other regions. (a) Emergy imports. (b) Emergy exports. (c) Service imports and tourism exports.

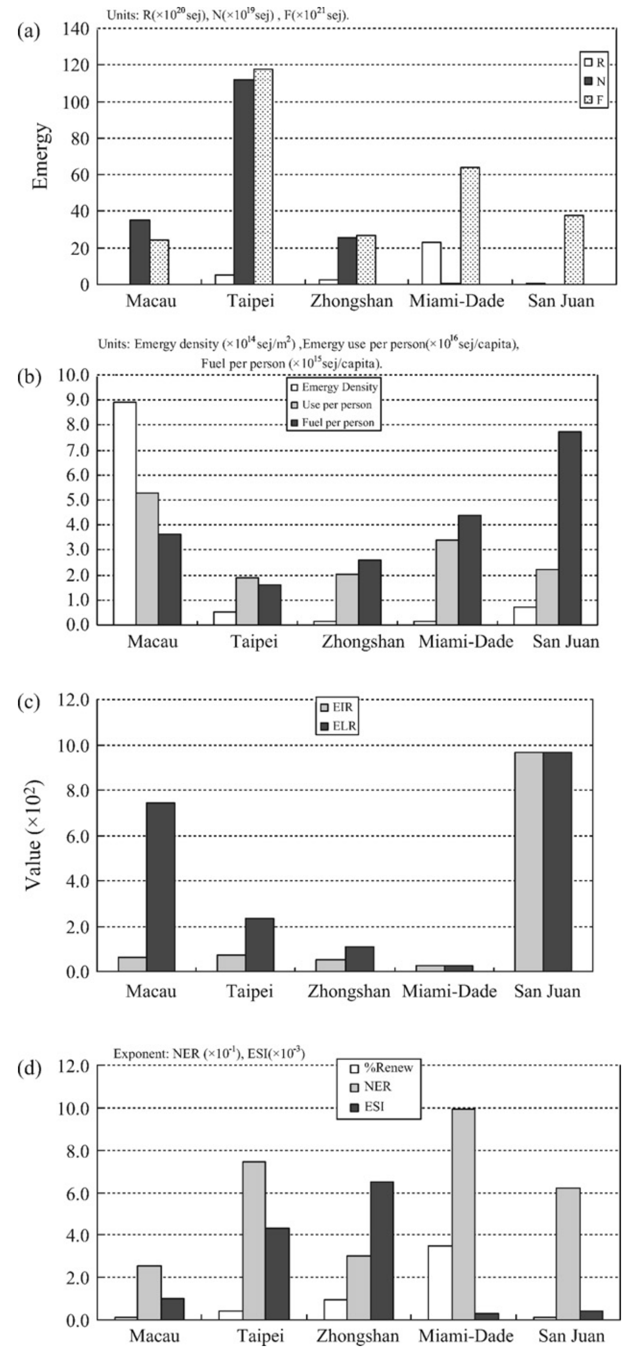

Fig. 7 – Comparison of emergy parameters between Macao (2004) and four other cities: Taipei (Taiwan) in 2002, Zhongshan (China) in 2000, Miami-Dade County (Florida) in 1990, and San Juan (Puerto Rico) in 1992. (a) Three components of emergy. (b) Emergy density, and emergy and fuel use per person. (c) Emergy investment ratio (EIR) and environmental loading ratio (ELR). (d) %*Renew*, the net emergy ratio (NER), and the emergy sustainability index (ESI).

for the city alone, but in 1992, the GDP of Puerto Rico was 39.8 billion US$ (Doherty, 1995).

Table 4 compares the main emergy indicators for Macao with those of the four other cities. These indicators will be compared in the five following sections.

3.2.1. *Comparison of the emergy components*

The emergy components shown in Table 4 are compared visually in Fig. 7a. Because of a lack of local resources, all five cities imported most (more than 95%) of the emergy they used (*U*). The percentages of emergy exports to emergy used ranged from 0.8% (Miami-Dade County) to 73.1% (Macao), indicating that all five cities had a rich net emergy surplus.

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Table 4 – Comparison of the emergy indices for Macao, Taipei (Taiwan), Zhongshan (China), Miami-Dade County (Florida), and San Juan (Puerto Rico)

No.	Index	Expression	Macao (2004)	Taipei (2002)	Zhongshan (2000)	Miami-Dade County (1990)	San Juan (1992)
1	Area	A (km^2)	22.75	271.77	1800.00	5060.00	537.00
2	Population	P ($\times 10^6$)	0.47	6.30	1.34	1.94	1.71
3	Renewable emergy flow	R ($\times 10^{20}$ sej)	0.32	5.02	2.52	23.1	0.39
4	Nonrenewable emergy flow[a]	N ($\times 10^{20}$ sej)	3.53	11.20	2.58	0.07	0.00
5	Imported emergy	F ($\times 10^{22}$ sej)	2.42	11.8	2.69	6.38	3.76
6	Emergy used (*U*)	$R+N+F$ ($\times 10^{22}$ sej)	2.46	11.9	2.74	6.61	3.76
7	Exports (*Y*)	P_1E+B+N_2 ($\times 10^{22}$ sej)	1.80	2.92	1.88	0.05	1.43
8	Emergy yield ratio (*EYR*)	Y/F	0.743	0.249	0.699	0.082	0.380
9	Emergy exchange ratio (*EER*)	*F/Y*	1.35	4.02	1.43	121.90	2.63
10	Percent of renewable resources to emergy used (*%Renew*)	$R/U \times 100\%$	0.13	0.42	0.92	3.50	0.10
11	Ratio of emergy use purchased	*F/U*	0.984	0.986	0.981	0.965	0.999
12	Ratio of emergy used free to *U*	$(R+N_0)/U$	0.0157	0.0055	0.0186	0.0351	0.0010
13	Emergy investment ratio (*EIR*)	$F/(R+N)$	6.27	7.24	5.27	2.75	9.641
14	Emergy density	*U/A* ($\times 10^{13}$ sej/m^2)	89.39	5.12	1.52	1.31	7.01
15	Emergy use per person	*U/P* ($\times 10^{16}$ sej/person)	5.28	1.89	2.05	3.41	2.20
16	Environmental loading ratio (*ELR*)	$(F+N)/R$	743	234	108	27.6	964
17	Emergy/US$ ratio	*U*/GDP ($\times 10^{12}$ sej/US$)	2.39	0.56	7.25	1.60	1.64
18	% of emergy use accounted for by electricity	(Electricity)/$U \times 100\%$	5.06	15.51	11.43	51.30	11.80
19	Fuel use per person	Fuel/*P* ($\times 10^{15}$ sej/person)	3.63	1.6	2.59	4.38	7.75
20	Emergy sustainability index (*ESI*)	EYR/ELR (10^{-3})	1.00	4.30	6.50	0.30	0.39
21	Net emergy (*NE*)	$R+F-Y$ ($\times 10^{22}$ sej)	0.63	8.88	0.83	6.56	2.33
22	Net emergy ratio (*NER*)	$(R+F-Y)/U$	0.25	0.75	0.30	0.99	0.62
23	Waste emergy ratio	W/U	0.12	0.15	0.18		

[a] Nonrenewable resources (*N*) can be divided into three parts: N_0 is the rural dispersal, N_1 is concentrated use, and N_2 is direct export (Odum, 1996).

3.2.2. *Emergy density, emergy use, and fuel use per person*

The emergy used per person in Macao in 2004 (5.28×10^{16} sej, Table 4) was the highest of the five cities by a considerable margin (Fig. 7b). Macao also has one of the highest population densities in the world (Maritime Administration, 2005), therefore its emergy density (89.4×10^{13} sej/m^2) was much higher than that of the other four cities. It was 17.5 times that of Taipei (5.1×10^{13} sej/m^2), 68.8 times that of Dade County (1.3×10^{13} sej/m^2), 59.6 times that of Zhongshan (1.5×10^{13} sej/m^2), and 12.8 times that of San Juan (7.0×10^{13} sej/m^2). Because of its small area, Macao had the highest emergy density, but San Juan had the highest average fuel emergy (7.75×10^{15} sej/person) of the five cities.

3.2.3. *Emergy/US$ ratio and emergy investment rate*

The emergy/US$ ratio represents the relationship between the emergy used and GDP, and can thus indicate the levels of development and industrialization of a city (Table 4). A higher ratio implies that more natural resources would be consumed to produce the same GDP. The emergy/US$ ratio in Macao in 2004 was 2.39×10^{12} sej/US$, which was lower than that of Zhongshan (7.25×10^{12} sej/US$) but higher than that of Miami-Dade County (1.60×10^{12} sej/US$), San Juan ($1.64 \times 10^{12}$ sej/US$), and Taipei ($0.56 \times 10^{12}$ sej/US$). In 2000, Zhongshan had experienced rapid industrial development accompanied by intense use of a rich supply of natural resources, so its emergy/US$ ratio was the highest of the five cities.

The emergy investment ratio (EIR) equals the emergy feedback (*F*) from the economy divided by the indigenous emergy inputs ($R + N$). This index thus measures the intensity of economic development and the resulting load on the environment; it is useful for evaluating the relative contribution of free environmental inputs. A high ratio means that the environment is supporting a higher economic input than other regions with lower ratios. The EIR values for the five cities were all high (Fig. 7c), ranging from 2.75 (Miami-Dade County) to 96.41 (San Juan). The dense input and high cost depressed the competitiveness of Macao's manufacturing industry, and higher prices forced many enterprises to move to South China in search of lower resource costs and lower salaries.

The emergy yield ratio (EYR) represents the ratio of output emergy (*Y*) to input emergy (*F*), so a lower ratio means more net emergy transferred into the city. Macao's EYR in 2004 was 0.74, which was higher than that of any of the other cities; this value means that an input of 1 sej will result in only 0.74 sej output to the market outside the system. Miami-Dade County had the lowest ratio (0.08) of the five cities.

3.2.4. *Emergy exchange ratio*

Emergy is an appropriate measure for evaluating the benefits to a nation from all types of international exchange (Odum, 1996). By definition, an EER value greater than 1 means that the emergy received by the system exceeds the emergy the system provides to external systems. As a result, the system stores emergy, which will be advantageous for its survival and development. Table 4 shows that Macao had the smallest EER (1.35), followed by Zhongshan (1.43), San Juan (2.63), Taipei (4.02), and Miami-Dade County (121.9). The detailed values for San Juan and Miami-Dade County were not directly available in the published literature. Thus, to estimate the yield (*Y*) for San Juan, we inferred the values for imported services, loans, and tourism from the data provided by Doherty (1995; p. 125, Table 1). Similarly, it was not possible to find published export emergy values for Miami-Dade County, so the value was inferred from the data provided by Woithe (1995; p. 111, Table 3), and the resulting value may have been underestimated.

Based on Eq. (5), the *EER* for Macao's tourism sector equaled 5, which means that Macao benefited from a high net emergy from visitors (1.69×10^{22} sej; calculated as T_m minus M_t using the values in Table 4). This value equals 2.7 times the overall net emergy of Macao. This result clearly indicates that tourism is the primary industry that supports Macao's urban ecosystem.

3.2.5. *%Renew, ESI, and NER*

The indicators and ratios developed by means of emergy analysis can account for both ecological and economic contributions, and permit international comparisons (Ulgiati and Brown, 1998). *%Renew* is the percent of the total energy driving a process that is derived from renewable sources (*R*/*U*). In the long run, only processes with high *%Renew* are sustainable (Brown and Ulgiati, 1997). *%Renew* can be used as a measure of the sustainability of a system: the higher the value, the higher the ability of the system to make use of the local available renewable resources (Odum, 1996). *%Renew* ranged from 0.1% (San Juan) to 3.5% (Miami-Dade County). Because these values are so small (Fig. 7d), comparing the cities based exclusively on *%Renew* would be ineffective because it would neglect the enormous emergy input that plays such an important role in these cities.

An aggregate measure of a system's sustainability is provided by ESI. If ESI > 1, it represents a net contribution to society. In contrast, a low ESI value (<1) indicates a net loss to society, which commonly occurs in highly developed consumer-oriented economies, and high ESI (>10) is indicative of economies that have been termed "undeveloped" (Ulgiati and Brown, 1998). The ESI values of all five cites were well below 1, ranging from 0.30×10^{-3} for Miami-Dade County to 6.5×10^{-3} for Zhongshan.

In a dense city such as Macao, ELR is usually very high because renewable resources inside the system are insufficient, which would produce a very small ESI (Table 4, Fig. 7c). Comparing cites based solely on ESI may reveal nothing of their true sustainability, because this indicator alone does not tell us which city is performing better and why. As others have noted, sustainability is determined by multiple social, economic, and ecological factors, and a single indicator does not tell us the relative contributions of these factors (Costanza and King, 1999). Therefore, a single ecological index can measure but not fully describe the degree of sustainable development of a system. A multi-vector indicator that reveals more roles of the system's components would thus be a more effective tool (Pearce and Barbier, 2000). Using ESI alone, the differences among the five cities are unclear because of their different societies, ecologies, and economies, although the emergy concept can embody the ecological and economic factors in a single parameter. Lacking a clear and uniform representation of emergy indices can make the reconciliation of different forms of data troublesome and intricate (Giannetti et al., 2006).

The genuine savings indicator (GS) is a monetary accounting aggregate designed to measure the net change in assets or wealth in a national balance sheet that includes natural and human capital. There is an intrinsic linkage between changes in wealth and the sustainability of a development path (Hamilton and Clemens, 1999). Development is sustainable if and only if the stock of capital (wealth) remains constant or rises over time. GS has been defined as follows (World Bank, 2001):

$$\mathrm{GS} = \text{Production} - \text{Consumption} - \text{Depreciation of all assets} - \text{Depletion of natural resources} \quad (6)$$

Thus, GS can be used to measure sustainability; a negative GS indicates an unsustainable situation. However, there are three shortcomings to the GS index:

1. GS is premised on perfect substitutability between different types of capital, including physical, natural, and human capital (Pillarisetti, 2005). However, there are obvious situations in which this is not true. If environmental limits have been exceeded, for example, then economic capital cannot substitute for the natural capital.
2. Economic methods have had only limited success placing a value on natural capital. So-called contingent valuation methods (CVM) are criticized by ecologists (Pillarisetti, 2005).
3. Like ESI, GS represents the combined effects of several factors, thus it is not possible to determine which of the factors is most responsible for a given value (e.g., excessive consumption or excessive depreciation of assets can both lead to a negative GS value).

In contrast, emergy takes into consideration all the resources used, both ecological and economic, and because emergy forms a common base for both types of resource, it can bridge the natural and artificial forms of capital (Lu et al., 2004), which simple monetary indicators cannot do. This suggests that aggregated net emergy should provide a better measure than GS of the sustainability of a system.

A balanced emergy indicator such as net emergy ratio (NER) is thus likely to provide a clearer picture of sustainability than ESI, and it can provide more reasonable results if we accept emergy as the common unit for measuring both the economy and the ecology. The NER values (Fig. 7d) for Macao (0.25) and Zhongshan (0.30) were moderate, and suggest that both cities have attained a suitable ratio of regional development, whereas those of Taipei (0.75) and San Juan (0.62) were too high for sustainability. But the biggest NER value was for Miami-Dade (0.99), and this value is so high that clearly too much weight has been placed on the foundation that underlies sustainability as a result of overexploitation of the surrounding regions that sustain the city.

3.3. *Detailed emergy synthesis of Macao's wastes*

In 1992, the Macao government adopted the incineration method to treat the city's solid wastes, and since 1997, sewage has been treated before being discharged into the sea. Considering that wastes are generated as byproducts of all activities, and are the outcomes of the foods, raw materials, and goods that we use, then these resources must inevitably waste emergy related to their generation and disposal (Björklund et al., 2001). Large investments of natural resources and technology are required for the treatment of wastes.

An emergy analysis should account for all the emergy flows in the system's material and energy transfer processes. Thus, emergy analysis must evaluate the emergy of wastes and of the labor, fuel and electricity, water, and machines required to handle wastes. Fig. 8 shows the transfer and treatment of

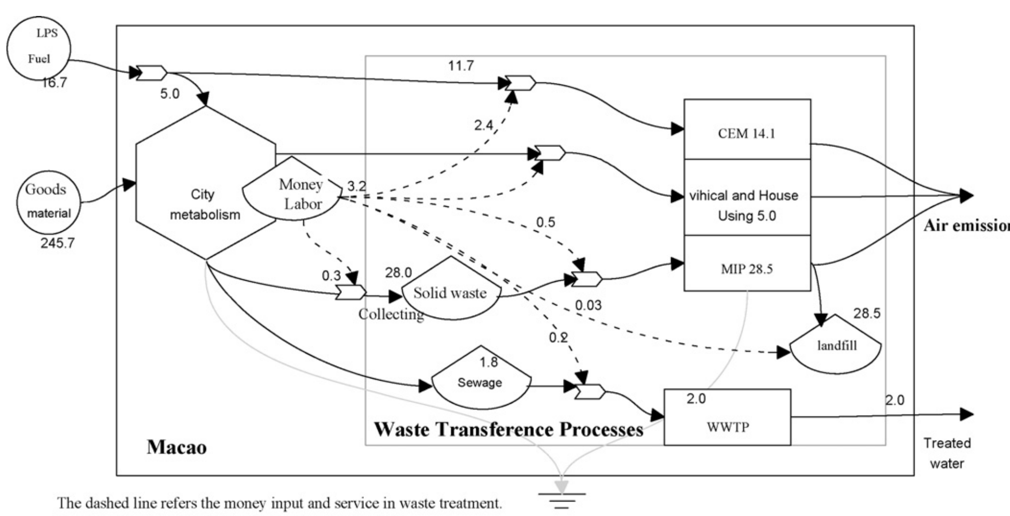

Fig. 8 – A concise diagram of the emergy components of waste in Macao in 2004 (values are ×10^20 sej). Dashed lines represent monetary values of inputs and services. Smaller rectangles at the right side of the diagram represent the waste treatment sites. CEM, the electric company of Macao; MIP, Macao Incinerator Plant; WWTP, Macao Wastewater Treatment Plant.

Table 5 – A summary of the components of waste emergy in Macao in 2004

Item	Expression	Units	Amount	Transformity (sej/g, sej/US$, or sej/J)	Emergy (sej)	Emergy investment (sej/g)
Solid waste	1 + 2 + 3 + 4 + 5	Mass (g)	2.56×10^{11}		2.85×10^{21}	1.11×10^{10}
1. Solid waste embodied		Energy (J)	1.56×10^{15}	1.80×10^{6}	2.80×10^{21}	1.09×10^{10}
2. Collection labor and equipment		Money (US$)	1.28×10^{7}	2.39×10^{12}	3.05×10^{19}	1.19×10^{8}
3. Incinerating service		Money (US$)	3.89×10^{6}	2.39×10^{12}	9.27×10^{18}	3.62×10^{7}
4. Depreciation of incinerating equipment		Money (US$)	4.57×10^{6}	2.39×10^{12}	1.09×10^{19}	4.25×10^{7}
5. Landfill service		Money (US$)	1.07×10^{6}	2.39×10^{12}	2.56×10^{18}	9.99×10^{6}
Sewage	6 + 7 + 8 + 9	Mass (g)	5.51×10^{13}		2.03×10^{20}	3.67×10^{6}
6. Sewage embodied		Energy (J)	2.71×10^{14}	6.66×10^{5}	1.80×10^{20}	3.27×10^{6}
7. Drainage service		Money (US$)	1.29×10^{6}	2.39×10^{12}	3.07×10^{18}	5.56×10^{4}
8. WWTP[a] sewage treatment service		Money (US$)	3.76×10^{6}	2.39×10^{12}	8.97×10^{18}	1.63×10^{5}
9. WWTP setup and depreciation		Money (US$)	4.32×10^{6}	2.39×10^{12}	1.03×10^{19}	1.87×10^{5}
Waste (W)	1 + 2 + 3 + 4 + 5 + 6 + 7 + 8 + 9				3.06×10^{21}	
Treatment (F')	2 + 3 + 4 + 5 + 7 + 8 + 9				7.56×10^{19}	

[a] WWTP = wastewater treatment plant.

Macao's wastes. We could not easily obtain detailed material and energy consumption data for Macao because the companies involved in waste management are reluctant to provide the necessary data, which they consider a commercial secret. However, they did provide money flow data for the processes of interest, and we were able to use this information as a proxy. Since these companies obtain their contracts through an open bidding process, the prices they receive for their services should be a reasonable reflection of the true costs. In addition, the monetary value of suitable treatment technologies should include emergy of the information content, including information used in the technological evolution of these processes, and this should be accounted for in the emergy analysis. Therefore, we used the money values to reflect the emergy used in the collection, treatment, and disposal processes for wastes. Table 5 presents the components of waste emergy in Macao in 2004, and these results are summarized visually in Fig. 8.

We found that the ratio of service and labor emergy to emergy of waste was only 0.025 (F'/W) in the treatment processes, but these processes were nonetheless valuable because they protect the welfare and health of the citizens. The ratio of W to U was 0.124, which is near the relative ratio (0.121) obtained with the conventional method ($(W - F')/U$, not accounting for the treatment services and the equipment input). Huang and Chen (2005) note that the waste emergy can be thought of as the entropy of the system within the overall metabolism of the city, and that this entropy will increase as a city develops. Waste treatment helps to sustain a steady-state condition for the city (i.e., it serves as a dissipative structure that prevents the accumulation of wastes).

4. Conclusions

The NER values for all cities (0.25 for Macao, 0.30 for Zhongshan, 0.62 for San Juan, 0.75 for Taipei, and 0.99 for Miami-Dade) were all too high for sustainability.

Unless steps are taken to assess the sustainability of urban development, this process is likely to continue to displace and relocate Earth's natural resources, leading to undesirable changes in human and ecological welfare. As the results in this study have shown, emergy analysis offers a powerful tool for linking the economy with the environment. Previous studies that have used the ESI indicator provide approximate assessments of sustainability that are insufficiently powerful as an analytical tool because they cannot explain differences among cities.

Real wealth includes both tangible things (e.g., food, minerals, fertile land, houses) and intangibles (e.g., information, art, quality of life), and thus cannot be measured solely in monetary terms (Odum, 1996; Ulgiati, 2004). However, because emergy can be used as an indicator of sustainability, and sustainability tends to improve the factors that comprise real wealth, emergy can provide a useful alternative to purely monetary measures of wealth. Brown and Ulgiati (2001) suggested that for a country's development to be sustainable, it must contribute to a net emergy benefit. Measured in emergy terms, a net emergy benefit means that the development causes more emergy to flow into the economy than flows out of the economy. However, because all systems exist within the finite resource of Earth's ecosystem, it's important to note that even though a high net emergy may be advantageous for a given system or country, an overly high net emergy may damage life-support regions elsewhere (i.e., the emergy surplus must come from somewhere), potentially creating feedback mechanisms that subsequently reduce the system's net emergy. Because an urban system constantly exchanges material and monetary emergy with external systems, the holistic emergy analysis described in this paper accounts for these exchanges, making net emergy (NER) a better indicator than ESI. It can provide a more accurate and clearer picture of a city's sustainability because it monitors the sustainability of the urban system more realistically, and reflects the system balance more comprehensively. Although a higher value of the NER was advantageous in terms of a city's sustainability, it also depicts the emergy balance between the city and its supporting areas. A low and a positive value of NER (<0.15) is better than a higher value for this reason. Based on our estimates, Macao's NER (0.25) indicates that its emergy saving ratio exceeds its limits within Macao's boundaries.

The benchmark for a sustainable society has been variously defined based on "strong" and "weak" criteria (Gutés, 1996). Although both aim at securing the best possible future well-being for people, strong sustainability assumes that natural capital is irreplaceable and aims to preserve natural capital, independent of the development of human-made forms of capital. In contrast, weak sustainability assumes that human well-being is better served if the value of all combined assets is preserved, rather than giving special attention to maintaining any one asset (such as natural capital), since technology is believed to be capable of replacing lost ecological services. In this sense, Macao's sustainability is clearly weak because the city's resource use is unsustainable (i.e., there are essentially no natural resources within the urban system) but the sustainable economy substitutes for the lack of natural resources by importing these resources from outside the system (Pearce and Barbier, 2000).

Our study demonstrated that the general principles of emergy analysis, originally designed for natural ecosystems, can also provide important insights into emergy flows in anthropogenic systems such as cities that contain relatively few natural resources, and that must instead import those resources from external systems. Since the ecosystem of a rapidly developing city is an immature ecosystem, it has not yet achieved homeostasis, thus its wastes have not yet achieved a steady state, and their emergy must also be analyzed. In particular, urban systems generate considerable amounts of solid and liquid waste that must be treated to prevent environmental degradation. This consequence results from the concentration of resources that are collected from a much larger area external to the city within the much smaller area of the urban system. Our analysis indicates that a limited feed-back emergy can treat more embodied emergy of waste. In Table 5, the value of F'/W was only 0.025, and decreasing this ratio will further increase the damage to the urban environment.

Implicit in the concept of sustainability is the concept of scale. On a global scale, our world is a closed system with a finite carrying capacity and a finite amount of natural capital. At that scale, it is clear that emergy flows must be in balance because there is no external system from which we can import resources and services. However, at a smaller scale such as that of a city, the larger external systems surrounding the city can supply resources and services that are lacking within the city, and in that context, sustainability is based on the net emergy increase. Nonetheless, if a city develops without any regard to its net emergy, it may import external resources and services at an unsustainable rate that leads to unsustainable development of other regions. Sustainability can clearly be measured at the global, regional, or urban level, or even at the scale of individual economic activities (Brown and Ulgiati, 1999). When we use emergy analysis to assess a city, the impact of that city on the external systems that sustain the city cannot be neglected, as including the city's impacts on these external systems provides a clearer and more comprehensive picture of the wider system's sustainability. The issue of how to scale emergy analysis from a smaller system such as a city to account for the effects of the system's emergy balance on other regions remains a problem for future research.

Acknowledgments

This research was supported by the University of Macau. We thank Professor Shu-li Huang of the Graduate Institute of Urban Planning, National Taipei University, and Professor F.P. Chen of South China Agricultural University, for their constructive suggestions on an earlier version of this manuscript. Opinion of the Author, Dr. Lei Kampeng does not reflect the views of the Macao Science Center Ltd.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.ecoleng.2007.08.008.

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