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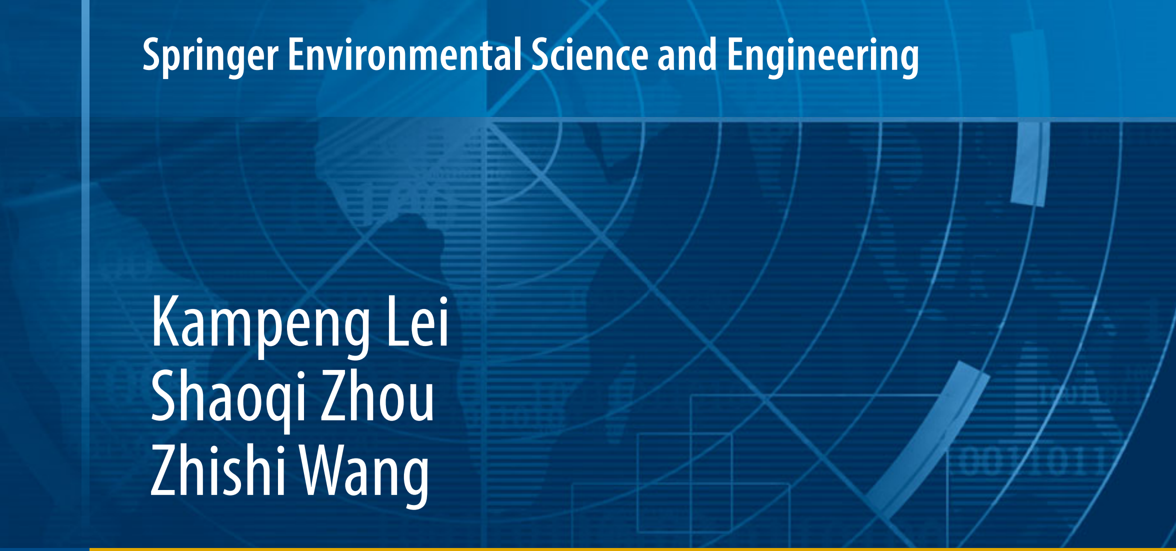

Kampeng Lei
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Ecological Emergy Accounting for a Limited System: General Principles and a Case Study of Macao

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Preface

In December 2000, the conference “New Challenge of Eco-city Development in 21st Century” was held in Macao by the Ecological Society of China. At this conference, one of us (Lei) first encountered the theory of ecological economics. Since then, Lei has become increasingly concerned about the sustainability of his home city, Macao. Macao is a city with a dense population that depends heavily on exogenous natural resources, but benefits greatly from the gambling and tourism income that flows into the city. Residents benefit greatly from the high net influx of materials and energy into Macao, and as a result of these inflows, the standard of living of the citizens has steadily increased during the past 30 years.

However, there are concerns over whether the city’s rapid development is sustainable. Sustainable development combines concerns about the carrying capacity of the natural systems that sustain human systems with concerns about the social challenges faced by humanity, and particularly the need for socioeconomic development. For development to be sustainable, it must meet the needs both of humans and of the natural environment. To study Macao’s sustainability, it was necessary to choose an approach and a system of metrics that could relate the natural environment’s flows to those of the socioeconomic system. Based on a careful review of the literature, Lei chose emergy synthesis. Emergy synthesis measures the flows of materials, energy, commodities, money, and services, and can easily quantify these values within a common analytical framework that integrates all the flows and allows direct comparisons among them. The clear advantage of emergy synthesis is that it combines the most insightful features of the ecological and economic methods of analysis, thereby providing a complete picture of the human and environmental meaning of the flows.

In this book, we have used the emergy synthesis approach to develop an accounting model that is suitable for describing systems with relatively clear boundaries, such as an urban system, thereby providing a comprehensive picture of the system. Our book has eight chapters, and is organized as follows:

Chapter 1 gives a general introduction to the basic theoretical background for emergy accounting and related fields, and defines many of the key parameters and indicators used in emergy studies.

Chapter 2 first presents a detailed emergy accounting for Macao in 2004, followed by a time series of the emergy flows in Macao's system from 1983 to 2004 and a comparison with Italy and Sweden to put these values in perspective. Finally, we present a statistical analysis of Macao's emergy-based indicators.

Chapter 3 presents the results of simulating Macao's system using the STELLA dynamic modeling software to investigate and characterize the evolution and development of Macao's natural and socioeconomic systems from 1983 to 2003. Based on the simulation results, we also predict the evolution of these systems in the coming 20 years and its relationship with the ongoing land reclamation from the sea that is occurring in Macao.

Chapter 4 focuses on an emergy accounting for the city's tourism industry. First, we introduce the historical evolution and economic contributions of the tourism industry, followed by a detailed emergy calculation and assessment of its contributions and impacts from 1983 to 2004. Finally, we determine the net emergy for Macao's tourism industry and draw conclusions about this sector's impacts.

In Chap. 5, we analyze the emergy flows in the gambling sector. Gambling and related tourism activities represent a special form of economic and societal activity, and have been crucial to Macao's success.

Chapter 6 describes a detailed emergy accounting of waste treatment in Macao, including some pioneering efforts to include previously neglected flows such as gaseous emissions. We describe the related feedback ratios for solid wastes, sewage, and gaseous emissions and use the results to determine the efficiency of Macao's waste treatment and calculate the transformities of these wastes using Macao's waste discharge data.

Chapter 7 shows how a comparison of the carrying capacity of a city's or a region's natural resources with the consumption of these resources at regional or global scales can reveal the system's sustainability. To illustrate how this comparison works in practice, we performed a case study of 17 representative countries, using data obtained from the National Environmental Accounting Database, and the results confirmed that to ensure long-term sustainability, it will be necessary to control population increases, reduce emergy consumption, and promote emergy efficiency.

Chapter 8 provides a final summary of the previous chapters, and identifies problems that will require additional research, as well as some shortcomings of the ecological energy accounting approach. It concludes with a research outlook for future researchers.

This book is intended for readers who want to learn more about how hybrid natural and socioeconomic systems function. This includes researchers and graduate students working in the fields of systems ecology, energy accounting, environmental management, and related areas. Readers will obtain a comprehensive understanding of the methodology of emergy synthesis, and of the dilemmas that government planners face as a result of the need to sustain socioeconomic development while protecting the environment, which will ultimately lead to sustainable socioeconomic development. We hope that by making this book available to students and researchers, we will promote the development of emergy analysis skills and increase knowledge of the importance of ecological energy accounting. We also hope that readers will be motivated to find ways to improve on the methods we describe in this book.

We gratefully acknowledge the assistance of Professor S. L. Huang of "National" Taipei University, Dr. H. F. Lu of the South China Botanical Garden of the Chinese Academy of Sciences, and Professor S. Ulgiati of Parthenope University of Napoli, Italy, for their constructive criticism of and comments on early versions of our manuscripts. We are also grateful for the efforts of the anonymous journal reviewers who rigorously critiqued the journal manuscripts that form the basis for the chapters of this book. We also gratefully acknowledge the assistance of Dr. S. Sweeney of the University of Florida, Gainesville, for providing the basic National Environmental Accounting Database data used in our technical analysis in Chap. 7, and for answering our questions about some categories in the calculations.

We thank the University of Macau, the South China University of Technology and the Guizhou Academy of Sciences for providing us with access to their rich research resources and with helpful support in many areas during our research and during the writing of this book. During the past 10 years we have received much professional and personal support and encouragement from people who are too numerous to list here. We thank all of them.

We are grateful for the financial support for our research from the Science and Technology Development Fund of Macau (grant 022/2007/A2), Macao Special Administrative Region, China; from the State Key Laboratory of Subtropical Building Sciences, South China University of Technology (grant 2012ZB06, 2013ZC03); the National Natural Science Foundation (21277052); and from the University of Macau. We also thank the Macao Foundation for sponsoring our publication.

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Contents

Chapter 1
Emergy Synthesis and Ecological Energy Accounting

To understand how emergy accounting can be used to study systems composed of both natural and human components, it is helpful to understand the evolution of the thought processes that led to this approach. In the first part of this chapter, we have summarized this evolution based on general overviews of systems theory (Wikipedia 2012a) and emergy (Wikipedia 2012b), supplemented by a consideration of the key papers that guided the development of this field of research. In the remainder of the chapter, we will develop the key equations and indicators used in this analytical approach and introduce how they can be used in a consideration of a hybrid natural/human system such as Macao's tourism economy.

Note: Because of the large number of parameters defined in this book, we have provided a summary of all parameters and their definitions in Appendix C.

1.1 The Evolution from Systems Theory to Emergy

During the last half of the 20th century, a dramatic change in our world view occurred: researchers in a range of fields began to recognize that many systems could not be understood by examining their component parts in isolation. Von Bertalanffy (1972) codified this recognition by defining a system as a set of interrelated elements that interact with each other and with the environment external to the system. The most important innovation of systems thinking is the shift from a focus on breaking a system into its component parts (an approach known as *reductionism*) to a focus on the system as a whole. This approach evolved from a growing understanding that living systems are integrated wholes, with properties that cannot be understood solely by examining the component parts. Howard Odum (1994a) noted that a system can no longer function as a system when its elements are taken apart and isolated.

Systems theory evolved as an attempt to unify the approaches of sciences that had formerly worked in isolation, thereby combining their strengths and unique insights to provide a more holistic view of a system. Systems theory focuses on complexity, interdependence, and wholeness (H. T. Odum 1994b). Although the science of

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ecology had always emphasized the *system* part of the word *ecosystem*, the new emphasis on system-based thinking reminded researchers who had adopted an increasingly narrow focus on individual components or processes to take a step back and examine how all these parts fit together. Odum was a leader in the development of the new approach to systems ecology. He defined systems ecology (H. T. Odum 1994a) as the study of a whole ecosystem by both measuring its overall behavior and studying the details of how that behavior emerges from interactions among the system's components. Odum also broadened the concept of an ecosystem to include all systems, including human systems; this is a key principle underlying the present book because it recognizes that no human system exists independently of the natural world, and that since the industrial revolution, the natural world has increasingly been affected by human systems. Systems ecology attempts to quantify the flows of energy, materials, and information within a system and between the system and its external environment. Odum envisioned systems ecology as a unifying theory that would be capable of consolidating our understanding of a wide range of quantitatively and qualitatively different systems. J. Björklund (2000) summarized the five key principles of systems ecology that Odum discussed in papers published between 1987 and 1996:

- The maximum empower principle: Systems self-organize to maximize their intake of energy and the efficiency of their use of this energy (H. T. Odum 1995). The maximum empower principle is a potential guide to understanding the patterns and processes of ecosystem development and sustainability. The principle predicts the selective persistence of ecosystem designs that can capture a previously untapped energy source (Cai et al. 2006).
- Self-organization principle: Self-organization is a process where some form of global order or coordination arises out of the local interactions between the components of an initially disordered system. A self-organizing system is typically very robust and able to survive and self-repair even substantial damage and to recover from even moderately severe perturbations. Self-organization generally requires feedbacks in which part of its high-quality energy is recycled and returned to upstream processes. Self-organization occurs in a variety of physical, chemical, biological, social, and cognitive systems.
- Energy transformation hierarchy: Different forms of energy have different levels of "quality"; here, *quality* refers to how efficiently energy can be used (i.e., the output of energy divided by the input) and to its suitability for a specific use.
- A theory of *pulsing*: Odum proposed that all systems pulse, on all scales. That is, the gradual accumulation of energy by a storage component of the system is followed by a short period of consumption of this energy and either modification of existing components or development of new components, leading to dispersion of materials and setting up of the next growth period.
- Phenomena occur at different spatial, temporal, and ecological scales: Although the overall processes that govern how a system functions will be similar at all scales, the details will vary among scales.

Howard Odum (1994a, 1995) referred to these points as "design" principles because they appear to be general properties of all systems, irrespective of their scale.

They are important because the existence of similar patterns at all scales provides a unified basis for modeling any ecological system.

All forms of systems theory emphasize a *holistic* world view. This means that the properties of a system cannot be determined or explained solely as the sum of its components. In contrast, advocates of *reductionism* believe that complex phenomena such as ecological systems can be reduced into their component parts and understood by examining the details of these components. In practice, both approaches are necessary: reductionism provides an understanding of the details of specific flows, allowing researchers to accurately quantify those flows, whereas the holistic approach lets researchers combine those quantities to provide an overall picture of the system.

Ecosystems provide *services* that are essential for human survival. Some of these services are natural (e.g., clean air) whereas others are artificial (e.g., mining to obtain raw materials), and some are highly concrete (e.g., clean water) whereas others are more abstract (e.g., scenic beauty). The *ecological footprint* concept attempts to quantify how human requirements for these services affect the system that provides them (Rees and Wackernagel 1996; Wackernagel and Rees 1996; Wackernagel and Yount 1998; Brown et al. 2000b).

Furthermore, Odum's model builds on *ecological energetics* (the balance between production and consumption) by explicitly measuring the integrated ecological and economic welfare of a system. This concept of ecological energetics was originally proposed by Phillipson (1966). Ecological energetics quantifies the flows of energy through ecological systems, with the goal of revealing the principles that describe the intensity of such energy flows through the trophic levels of an ecosystem. This approach is sometimes referred to as *production ecology*, because ecologists use the word *production* to describe the process of energy input and storage in *ecosystems*.

Ecological energetics provides information on the *interdependence* of organisms within ecological systems and on the efficiency of energy transfers within and between organisms and trophic levels. In a natural ecosystem, nearly all of the energy enters the system when plants (autotrophs) capture the sun's light energy and transform it into chemical energy through photosynthesis (*primary production*). This energy is used by plants to power their metabolism, and by animals that consume the plants to sustain their life, growth, and reproduction. This metabolic use of the energy captured by plants is termed *secondary production*. As energy passes through the trophic levels in the food chain (from plants to herbivores, from herbivores to carnivores, and finally, from both herbivores and carnivores to decomposers), the energy performs work and in the process is degraded into heat. In a closed system, the laws of thermodynamics state that the total light energy captured by plants will equal the sum of the energy used by the plants for their growth and metabolism, the energy transferred to other organisms, and losses of energy as heat. In practice, ecosystems are not truly closed (i.e., they always exchange energy or materials with their external environment), so energy is gained or lost when matter is (respectively) transferred into and out of the system. A system's energy budget quantifies all the pools of stored energy, and the directions and magnitudes of the energy flows between pools.

Ecology and economics are both disciplines that address complex systems, but have traditionally worked in isolation from each other. Although traditional economics focuses on the efficient allocation of resources, and should therefore include natural resources and ecosystem services, it has mostly ignored these aspects of economic problems. The result has often been actions and ecological policies that neglect either the natural or the human part of a hybrid human/natural system, often with disastrous consequences. The discipline of *ecological economics* attempts to adapt traditional economics so that it accounts for the interdependence and coevolution between human economies and natural ecosystems. The objective is to integrate the natural environment with economic thinking so that both the human and the natural components of the system are adequately accounted for. This combines the goal of improved human well-being through socioeconomic development with the goal of sustainable use of the services provided by ecosystems. This philosophy explicitly unites the human components of a system with the natural components that sustain them, and explicitly accounts for the effects of each component on the other components.

The theoretical and conceptual basis for the emergy methodology is grounded in a consideration of thermodynamics within the context of systems ecology (H. T. Odum 1983). Odum's early investigations of the energy flows in ecosystems and of the differences in the ability of sunlight, water currents, wind, and fossil fuels to do work made it clear that different forms of energy have different quality levels. This was first formally addressed in Odum's book *Environment, Power and Society* (H. T. Odum 1971). The lack of direct comparability between energy with different qualities makes it impossible to combine the flows of energy by means of simple addition. Odum therefore developed the concept of a need for a common denominator for energy, which he originally named the *energy cost*.

Energy can be expressed in many units (e.g., kcal, Btu, $kW \cdot h$) ($1\ Btu = 1.05506 \times 10^3\ J$), but these units cannot communicate the *quality* of the energy. The ability of energy to do work depends on its quality, not just on its quantity, and a large amount of energy of a lower quality is required to create energy of a higher quality. In a sense, quality reflects how concentrated energy is and how easy it is to use; thus, it is analogous to energy density. The energy with the lowest quality is sunlight, and the quality increases as the solar energy is transformed into plant matter, coal, and oil, with electricity and information representing the highest qualities of energy.

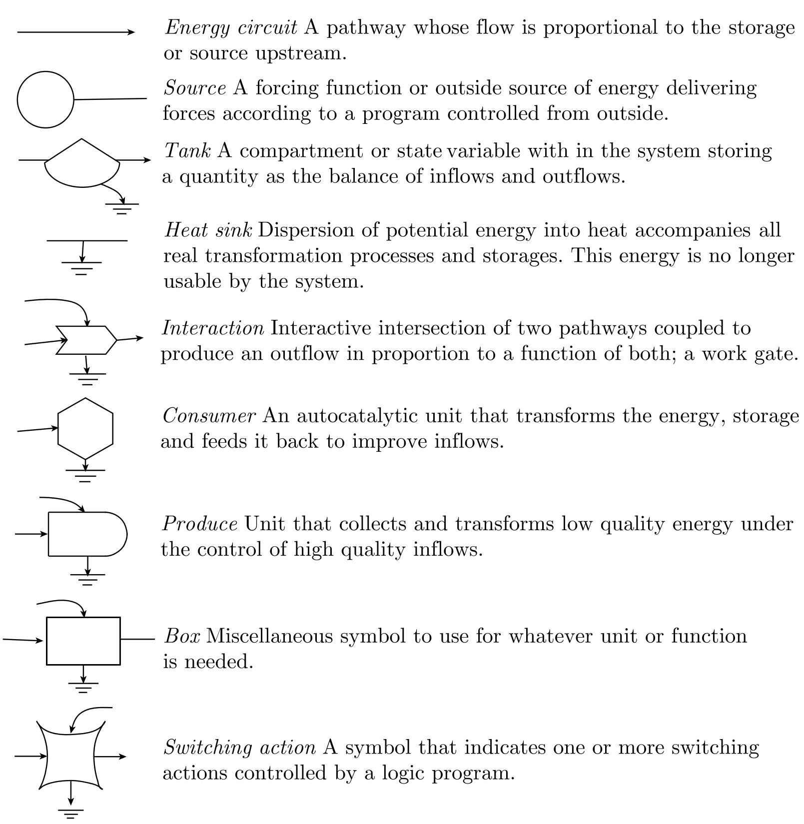
The first quantitative evaluation of energy quality appears to have been in Odum's 1975 speech when he accepted a prize from the Institut de la Vie, Paris, in which he presented a table of "energy quality factors". These represented the amount of solar energy (in kcal) required to create 1 kcal of energy with a higher quality (H. T. Odum 1976). This introduced the concept of an energy hierarchy, in which energy quality changes during the transformations from one type of energy to the next. Initially, the equivalence among types of energy with different qualities was expressed in *fossil fuel work equivalents*, with a rough equivalence between 1 kcal of fossil fuel and 2000 kcal of sunlight. *Energy quality ratios* were calculated by computing the quantity of energy consumed during the transformation of one type of energy into another type. These ratios could therefore be used to convert different forms of energy into a common set of units that allowed direct comparisons and direct addition of flows of different types of energy. The concept of fossil fuel work equivalents was replaced with *standard coal equivalents* in recognition of the fact that not all fossil fuels have equally high quality, then the quality evaluation system was converted into a solar energy basis, with the energy units termed *solar equivalents* (H. T. Odum 1977), in recognition of the crucial role of the sun in providing the energy for all natural systems.

The term *embodied energy* was used for the first time in the early 1980s to refer to energy quality differences (e.g., E. C. Odum and Odum 1980). However, since this term was being used by other researchers who were evaluating the fossil fuel energy required to generate various products, and these researchers neither included all forms of energy nor used the concept to account for differences in energy quality, ecological researchers developed the term *embodied solar calories* and defined the conversion factors between types of energy as *transformation ratios*. “Embodied energy” was abandoned altogether in 1986, when David Scienceman proposed the term *emergy* and the use of *emjoules* as the units of measurement to distinguish emergy units from the units of available energy (Scienceman 1987). The term *transformation ratio* was shortened to *transformity* around that time. It is important to note the shift that occurred throughout this period from fossil fuels to solar energy.

Since this early research, the theoretical and practical bases for emergy accounting have slowly matured, accompanied by standardization of the terminology and calculation methods. In the rest of this chapter, we will describe that terminology and the methodology.

1.2 Energy System Diagrams

The energy systems diagrams developed by Odum can be used to clarify the flows of energy among the components of a system (Fig. 1.1). Figure 1.2 illustrates the pathways (flows) and conservation of energy within a typical system. The key aspects of any system include flows of energy into and out of the system, transformation of energy and its storage in various pools within the system, consumption of energy by a process to do work, and flows of energy between storage pools. The laws of thermodynamics also suggest that there will inevitably be a loss of energy during storage, transformation, and flows between pools. In Odum’s diagrams, energy of low quality enters the system on the left side, and as the energy flows towards the right side of the diagram, its quality increases through feedback loops within the system. These *autocatalytic loops* are a prevalent design because they reinforce power intake and efficient use, following the maximum empower principle (Brown 2003).



Energy circuit A pathway whose flow is proportional to the storage or source upstream.

Source A forcing function or outside source of energy delivering forces according to a program controlled from outside.

Tank A compartment or state variable with in the system storing a quantity as the balance of inflows and outflows.

Heat sink Dispersion of potential energy into heat accompanies all real transformation processes and storages. This energy is no longer usable by the system.

Interaction Interactive intersection of two pathways coupled to produce an outflow in proportion to a function of both; a work gate.

Consumer An autocatalytic unit that transforms the energy, storage and feeds it back to improve inflows.

Produce Unit that collects and transforms low quality energy under the control of high quality inflows.

Box Miscellaneous symbol to use for whatever unit or function is needed.

Switching action A symbol that indicates one or more switching actions controlled by a logic program.

Fig. 1.1 Primary symbols used in the energy systems diagrams developed by Odum

1.3 Emergy Values and Their Transformation

Emergy is the amount of energy required to produce something, and accounts for the conservation and loss of energy that result from the laws of thermodynamics (Scienceman 1987). The more work that is done to produce something, the more energy must be transformed to perform that work, and the higher the emergy value stored in the product. Emergy therefore measures the environmental work, in both the past and the present, that is necessary to produce a given resource or provide a given service. It is therefore a global measure of the sum of the energy flows in the processes required to produce something, expressed in consistent units of solar emergy (Fig. 1.3).

This method is grounded in thermodynamics and general systems theory (Bakshi 2002). Since all driving processes that support the biosphere (the sun, Earth's deep heat, tidal energy, and the energy of wind and rain) are incorporated in this framework, emergy evaluation accounts for all of the processes and resources required to support a system (Herendeen 2004).

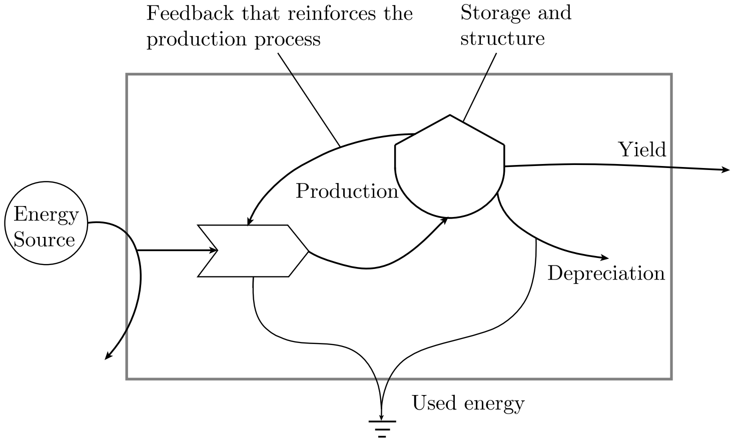


Fig. 1.2 Energy input, transformation, storage, and feedbacks within a system (Odum 1998)

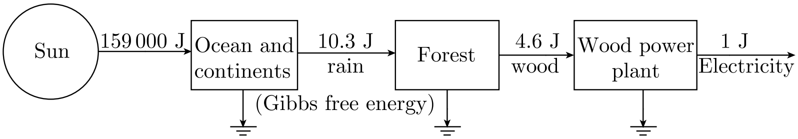


Fig. 1.3 An example of the chain of energy transformations required to generate a product (here, electricity) (Huang and Odum 1991): Transformation of rain = 159 000 solar emjoules/10.3 joules = 1.54×10^4 sej J^{-1}; Transformation of wood = 159 000 solar emjoules/4.6 joules = 3.46×10^4 sej J^{-1}; Transformation of electricity = 159 000 solar emjoules/1 joule = 15.90×10^4 sej J^{-1}

Transformity is the emergy of one type required to create a unit of energy of another type. An important concept in emergy analysis is the *solar transformity*, which represents the solar emergy (in solar emjoules, sej) required to provide 1 J of a service or product (H. T. Odum 1996; Brown and Ulgiati 2004a). Solar transformity is therefore measured in sej J^{-1}. For example, 159 000 joules of solar energy can be transformed into a quantity of wood through photosynthesis, though with some loss of energy during the transformation processes. If that wood can release 1 joule of energy by combustion, the transformity of the wood will be 159 000 sej J^{-1}.

The solar transformity of a product equals its solar emergy divided by its available energy (Hau and Bakshi 2004):

$$\text{Solar transformity} = \text{Solar emergy input/energy output} = E_\mathrm{m}/E_\mathrm{n} \qquad (1.1)$$

Since solar energy is the baseline for all emergy calculations, the transformity of solar energy = 1. Figure 1.3 provides an example of the chain of energy transformations and the corresponding solar transformities for the products that result from each progressive transformation. The transformity value of a given product indicates the position of that product in the energy hierarchy. The higher the energy quality, the higher its transformity and the higher its position in the hierarchy (Huang and Odum 1991).

This form of analysis makes it possible to evaluate the main inputs from the human economy as well as those inputs provided by the environment that are usually considered to be "free"; these include mineral resources that result from biological or geological processes, biological resources such as wood, and economic products such as machines produced by industrial processes (Brown et al. 2000a). In the case of raw agricultural products, relying solely on the market price may underestimate the real contribution of these products to an economy's welfare because the market price does not represent the environmental work required to create these products.

Howard Odum and his colleagues at the University of Florida developed the methodology of *emergy synthesis* as a tool for understanding systems (Brown and Ulgiati 2004b). Emergy synthesis evaluates resources and services in both ecological and economic systems on a common energy basis (solar emergy) by quantifying the direct and indirect environmental work required to generate a resource or a service and the energy required to perform that work (H. T. Odum 1996). The advantage of this approach is that it includes both socioeconomic and ecological factors, and thereby provides a more comprehensive understanding than approaches based on only one of these two groups of factors. A more comprehensive description of the concept, principles, and applications of the methodology can be found in H. T. Odum (1994b, 1996) and Brown and Herendeen (1996).

Emergy synthesis has been applied to studies with a variety of temporal and spatial scales, including the evaluation of ecosystems (H. T. Odum and Arding 1991; Ulgiati and Brown 1998; Brandt-Williams 1999; Brown and Bardi 2001; Brown and Ulgiati 2004c; Lu et al. 2006; Brown and Cohen 2008; Ulgiati and Brown 2009), an economy (H. T. Odum 1996; Cialani et al. 2005; Ferreyra and Brown 2007; Lomas et al. 2008; Jiang et al. 2008; Lei and Wang 2008a; Z. F. Yang et al. 2010), history (Sundberg et al. 1994), environmental policies and management (Brown and McClanahan 1996; Campbell 2004), trade (Brown 2003; Cuadra and Rydberg 2006), energy policies (Brown and Ulgiati 2002; Rydberg and Jansén 2002; Giannetti et al. 2006, 2010; Lu et al. 2007), agriculture and agricultural products (H. T. Odum and Arding 1991; Ulgiati et al. 1993; Johansson et al. 2000; Brandt-Williams 2001; Lefroy and Rydberg 2003; Cohen et al. 2006; Cavalett et al. 2006; Lu and Campbell 2009), industrial processes (Ulgiati and Brown 2002; Brown and Ulgiati 2002; Brown and Buranakarn 2003; Peng et al. 2008; Almeida et al. 2010; Ren et al. 2010), waste treatment (H. Björklund et al. 2001; Brown and Buranakarn 2003; Bastianoni et al. 2005), decision-support models (H. T. Odum and Odum 2001; Huang and Odum 1996; Huang and Chen 2005; Laganis and Debeljak 2006; Brown et al. 2009; Ingwersen 2010; Lei and Wang 2008b), thermodynamics (H. T. Odum 1995; Giannantoni 2002, 2003; Cai et al. 2004, 2006), and the evolution and metabolism of cities (Huang and Hsu 2003; Huang et al. 2006; L. X. Zhang et al. 2009; Ascione et al. 2009).

Howard Odum (1994a) considered sustainability to represent the process of adapting to variations in the availability of natural capital so as to maintain a stable (equilibrium) or improving state, and recognized that pulsing and oscillating states were common natural patterns. Odum's definition of sustainability is more comprehensive than many other definitions because it considers the dynamics of the whole ecosystem and because its definition of an ecosystem is much wider: it also includes human systems such as farms, industrial facilities, and cities. Because emergy analysis accounts for all of these aspects of sustainability and ecosystems, the approach can be employed to address ecological sustainability and carrying capacity in a wide range of systems (H. T. Odum 1988, 1996; Ulgiati et al. 1994, 1995; Brown and Ulgiati 1997, 1999, 2002; Ulgiati and Brown 1998).

1.4 The Ecological Energy Calculation Method

1.4.1 Definitions of Exergy, Emergy, and Transformity

To understand the concept of emergy, it is first necessary to understand *exergy*, which represents the real proportion of the energy that is available to perform mechanical work:

$$E_\mathrm{x} = (\text{Gibbs free energy}) + (\text{gravitational energy}) + (\text{kinetic energy}) \qquad (1.2)$$

where E_x represents exergy, the Gibbs free energy is the available thermodynamic or chemical energy, and kinetic energy represents the energy contained by a moving substance or object. Forms of energy such as radiation and thermal energy cannot be converted completely into work, and therefore have an exergy content less than their energy content.

The *exergy power* is the rate of change of exergy with time; P_x is the equivalent of power for exergy:

$$P_\mathrm{x} = \mathrm{d}E_\mathrm{x}/\mathrm{d}t \qquad (1.3)$$

Emergy (E_m) is defined as the integral of the exergy power over time, which represents the total change in exergy until t_0, the time when emergy is evaluated. This is a slight simplification of the formula in Giannantoni (2002):

$$E_\mathrm{m} = \int_{t=-\infty}^{t_0} P_\mathrm{x}\mathrm{d}t \qquad (1.4)$$

Brown and Ulgiati (2001) defined the solar emergy (E_m) of the flow from a given process as the solar energy that is directly or indirectly required to drive the process. The unit of solar emergy is the solar emjoule (sej):

$$E_\mathrm{m} = \sum E_i T_{ri} \qquad (1.5)$$

where E_i is the available energy (free energy) content of the ith independent input flow into the process, and T_{ri} is the solar transformity of the ith input flow. The solar transformity of direct solar radiation ($T_{r\mathrm{s}}$) is set to 1.

However, the term *energy output* refers to both the *useful* energy output and the *non-useful* energy output. Dincer and Cengel (2001) noted that an alternative name

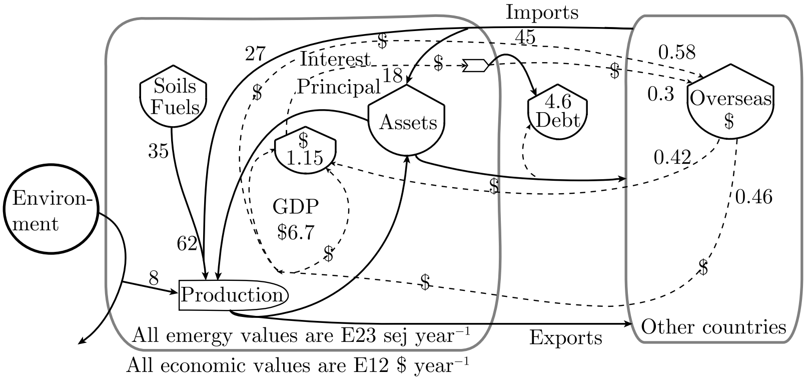


Fig. 1.4 An example of flows of the monetary components of emergy, based on the macroeconomy of the United States in 1994 (H. T. Odum 1998): Emergy/money ratio = $[(45 + 35 + 8) \times 10^{23}\ \text{sej year}^{-1}]/(6.7 \times 10^{12}\ \$\ \text{year}^{-1}) = 1.33 \times 10^{12}\ \text{sej}\ \$^{-1}$

for useful energy is the *available energy* (i.e., the exergy), since exergy is the energy that is available to be used. After the system and surroundings reach equilibrium, the exergy is zero. However, Sciubba and Ulgiati (2005) noted that transformity captures the emergy invested per unit of product (i.e., per unit of useful output). Transformity (T_r) can therefore be further specified as the ratio of input emergy that is dissipated (available energy that is used up) to the output exergy:

$$T_r = E_{\mathrm{m}}/E_{\mathrm{x}} \tag{1.6}$$

Substituting Eq. 1.4 into Eq. 1.6 provides the following equation (Giannantoni 2002):

$$T_r = \frac{\int_{t=-\infty}^{t_0} P_{\mathrm{x}}\mathrm{d}t}{E_{\mathrm{x}}} \tag{1.7}$$

1.4.2 General Emergy Calculation Method

When the transformity is known, as is the case for conventional energy values, the total emergy of an item can be calculated using Eq. 1.5. *Specific emergy* is defined as the emergy per unit of mass in the output (sej g^{-1}). This captures the degree of concentration of the emergy. Flows and storage of matter carry available energy and emergy along with the mass. In practice, it is convenient to develop an equation for specific emergy for use in emergy calculations:

$$E_{\mathrm{m}} = T_r/M \tag{1.8}$$

where M is the mass of the substance.

To account for the economic components of a system, it is necessary to account for the flows of money. By dividing the total emergy by the associated gross domestic product (GDP), an emergy to money ratio can be obtained (Fig. 1.4). The proportion of GDP created by each emergy contribution can be estimated as the emergy value divided by the emergy/money ratio. The result is expressed in *emdollars* (em$).

The emergy of economic inputs measured in terms of money is determined by multiplying the input in monetary units (e.g., U.S. dollars) by the ratio of the nation's total emergy to its economic gross domestic product:

$$E_{\mathrm{m}} = (U/\mathrm{GDP})C = (E_{\mathrm{m}}/\$)C \tag{1.9}$$

where U is the total emergy used by a region, GDP is the gross domestic product of that region, and C represents a particular economic monetary input (Hau and Bakshi 2004). The ratio of U/GDP is also expressed as $E_{\mathrm{m}}/\$$.

1.5 Indices Used in Emergy Synthesis

Because emergy measures everything that enters and flows out of a system, it is a property of both the system and the larger environmental system that surrounds it, and therefore it cannot be evaluated without some knowledge of the larger environment. It is therefore desirable to divide a system into two systems: the first system is the one being evaluated, and the second represents how that system is affected by and affects its surroundings (H. T. Odum 1996). All resources that are needed to produce something are accounted for, and can be aggregated into renewable resources (R), non-renewable resources (N), purchased goods (G), and purchased services (S). The renewable and non-renewable resources are drawn from the environment and are free in the sense that we do not pay for them. The goods and services are invested resources obtained from the societal component of the system being evaluated, and they are also regarded as feedback from the society to the system that supports it to produce an emergy yield (Y), which is considered to be an export from the system. A fuller explanation of the concepts, principles, and applications of synthesis can be found in *Environmental Accounting* (H. T. Odum 1996).

Emergy synthesis uses many emergy indices (Table 1.1). These indices were developed and used in many papers (H. T. Odum 1988, 1996; Ulgiati et al. 1995; Brown and Ulgiati 1997, 1999, 2001; Ulgiati and Brown 1998; Huang and Chen 2005).

Both ESI and NER can provide an indication of a system's sustainability. ESI provides an aggregate measure of a system's sustainability (Ulgiati et al. 1995). If ESI > 1, this represents a net contribution to the system (i.e., the system's emergy increases). In contrast, a low ESI value (< 1) indicates a net loss by the system, which commonly occurs in highly developed consumer-oriented economies. A particularly high ESI (> 10) is indicative of economies that have been termed "undeveloped" (Ulgiati and Brown 1998). In a dense area such as Macao, ELR is usually very high because the quantity of renewable resources inside the system are insufficient to sustain the system's consumption of resources, and this would produce a very small ESI.

Table 1.1 Definition of the main indices used in emergy synthesis

Index	Definition
Renewable resources (R)	The flows of free renewable resources that are locally available
Non-renewable resources (N)	The flows of non-renewable resources that are locally available
Imported emergy (F)	The flow of emergy imported in the form of goods and services from outside the system, including fuels, minerals, raw materials, goods, and imported services
Exported emergy (Y)	The flow of emergy exported in the form of goods and services to the outside market, including exported goods and tourism. This is also called the "emergy yield"
Exported emergy of production (B)	The flow of emergy exported in the form of products to the market outside the system being studied
Emergy used (U)	The total emergy used to support the system
Emergy self-sufficiency ratio (ESR)	The proportion of the total emergy used (U) that is accounted for by indigenous emergy (emergy available within the system)
%Ren	The proportion of the total emergy used (U) that is accounted for by renewable resources (R)
Emergy investment ratio (EIR)	The imported emergy (F) divided by the indigenous emergy available within the system ($R + N$)
Emergy density (U/area)	The ratio of total emergy used to the area of the system
Emergy money ratio (EMR, $E_{\mathrm{m}}/\$$)	In emergy units, the value of one unit of currency spent within the local economy. It is computed by dividing the total emergy used (U) by the GDP (gross domestic product)
Emergy yield ratio (EYR $= Y/F$)	The emergy embodied in the system's yield (Y) divided by the imported emergy (F)
Emergy exchange ratio (EER)	The emergy exchange as a result of a trade or purchase, which equals the emergy obtained as a result of the transaction divided by the emergy given away as a result of the transaction
Environmental loading ratio [ELR $= (U - R)/R$]	The ratio of non-renewable emergy (N) plus imported emergy (F) to the renewable emergy (R)
Emergy sustainability index (ESI)	The ratio of EYR to ELR
Net emergy (NE $= F + R - Y$)	The sum of the imported emergy (F) and the renewable resources emergy (R), minus the emergy yield (Y)
Net emergy ratio (NER $=$ NE$/U$)	The ratio of net emergy (NE) to the total emergy used (U). This index has been demonstrated to provide the best index of the sustainability of a system. (See the text following the table for an explanation of why)

However, comparing regions based solely on ESI may reveal little about their true sustainability, because this indicator alone does not tell us which country's sustainability is performing better and why. As others have noted, sustainability is determined by multiple social, economic, and ecological factors, and a single indicator cannot reveal the relative contributions of each 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-part indicator that reveals more roles of the system's components would thus be a more effective tool (Pearce and Barbier 2000). 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).

An advantage of emergy indices over traditional economic indices is that the former account for all of the resources used, both ecological and economic, and because emergy forms a common basis for both types of resource, it can bridge the gap between natural and artificial forms of capital (Lu et al. 2005). Simple monetary indicators cannot accomplish this. This suggests that aggregated NE should provide a better measure than ESI of the sustainability of a system.

The net emergy ratio (NER) is likely to provide a clearer picture of sustainability than ESI because it indicates whether the emergy of a system increases more clearly than any of the ratios that make this change implicit. In addition, it can provide more reasonable results if we accept emergy as the common unit for measuring both the economy and the ecology. A too-high value of NER means that too much weight has been placed on the foundation that underlies sustainability (i.e., the environment that supports a system) as a result of overexploitation of the surrounding regions that sustain the city (Lei et al. 2008).

1.6 Emergy Balance and Storage

Ulgiati et al. (1995) developed emergy-based indices to judge the level of sustainable development based on the assumptions that the sustainability of a system should include the net yield of the system (Y), its environmental load (measured by the consumption of renewable and non-renewable resources, $R + N$), and its imports of emergy (F) from the external environment (Fig. 1.5, Eq. 1.10).

$$Y = R + N + F \tag{1.10}$$

The concept of NE was developed in several papers (Ulgiati et al. 1995; H. T. Odum 1996; Brown and Ulgiati 1997). Brown and Ulgiati (1997) proposed that the input emergy for a small system or production process that is not changing in size should equal the output emergy. However, at a large scale such as that of a country, which includes many processes, their hypothesis seems untenable, and the emergy exports usually do not equal the emergy imports (Huang and Odum 1991, 1996; Ulgiati et al. 1995; H. T. Odum 1996; Lan et al. 2002). Brown and Ulgiati (2001) suggested that for a country's development to be sustainable, there must be a net benefit, which means a positive NE value. Measured in emergy terms, this means that the development causes more emergy to flow into the system than the system consumes.

As a system grows larger, it becomes more capable of storing emergy, and its emergy use increases. The stored emergy can be transformed into buildings, roads,

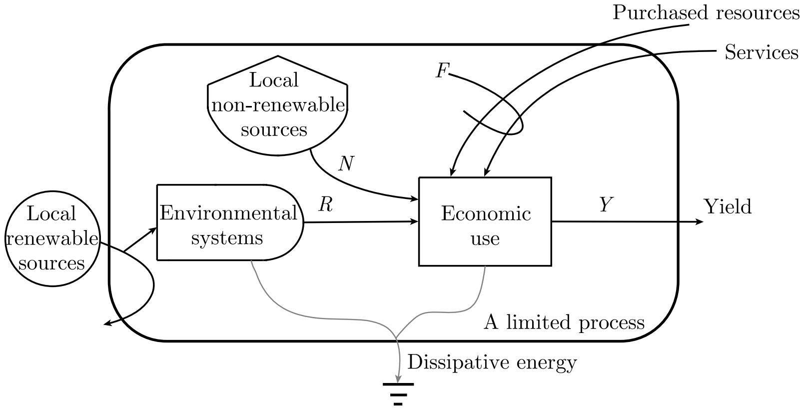


Fig. 1.5 Emergy-based indices for a simple system account for the flows of local renewable emergy inputs (R), local non-renewable inputs (N), and purchased inputs from outside the system (F) (Lei et al. 2008): Yield $(Y) = R + N + F$; Emergy yield ratio $= Y/F$; Emergy investment ratio $= F/(R + N)$; Environmental loading ratio $= (F + N)/R$

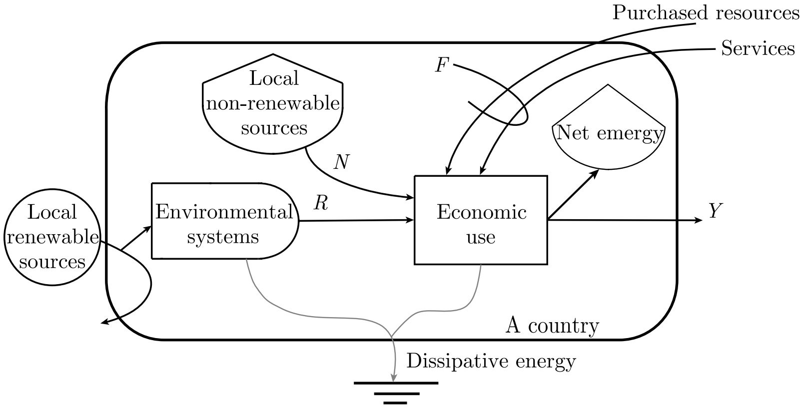


Fig. 1.6 A modified system diagram for a more complex system such as a country or region using emergy-based indices. Emergy storage (net emergy, NE) has been added to the simpler diagram in Fig. 1.5, as well as outflows of emergy (Y) (Lei et al. 2008): $F + R =$ Net emergy $+ Y$; Net emergy $= F + R - Y$; Net emergy ratio = Net emergy$/U$; $U = R + N + F$

and infrastructure, or into exports that are transferred to another system. To elucidate the concept of NE, we have proposed a modified framework (Fig. 1.6) that is capable of addressing the NE for a large system. This framework adds a storage frame (NE) to the system diagram. NE (Lei et al. 2008; Lei and Wang 2008a) is then defined as follows (Fig. 1.6):

$$\mathrm{NE} = F + R + N - Y \tag{1.11}$$

In 2004, we consulted S. L. Huang (Professor of the Graduate Institute of Urban Planning, "National" Taipei University), who suggested that we widen our view and try to see whether a system can expand when the net emergy is positive. For a system that is increasing in size, the output must be less than the input emergy (i.e., $Y < F + R + N$) and the emergy storage (NE) should increase (S. L. Huang, personal communication, 2005). Although non-renewable resources are changed into production or storage emergy, the inflow emergy ($F + R + N$) should equal the outflow emergy (Y) plus the emergy storage (NE). That is,

$$Y + \mathrm{NE} = F + R + N$$

Or

$$\mathrm{NE} = F + R + N - Y \tag{1.12}$$

If a system exports non-renewable resources (N_2), then Eq. 1.12 should be modified to become $\mathrm{NE} = F + R + N - Y - N_2$, since N_2 reduces the emergy storage of the system. On the other hand, if a system exports more emergy than it imports in the form of non-renewable resources, its natural resources will decrease, the system will diminish the natural capital that sustains it, and the net emergy will be negative ($Y > F + R + N - N_2$).

In comparison with other emergy-based indicators, the advantages of NE and NER are:

1. They provide a common basis for emergy evaluation. All the natural and economic resources are converted into solar emergy units and calculated on the same basis throughout the analysis.
2. NE is analogous to the asset balance in a financial analysis, and for a region's development to be sustainable, NE must be balanced ($\mathrm{NE} = 0$) or positive ($\mathrm{NE} > 0$) in the long run.

   If $\mathrm{NE} > 0$, then NER would also be a positive number, which means that the inflow emergy is more than the outflow emergy; as a result, the system will expand and develop.

1.7 Ecological Energy Accounting for Tourism

Since the early 2000s, the framework of emergy analysis has been used to analyze tourism (e.g., Abel 2000, 2003; Brown and Ulgiati 2001). Brown and Ulgiati (2001) studied tourism resorts in Mexico and Papua New Guinea, and proposed that sustainable development required a net positive NE that resulted from a positive emergy trade balance.

In recent published papers, most authors have treated the monetary flows generated by tourism as an income resource (Ulgiati et al. 1994; Huang and Odum 1996; H. T. Odum 1996; Brown and Ulgiati 2001; Lan et al. 2002), and have calculated this income as a kind of external investment in the ecosystem of the tourism sec-

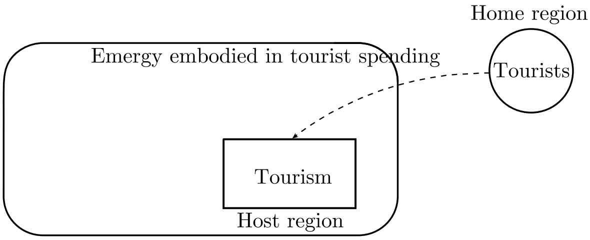


Fig. 1.7 The relationship between tourists and a tourism system when only money flows are calculated

tor (shown as the embodied emergy that tourists spend in Fig. 1.7). This treatment seems unreasonable in emergy synthesis because the money paid by tourists is used to purchase fuels, goods, and services, some of which were provided by the external system and which have therefore been accounted for in purchases of these resources (F). If the tourism payments are added to the emergy used (U), this would therefore lead to double counting.

Some authors have analyzed tourism flows from the opposite perspective by treating these flows as an export industry (Abel 2000), with goods and services leaving the host region and being exported to the tourists' home regions. Goods and services provided from a tourism host region are purchased by foreigners who use the host region's hotel facilities, eat in the host region's restaurants, and buy the host region's goods for their personal use (Abel 2000). Thus, these flows can be thought of as the exported emergy of tourism (Lei et al. 2006).

Tourism emergy inflows can be divided into several categories:

- Transportation is an essential ingredient because it brings the tourists to and from the host system.
- Local services are consumed, in direct and indirect forms, to maintain and promote the hotel and restaurant industry, as well as other retail sectors.
- Imported goods, including the emergy embodied in the shipping of imports and foods, are present in the emergy inflows that supply the retail subsystem.
- Tourism requires a large labor force, and the emergy inflow from labor is substantial.

The sum of these emergy inputs represents the total emergy export by tourism, even though the exchange processes happen within the host region (Fig. 1.8).

The embodied emergy of the money that tourists spend in the host region does not equal the emergy the tourists consume within that region (Fig. 1.9). To express the difference in the exchange processes between the tourism system and the tourists, we have proposed a more reasonable calculation method for the emergy consumed by tourists (M_t). This method is based on a holistic analysis that combines the calculation methods in which tourism emergy flows are considered as exports of both materials and money (Fig. 1.9). The emergy of the purchasing power that the tourists

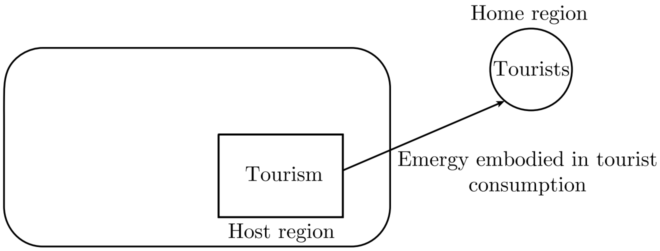


Fig. 1.8 The relationship between tourists and the tourism sector when tourist consumption of host resources is calculated as an outflow (export) of emergy

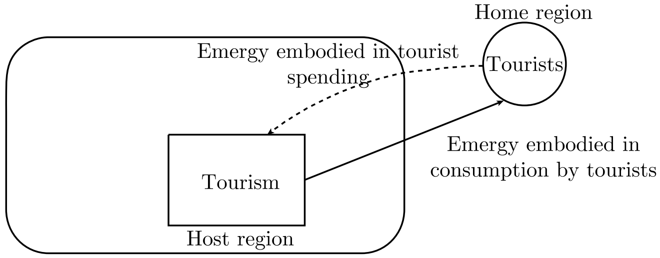


Fig. 1.9 A holistic diagram of the tourism sector and tourists that accounts for both imports and exports of emergy as a result of tourist activities

bring to the system through their spending (T_m) and the emergy consumed by the tourists (M_t) flow in opposite directions and have very different magnitudes (Lei et al. 2008).

Two methods can be found in the literature for how to calculate the imports and exports of emergy by tourism:

1. The goods and services provided to tourists (i.e., exported emergy) equal the total emergy inputs (renewable resources, non-renewable resources, purchased inputs). This approach has been used successfully to study tourist resorts (Brown and Ulgiati 2001; Abel 2003). The imported emergy of tourism is calculated using the following equation:

$$T_\mathrm{m} = (E_\mathrm{m}/\$)C_\mathrm{t} \tag{1.13}$$

   where C_t is the monetary income provided by the tourism activities. Brown and Ulgiati (2001) thought that the $E_\mathrm{m}/\$$ ratio from a tourist's home country should be adopted in Eq. 1.13. When tourists stay in the host country, the emergy that is initially embodied in their bodies corresponds to the inputs provided by their home country's technology and resources. We therefore disagree with the authors who have used the $E_\mathrm{m}/\$$ ratio of the host country (e.g., Huang and Odum 1996). In our research on Macao, we used the world $E_\mathrm{m}/\$$ ratio, since the tourists came from many different countries.

Table 1.2 Shopping spending by tourists, by type of expense, in 2003. All monetary values were converted from Macao patacas (MOP) to U.S. dollars based on a conversion rate of MOP8.021 per US$

Category of shopping	Spending ($)
Clothing	15.5
Jewelry and watches	21.8
Souvenirs and handicrafts	1.1
Cosmetics	6.2
Tobacco	1.9
Alcohol	1.4
Medicine	2.2
Shoes and handbags	3.7
Pastry and candy	5.2
Other	9.5
Total spending per tourist	68.6
Total spending per tourist per day	57.2

2. Tourism cities are shared by local residents and by tourists, so tourist consumption could be accounted for as a proportion of the total emergy used (U) by the host country (Lei et al. 2006; Lei and Wang 2008a, 2008b). On this basis, the emergy consumed by tourists (M_t) can be expressed as:

   $$M_t = R_t U \tag{1.14}$$

   where R_t is the proportion of the total emergy used (U) that is consumed by tourists, which can be obtained using the following equation:

   $$R_t = Tdr/(Tdr + 365P) \tag{1.15}$$

   where T refers to the number of tourists, d is the average duration of their stay (days), r is the consumption factor of the tourists (i.e., the ratio of their spending to the spending of residents of the host region), P represents the population of the host region (Macao in the context of this book), and 365 represents the number of days in a year. We determined r using a large collection of statistical data from the Macao government Web site (www.dsec.gov.mo) combined with a survey of tourists. Based on this data, the average r equaled 1.91 for Macao in 2003, which means that a tourist consumed 1.91 times the emergy consumed by a local resident. The data used in this calculation are presented in Tables 1.2 and 1.3. Using the same method, r was 1.77 in 1997 and 2.0 in 2000. We have used the average value from these three years ($r = 1.9$) for all relevant calculations (Lei and Wang 2008a).

It was suggested (S. L. Huang, Professor of the Graduate Institute of Urban Planning, “National” Taipei University) that in a leading tourism city such as Macao, the emergy contribution by and the impacts of tourists should be studied carefully. EER is always expressed relative to one of the two trading partners, and is a measure of

Table 1.3 The data used in the consumption factor calculation process (data from 2003)

Category	Tourist	Local resident	Tourist/resident ratio	Emergy (proportion of U)	Tourist/resident[a]
Water (m^3 person-day^{-1})	0.31[b]	0.16[c]	1.89	0.008[d]	0.02
Electricity (kW · h person-day^{-1})	7.44[e]	3.47[f]	2.14	0.07[g]	0.14
Shopping spending (\$ person-day^{-1})	57.2[h]	17.3[i]	3.3	0.33	1.07
Food	Survey data		1.3[j]	0.15	0.20
Travel spending	Survey data		1.5[k]	0.05	0.08
Other	Hypothesis		1[l]	0.391	0.39
Total					1.91

Notes: Except where otherwise noted, all data were obtained from the Department of Statistics of the government of Macao (www.dsec.gov.mo)

[a] The value results from multiplying the two previous columns

[b] The hotels spent 19 288 000 MOP for water, the tourists spent 11 887 900 MOP, the water cost 4.39 MOP m^{-3}, and the average duration of the stay was 1.2 days, so the water spending per tourist per day = 19 288 000/4.39/11 887 900/1.2 = 0.308

[c] The household water consumption was 26 658 127 m^3 (Macao Water Company 2004), so the water spending per resident per day = 26 658 127/448 495/365 = 0.163

[d] Water emergy/emergy used (U) in 2003 = 1.85×10^{20} sej/2.20×10^{22} sej = 0.0084

[e] Data were obtained from DSEC (2004)

[f] Data from the Macao Electricity Company (Companhia de Electricidade de Macau 2004)

[g] Data deduced from DSEC (2004)

[h] Data from Table 1.2

[i] Data were obtained from DSEC (2004)

[j] We surveyed 400 tourists who ate at restaurants or hotels. They ate more food than they did at home, and generally did not take leftover food with them when they left. For residents, leftover food was usually stored in the refrigerator and eaten later. Thus, we estimated that a tourist consumes 1.3 times as much food as a local resident

[k] The tourists were generally not familiar with the city, and consequently made greater use of vehicles, which we estimated at 1.5 times the usage by local residents

[l] For other items such as environmental services and public equipment, we hypothesized that a tourist would use the same emergy as a resident

the relative trade advantage of one partner over the other (H. T. Odum 1996). The proposed impact of tourism can be thought of in terms of EER:

$$\text{EER of tourism} = T_m / M_t \tag{1.16}$$

In this calculation, we used the global average E_m/\$ ratio. The NE will be used by Macao's tourists, so the NER then equals the NE divided by the emergy used:

$$\text{NER of tourism} = (T_m - M_t) / T_m \tag{1.17}$$

1.8 Conclusions

Systems theory is the interdisciplinary study of systems in general, with the goal of elucidating principles that can be applied to all types of systems at all hierarchical levels and in all fields of research. Systems are specifically considered to be shaped by feedbacks within the system. Self-regulating systems are found in nature, including the physiological systems of our body, in local and global ecosystems, in climate, and in human learning processes.

Contemporary ideas from systems theory have been adopted by many areas of research, as exemplified by the work of Howard Odum on ecological systems. Systems biology is a term used to describe how the principles of systems theory can be applied in biological research, and a large movement that draws on these principles has emerged in recent years.

Emergy is the available energy (i.e., the exergy) of one kind that is used up in direct and indirect transformations to make a product or provide a service. Emergy accounts for and therefore measures quality differences between different forms of energy. Emergy is an expression of all the energy used in the work processes that generate a product or service, and is expressed in consistent units that allow comparisons among flows of energy, money, or materials that have different energy units. Each form of emergy is generated by natural and anthropogenic transformation processes, and each form has a different ability to support work due to differences in emergy quality between forms. The recognition of these differences in quality is a key concept of the emergy methodology.

Emergy accounting relies on the thermodynamic basis of all forms of energy, resources, and human services, and converts them into equivalents of one form of energy, usually solar emergy. To evaluate a system, a system diagram must first be drawn to organize the evaluation process and account for all inputs and outflows. A table of the actual flows of resources, labor, and energy is constructed from the diagram and all flows are evaluated. The final step of an emergy evaluation involves quantifying and comparing the flows. In some cases, the evaluation is done to determine how well a development proposal will fit within its environment. In others, the goal may be to compare alternatives to determine which ones are most sustainable or to identify the use of resources that maximizes economic vitality.

Emergy evaluations are both synthetic and analytical. Synthesis is the act of combining elements into coherent wholes to facilitate understanding of the overall system, whereas analysis is the process of dissecting or breaking apart systems to build an understanding of their component pieces. In the emergy method of evaluation (i.e., emergy synthesis), the whole system is considered first through diagramming, then the flows of energy, resources, and information that drive the system are analyzed. By evaluating complex systems using emergy methods, the major inputs from the human economy and those provided "free" from the environment are integrated, and the results can support analyses of public policy questions and environmental management options.

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Chapter 2
Ecological Energy Accounting for Macao's Socioeconomic and Ecological Systems

2.1 Social and Economic Characteristics of Macao

China's Macao special administrative region is located on the western coast of the Pearl River estuary (Fig. 2.1). It lies between 111°31′33″E and 111°35′43″E, and between 22°06′39″N and 22°13′06″N. The city is located near the southern edge of the northern hemisphere's tropics and therefore lies near the southern hemisphere's tropics. As a result, Macao's average annual temperature is 22.3 °C, and the wind comes from opposite directions in winter and summer. The temperate climate is warm and wet in summer, with frequent tropical typhoons during both the summer and the autumn. Winter comes in January and February each year, and temperatures may drop below 4 °C, with a low amount of rainfall.

Macao is a unique Asian city, and has been the site of more than 400 years of cultural exchange between the western world and Chinese civilization (Maritime Administration 2005). In 2010, Macao's population was 544 600 (DSEC 1984–2011, 2011 data). The annual number of tourist arrivals averages 26 times the local population (DSEC 1984–2011, 2005 data). Macao has been expanding for many years since 1990 by means of progressive land reclamation along the coast to meet the needs of socioeconomic development. In 2010, the area reached 29.7 km^2, and comprised the Macao Peninsula (9.3 km^2), Taipa (6.8 km^2), Coloane (7.6 km^2), and the Cotai Reclaimed Land (6.0 km^2). The population density of Macao was about 18 337 persons per km^2 in 2010. The Macao Peninsula and Taipa are linked by three bridges, whereas Taipa and Coloane are connected by reclaimed land. Macao is therefore a small region, with a high population density and a large number of tourist visits annually.

Because Macao is characterized by a cultural mixture between the Western world and China that has developed over the past 400 years, "The Historic Centre of Macao", which has more than 20 monuments, was added to UNESCO's list of World Cultural Heritage sites in July 2005 (ICGRAEM 2006).

The currency is the Macao pataca (MOP), which is generally held at a constant ratio with the Hong Kong dollar of 1.032 to 1, so its value is also controlled by fluctuations in the U.S. dollar. (In the rest of the book, all economic values are

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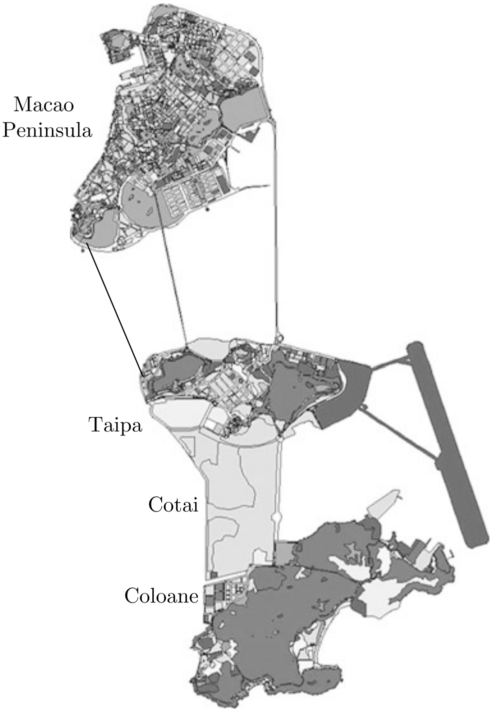
Fig. 2.1 Macao comprises the Macao Peninsula, Taipa, Cotai, and Coloane. (The map is based on the 2008 boundaries)



expressed in U.S. dollars unless otherwise noted.) The major products exported from Macao are ready-made garments, which account for about 70 % of total exports, and textile products. The main export markets are the United States, the EU, Hong Kong, and mainland China. The imported goods are mainly raw materials and partially finished products as well as consumer goods. Imported goods mainly originate from mainland China, Hong Kong, the EU, Japan, and the United States.

Since 1990, Macao has increasingly become a consumer society, following the abandonment of agriculture and the decline of the local fishing industry. Although most of the daily necessities of life, such as fresh water, food, fuel, raw materials, and goods, are imported, Macao's economy has maintained a robust growth rate with sustained prosperity as a result of the gaming and tourism industries.

Macao's government has implemented an economic development strategy that designated the tourism and gaming industries as the leading engines for economic growth (Wikipedia 2012). These industries are supported by a service sector, with parallel development of other sectors designed to develop a more diversified economy. By capitalizing on its particular geographic and socioeconomic advantages, Macao is making every effort to become a hub for regional trade, and particularly to support economic cooperation between mainland China and Portuguese-speaking countries and cooperation with expatriate Chinese entrepreneurs.

Despite these plans for diversification, the gaming and tourism industries contribute the largest single portion of the region's overall economic development.

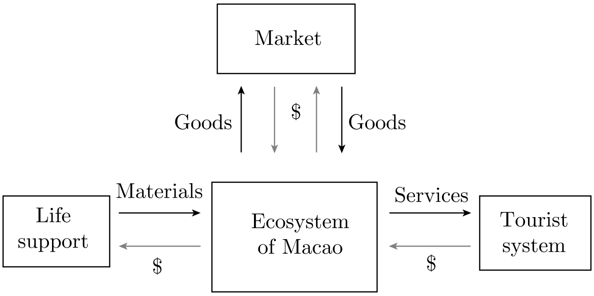


Fig. 2.2 Illustration of the flows of material and money for Macao's ecosystem. *Dark arrows* represent flows of goods, materials, and services; *light arrows* represent monetary flows

Gaming tax revenues alone account for 40 % of the government's total tax revenues, and about one-third of the total workforce is employed in this industry.

Macao's government opened the gaming industry to the private sector in 2002 by issuing three gaming concessions, which attracted many investors both at home and from North America and Hong Kong. With this liberalization of the gaming industry, the government expected to bolster other related industries, but also expected to benefit Macao's overall economic development.

Macao's economy has maintained robust growth and sustainable prosperity based on the gaming and tourism industries, which we will refer to as the "tourism" industry in the rest of this chapter. In 2004, real GDP reached $\$9.97 \times 10^9$ (DSEC 1984–2011, 2005 data). Tourism, manufacturing, finance and insurance, and construction and real estate have been the four pillars of Macao's economy since 1980. Tourism has been the main driver of development since the mid-1990s. The booming tourism industry contributed gaming tax receipts of $\$1.9 \times 10^9$ in 2004 (DSEC 1984–2011, 2005 data). The Mainland and Macao Closer Economic Partnership Arrangement (CEPA), which was implemented in 2004, has benefited many sectors of Macao's economy, but especially the tourism sector; the "free individual traveler" provision alone was responsible for tremendous growth of the number of tourists from mainland China (DSEC 1984–2011, 2005 data). Gambling is legal in Macao, but not in China, and previously, Chinese citizens were strictly limited from entering Macao. Under this provision, residents of most Chinese cities can now legally travel to Macao for gambling.

Figure 2.2 illustrates the exchanges between the three essential natural and socioeconomic components of Macao's ecosystem. The life-support system is represented by the block on the left side of the diagram. Almost all raw materials, foods, and water flow into Macao, whereas most money (currency) flows in the opposite direction as it leaves Macao to pay for the imported materials. The tourist system is represented by the block on the right side of the diagram. Tourists come to Macao to consume and to gamble, representing an import of money, whereas Macao's tourism sector supplies them with goods and services, which are mostly considered to be exports (as we discussed in Chap. 1). The external market is represented by the block

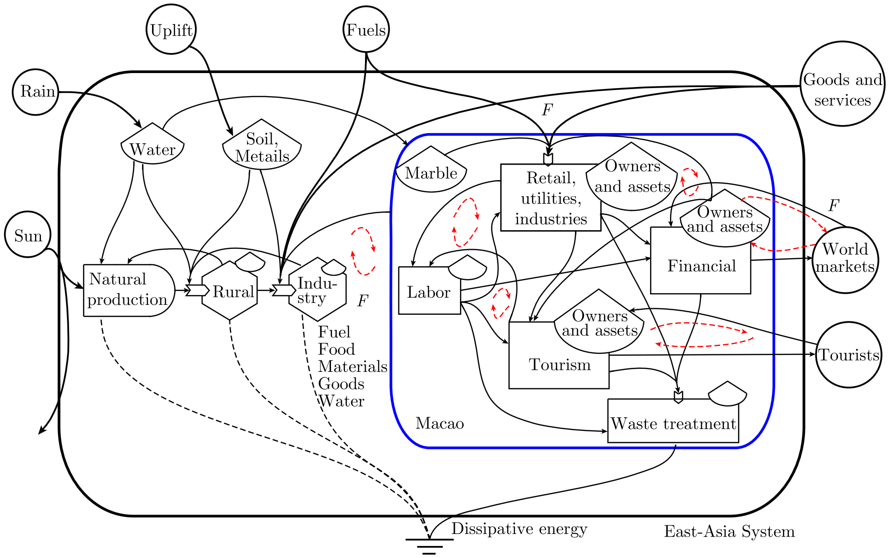


Fig. 2.3 Illustration of the materials, energy, and information transfer processes for Macao

at the top of the diagram. Macao exports its products to this market, and at the same time imports fuel, goods, and equipment that Macao does not produce internally.

Note: Because of the large number of parameters defined in this book, we have provided a summary of all parameters and their definitions in Appendix C.

2.2 Emergy Synthesis for Macao's Eco-economic System in 2004

Urban ecosystems consist of a large number of people living in close proximity. They serve as centers for both residential and commercial activities. The existence of a city or town and the maintenance of its internal structures depend on the inflow and outflow of the goods and services required to sustain these activities (Huang and Chen 2005). Despite their largely artificial nature, urban ecosystems exhibit the same basic kinds of interactions exhibited by other ecosystems. Most importantly, from the perspective of the living species contained by the urban ecosystem, none of these ecosystems are ecologically self-contained or self-sufficient; that is, all cities are sustained by life-support processes that occur mainly outside the city's boundaries.

Densely populated cities such as Macao could not exist without the support of a larger surrounding ecosystem (Huang and Odum 1996). We performed an emergy analysis for Macao to ensure that the importance of these external inputs was recognized in our analysis, and created a diagram (Fig. 2.3) that depicts the environmental resources provided by the natural area surrounding Macao. These resources are concentrated in rural areas, where solar energy is captured by plants and other organ-

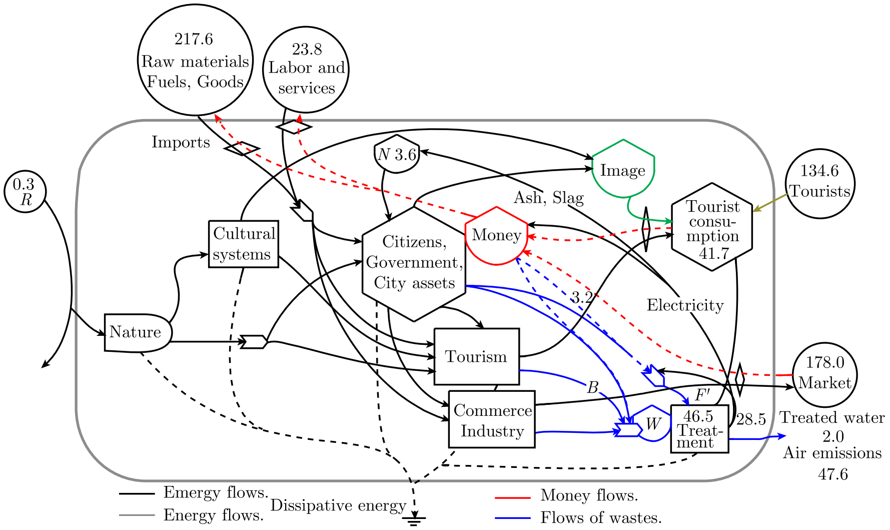


Fig. 2.4 A concise emergy flow diagram for Macao's ecosystem in 2004 (all values are $\times 10^{20}$ sej)

isms, accumulated (stored), and used to support the city of Macao, which exchanges emergy with the surrounding ecosystem (Huang and Odum 1996). In the case of our study area, Macao's life-support energy and materials are mostly provided by the surrounding areas of Mainland China. Figure 2.4 is a concise emergy-flow diagram for Macao's internal and external environment and economy.

Most of the data used in the remainder of this chapter were provided by DSEC (1984–2011, 2005 data), the Cartography and Cadastre Bureau of Macao (2012), the Meteorological and Geophysical Bureau of Macao (2006), and the Environment Council of Macao (ECM 2000, 2004, 2005).

Table 2.1 summarizes the flows of materials (imports and exports) for Macao in 2004. Imports totaled about 588 $\times$ 10^8 kg of fresh water annually, versus 29.3 $\times$ 10^8 kg of other goods and raw materials. This contrasts with exports of 551 $\times$ 10^8 kg of sewage discharged and 3.8 $\times$ 10^8 kg of products exported to regions outside Macao. We found that the total exports equaled only 0.6 % of the total imported materials (on a weight basis). Fresh water was the main imported material, and amounted to 95.3 % of the total weight of imported material. Raw and processed materials were the main exports, and accounted for 72.3 % of the total exports. About 98.2 % of the imported materials came from China, whereas only 48.0 % of the products were exported to China. The electricity imported from China totaled 151.3 GW · h in 2004.

In 2004, the total emergy used in Macao was 245.2 $\times$ 10^{20} sej, the imported emergy was 241.3 $\times$ 10^{20} sej, and the exported emergy was 136.3 $\times$ 10^{20} sej (Lei and Wang 2008b). Table 2.2 summarizes the renewable (R) and indigenous non-renewable resources (N) that contributed to these totals. They accounted for 0.1 % of the total emergy use (U) in 2004. The indigenous non-renewable environmental

Table 2.1 Material flows for Macao in 2004. Totals may not add up precisely due to rounding errors

Item	Imports ($\times 10^8$ kg)	% of total imports	Exports ($\times 10^6$ kg)	% of total exports	Sewage ($\times 10^9$ kg)	Solid wastes ($\times 10^9$ kg)
Water	588.49	95.3	0	0		
Food	3.36	0.5	7.2	1.9		
Fuels	7.47	1.2	276	0.01		
Minerals	8.99	1.5	12.4	3.25		
Raw and processed materials	5.41	0.9	275.6	72.3		
Goods	4.03	0.7	86.0	22.6		
Total	618.26	100.0	381.2	100.0	55.1	0.3

resources (N) of Macao comprised mined marble (3.60×10^{20} sej) and the loss of topsoil (1.19×10^{14} sej), which together accounted for about 1.5 % of Macao's emergy use in 2004. By using Eq. 1.11, we can calculate that Macao's net emergy was 63.6×10^{20} sej (Lei and Wang 2008b).

Table 2.3 summarizes the emergy trade exchange (imports versus exports), and Table 2.4 summarizes the emergy flows for Macao in 2004. Figure 2.4 shows imports of 23.8×10^{20} sej (labor and services), of 241.3×10^{20} sej of purchased emergy (F), and of 134.6×10^{20} sej of tourist payments for their consumption flowing into Macao to support the system's metabolism. The imported water and food accounted for 14.8 % of the emergy used, whereas the imported fuel, minerals, and electricity accounted for 12.3 % of the emergy used in 2004. The imports of purchased goods and raw materials (G, including water and food) accounted for 76.5 % of the emergy used, whereas the imported services accounted for 9.7 % of the emergy used. In 2004, the imported emergy (F) accounted for 98.4 % of the total emergy used. Inexpensive raw materials usually carry plentiful emergy, thus the $E_m/\$$ for China was 4.94×10^{12} sej $\$^{-1}$ in 2004 (Zhao 2002), versus only 2.38×10^{12} sej $\$^{-1}$ for Macao. Thus, when Macao exchanges goods with China that have the same total monetary value, more of the emergy assets flow into Macao. Analysis of other development projects (Ulgiati et al. 1995) suggests that one of the main driving forces behind international trade is the fact that developed countries benefit greatly from an unequal emergy exchange with developing countries when they exchange goods with the developing region. Unequal emergy exchange related to the primary materials provided by different regions will lead to an emergy surplus when spending the same amount of money (H. T. Odum 1996).

The consumer emergy of tourists:

$$M_t = R_t \times U = 0.17 \times 2.45 \times 10^{22} \text{ sej} = 4.17 \times 10^{21} \text{ sej}$$

Wastes were not included in the renewable resources category, since wastes are not exchanged. Figure 2.5 summarizes Macao's emergy flows. In 2004, Macao exported about 73.8 % of its total emergy used (U, including tourism consumption),

Table 2.2 Annual emergy flows for Macao's renewable and non-renewable resources in 2004

Item	Raw units	Transformity (sej per raw unit)	Source of published value for transformity	Emergy (sej)	Emdollars (em$)
Renewable					
1. Sunlight[a]	1.16×10^{17} J	1	H. T. Odum (1996)	1.16×10^{17}	4.85×10^{4}
2. Wind, kinetic[b]	2.22×10^{14} J	1470	Campbell (2004)	3.27×10^{17}	1.37×10^{5}
3. Rain, chemical[c]	2.06×10^{14} J	18 100	Campbell (2004)	3.73×10^{18}	1.56×10^{6}
4. Rain, geopotential[d]	4.09×10^{13} J	10 300	Campbell (2004)	4.21×10^{17}	1.76×10^{5}
5. Waves[e]	8.9×10^{14} J	25 900	H. T. Odum (1996)	2.31×10^{19}	1.12×10^{7}
6. Earth cycle[f]	3.99×10^{13} J	33 700	Campbell (2004)	1.34×10^{18}	5.63×10^{5}
Total (3 + 5 + 6)	1.11×10^{15} J		–	2.71×10^{19}	1.14×10^{7}
Non-renewable					
7. Marble	3.60×10^{11} g	1 000 000 000	H. T. Odum (1996)	3.60×10^{20}	1.51×10^{8}
8. Topsoil loss	1.90×10^{9} g	62 500	H. T. Odum (1996)	1.19×10^{14}	4.98×10
Total (7 + 8)	3.62×10^{11} g		–	3.60×10^{20}	1.51×10^{8}

[a] Sunlight: Energy (J) = (area of country) × (mean insolation) × (1 − albedo) × conversion factor (kcal to J) = $(2.75 \times 10^{7}\ \mathrm{m}^2) \times (1.31 \times 10^{6}\ \mathrm{kcal\,m^{-2}\,y^{-1}}) \times (1 - 0.2) \times (4186\ \mathrm{J\,kcal^{-1}}) = 1.16 \times 10^{17}\ \mathrm{J\,year^{-1}}$

[b] Wind, kinetic: Energy (J) = (area) × (air density) × (drag coefficient) × (velocity^3) × conversion factor (years to seconds) = $(2.75 \times 10^{7}\ \mathrm{m}^2) \times (1.3\ \mathrm{kg\,m^{-3}}) \times (1.00 \times 10^{-3}) \times (5.83\ \mathrm{m\,s^{-1}}) \times (3.15 \times 10^{7}\ \mathrm{s\,year^{-1}}) = 2.22 \times 10^{14}\ \mathrm{J\,year^{-1}}$

[c] Rain, chemical: Energy (land, J) = (area) × (rainfall) × (water density) × (Gibbs number) = $(2.75 \times 10^{7}\ \mathrm{m}^2) \times (1.52\ \mathrm{m}) \times (1000\ \mathrm{kg\,m^{-3}}) \times (4.94 \times 10^{3}\ \mathrm{J\,kg^{-1}}) = 2.06 \times 10^{14}\ \mathrm{J\,year^{-1}}$

[d] Rain, geopotential: Energy (J) = (area) × (rainfall) × (water density) × (mean elevation) × (acceleration due to gravity) = $(2.75 \times 10^{7}\ \mathrm{m}^2) \times (1.52\ \mathrm{m\,year^{-1}}) \times (1000\ \mathrm{kg\,m^{-3}}) \times (763\ \mathrm{m}) \times (9.8\ \mathrm{m\,s^{-2}}) = 4.09 \times 10^{13}\ \mathrm{J\,year^{-1}}$

[e] Waves: Energy (J) = (shoreline length) × (1/8) × (density of seawater) × (acceleration due to gravity) × (wave height)^2 × (wave velocity) × conversion factor (years to seconds) = $(4.086 \times 10^{4}\ \mathrm{m}) \times (1/8) \times (1.025 \times 10^{3}\ \mathrm{kg\,m^{-3}}) \times (9.8\ \mathrm{m\,sec^{-2}}) \times (0.5\ \mathrm{m})^2 \times (2.21\ \mathrm{m\,s^{-1}}) \times (3.14 \times 10^{7}\ \mathrm{s\,year^{-1}}) = 8.94 \times 10^{14}\ \mathrm{J\,year^{-1}}$

[f] Earth cycle: Energy (J) = (area) × (heat flow) = $(2.75 \times 10^{7}\ \mathrm{m}^2) \times (1.45 \times 10^{6}\ \mathrm{J\,m^{-2}\,year^{-1}}) = 3.99 \times 10^{13}\ \mathrm{J\,year^{-1}}$

Table 2.3 The evaluation of emergy imports and exports by Macao in 2004

Item	Raw units (g)	Quantity	Transformity (sej per unit)	Reference for transformity value	Emergy ($\times 10^{20}$ sej)	Emdollars (em$)
Imports						
1. Foods	3.36×10^{11}	3.52×10^{15} (J)	38 categories	See Table A.1[a]	39.15	7.94×10^{8}
2. Fresh water	5.88×10^{13}	2.91×10^{14} (J)	660 000	Lan et al. (2002)	1.92	3.88×10^{7}
3. Electricity	151 GW · h	5.45×10^{14} (J)	159 000	H. T. Odum (1996)	0.87	1.76×10^{7}
4. Fuels	7.47×10^{11}	3.10×10^{16} (J)	54 000	H. T. Odum (2000)	16.70	1.01×10^{9}
5. Minerals	9.50×10^{11}	9.50×10^{11} (g)	9 categories	See Table A.2[b]	12.57	2.55×10^{8}
6. Raw and processed materials	5.41×10^{11}	3.18×10^{15} (J)	38 categories	See Table A.3[c]	120.77	7.27×10^{9}
7. Goods	4.03×10^{11}	2.92×10^{11} (J)	34 categories	See Table A.4[d]	25.66	1.54×10^{9}
Total (1–7)	6.18×10^{13}	3.86×10^{16} (J)	–	–	217.65	1.09×10^{10}
Exports						
1. Foods	7.22×10^{9}	9.87×10^{13} (J)	27 categories	See Table A.5[e]	0.99	4.17×10^{7}
2. Fuels	2.76×10^{7}	1.16×10^{12} (J)	54 000	H. T. Odum (2000)	0.00	2.63×10^{4}
3. Cement	1.24×10^{10}	1.24×10^{10} (g)	2.07×10^{9}	See Table A.6[f]	0.26	1.07×10^{7}
4. Raw materials	2.76×10^{11}	2.90×10^{15} (J)	37 categories	See Table A.7[g]	121.36	5.10×10^{9}
5. Goods	8.60×10^{10}	7.08×10^{10} (J)	30 categories	See Table A.8[h]	13.68	5.75×10^{8}
Total (1–5)	3.81×10^{11}	3.00×10^{15} (J)	–	–	136.29	5.73×10^{9}

Table 2.3 (*Continued*)

Item	Raw units (g)	Quantity	Transformity (sej per unit)	Reference for transformity value	Emergy ($\times 10^{20}$ sej)	Emdollars (em$)
Service imports and tourism exports		\$	E_m/\$		Emergy	Emdollars
1. Service imports ($P_2 I_3$)		1.43×10^9 (\$)	4.94×10^{12}	Zhao (2002)	23.77	9.99×10^8
2. Service exports (Tourism income, T_m)[i]		8.10×10^9 (\$)	1.66×10^{12}	Abel (2000)	134.56	5.66×10^9
3. Tourist consumption (M_t)[j]		The tourists consumed 17.4 % of the total emergy used (U)			42.60	1.79×10^9
Waste emergy	Mass	Heat value (kcal kg^{-1})	Transformity (sej J^{-1})	–	Emergy	–
1. Solid wastes	2.56×10^8 (kg)	6.07×10^6	1.80×10^6	Zhao (2002)	28.00	1.18×10^9
2. Sewage	5.51×10^{10} (kg)	4.91×10^3	6.66×10^5	Zhao (2002)	1.80	7.57×10^7

[a] Imported food was classified into 38 categories, and the results of the emergy calculation process are listed in Table A.1

[b] The imported and exported items were classified into various categories, and the results of the emergy calculation process are listed in Table A.2

[c] The imported and exported items were classified into various categories, and the results of the emergy calculation process are listed in Table A.3

[d] The imported and exported items were classified into various categories, and the results of the emergy calculation process are listed in Table A.4

[e] The imported and exported items were classified into various categories, and the results of the emergy calculation process are listed in Table A.5

[f] The imported and exported items were classified into various categories, and the results of the emergy calculation process are listed in Table A.6

[g] The imported and exported items were classified into various categories, and the results of the emergy calculation process are listed in Table A.7

[h] The imported and exported items were classified into various categories, and the results of the emergy calculation process are listed in Table A.8

[i] The exported tourism emergy was calculated according to Eq. 1.13. The global transformity value was obtained from M. T. Brown (University of Florida, Gainesville, personal communication, 2004)

[j] According to Eqs. 1.14 and 1.15:

$$R_t = \frac{16\,672\,600 \times 1.1 \times 1.9}{16\,672\,600 \times 1.9 \times 1.1 + 365 \times 465\,333} = 0.17$$

Table 2.4 Summary of emergy flows for Macao in 2004

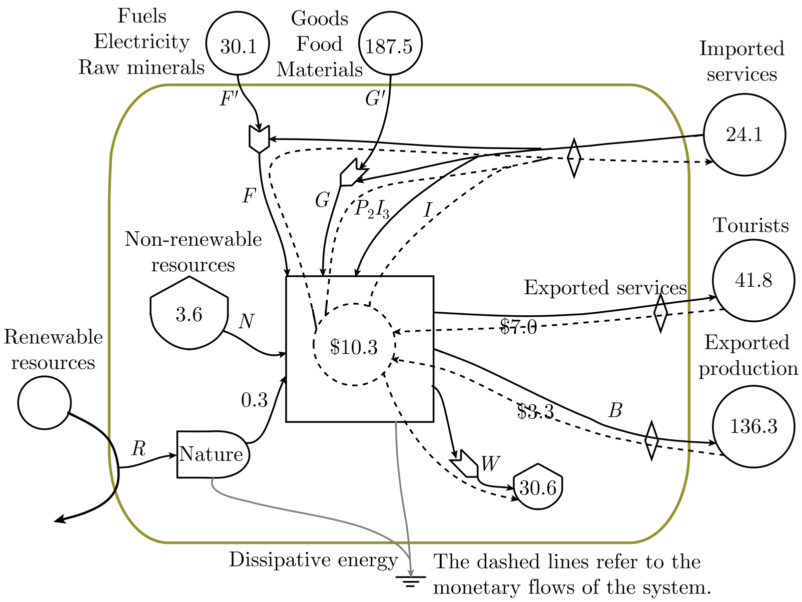
Variable	Explanation	Energy or mass or money	Solar emergy (sej)	Emdollars (em$)
R	Renewable resources	1.11×10^{15} (J)	2.71×10^{19}	1.14×10^{7}
N	Non-renewable resources	3.62×10^{11} (g)	3.60×10^{20}	1.51×10^{8}
Fuel	Imported fuels and minerals	3.16×10^{16} (J)	3.05×10^{21}	1.28×10^{9}
G	Imported foods, goods, and raw materials	7.03×10^{15} (J)	1.87×10^{22}	7.86×10^{9}
P_2I_3[a]	Emergy of services from other places	1.43×10^{9} ($)	2.38×10^{21}	9.99×10^{8}
F (imported)	Imported emergy: Fuel $+ G + P_2I_3$	3.86×10^{16} (J)	2.41×10^{22}	1.01×10^{10}
U[b]	Total emergy used: $R + N + F$	3.97×10^{16} (J)	2.45×10^{22}	1.03×10^{10}
B	Exported production	3.00×10^{15} (J)	1.46×10^{22}	5.73×10^{9}
Y (exported)	Exported emergy $(B + M_t)$[c]			
ELE	Electricity: 1880 GW · h	7.36×10^{15} (J)	1.45×10^{21}	6.10×10^{8}
GDP	Gross domestic product (US$)	1.03×10^{10} ($)		
W[d]	Waste emergy		2.98×10^{21}	
P_2	World E_m/$ ratio, used in imports		1.66×10^{12}	
P_1	Macao E_m/$ ratio		2.38×10^{12}	

[a] This calculation method is based on the method of H. T. Odum (1996)

[b] The total emergy used does not include tourism emergy so as to avoid double counting. The tourist consumption will increase the amount of imported materials (F)

[c] This equation is deduced from Fig. 2.5

[d] Waste emergy here includes the emergy of sewage and solid wastes



The dashed lines refer to the monetary flows of the system.

Fig. 2.5 Summary of Macao's emergy flows in 2004. Values with no units of measurement are $\times 10^{20}$ sej year^{-1} (Lei and Wang 2008b)

and the production component (P) accounted for about 56.5 % of the imported emergy (F). Exported products that supported the human labor expended in the production activities as well as in providing other services totaled 136.29×10^{20} sej. Textiles were the main exported products, and accounted for 96.5 % of the total exported emergy (Lei and Wang 2008b).

Macao has a high wastes emergy ($W = 30.8 \times 10^{20}$ sej) based on combining the embodied emergy in wastes (29.8×10^{20} sej) with the treatment inputs and services (1.0×10^{20} sej) for the sewage and solid wastes that the city produces. Reducing Macao's environmental impact despite its limited area has become an important goal to ensure long-term sustainable development. We will discuss this further in Chap. 6.

"Unfair" emergy exchanges, in which one partner in the exchange benefits more than the other, bring plentiful net emergy benefits into the boundaries of Macao's system. In 2004, Macao's gross net emergy surplus was 146.78×10^{20} sej. This resulted from the following four exchange processes (Table 2.4, Fig. 2.6):

1. The tourism income was $\$8.10 \times 10^9$; the equivalent emergy was 134.56×10^{20} sej, whereas Macao only provided 41.74×10^{20} sej of goods and services for the tourists. This resulted in an emergy surplus of 92.82×10^{20} sej.
2. The imported labor and services cost $\$1.43 \times 10^9$. Macao paid for 34.04×10^{20} sej of this emergy, and gained only 23.77×10^{20} sej of emergy in return. The net emergy loss was therefore 10.27×10^{20} sej in this exchange process.

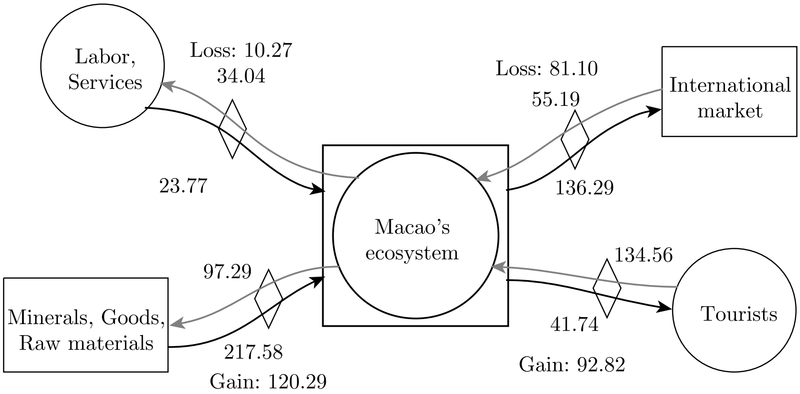


Fig. 2.6 Summary of the emergy exchange between Macao and the external systems that interact with the city in 2004 (all values are $\times 10^{20}$ sej. Macao's net emergy totaled 146.78×10^{20} sej in 2004)

3. The embodied emergy of imported goods and raw materials was 217.58×10^{20} sej, with only \$$4.09 \times 10^9$ (converted to 97.29×10^{20} sej) paid for this exchange. Thus, these imports generated a net emergy surplus of 120.29×10^{20} sej in import process.
4. The exports of products to the international market equaled 136.29×10^{20} sej, which earned Macao \$$3.32 \times 10^9$ (for an equivalent emergy of 55.19×10^{20} sej). Thus, a net emergy loss of 81.10×10^{20} sej occurred as a result of these exports.

The exchanges between Macao's tourism industry and the large number of tourists produced a large excess of emergy. Since this point is so important, we will discuss it further in Chap. 4.

2.3 Comparison of the Emergy-Based Indices of Five Cities

The preceding examination of Macao's emergy flows shows the insights into a city's ecosystem that can be obtained from emergy accounting. This approach provides additional insights when it is used to compare two or more cities. To provide an example of these insights, we compared the following four cities with Macao using data from previous studies (Lei et al. 2008):

- Taipei (Huang and Hsu 2003)
- Zhongshan (Zhao 2002)
- Miami-Dade County (Woithe 1995)
- 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 6.3 million, having increased by about 25 % during the past decade. On average, approximately 2×10^6 m^2 of building floor space per annum were constructed between 1981 and 1998, mainly in response to rapid urbanization. During recent decades, Taiwan has experienced rapid economic growth, with associated expansion of urban areas and high rates of per capita consumption. Its GDP reached \$211.21 × 10^9 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 from other countries due to a lack of indigenous 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 1.34 million, of whom about 60 % live in the city, compared with 18.3 % in 1978. During the past 20 years, Zhongshan has experienced rapid growth in the manufacturing and electronics industries and in various types of services, accompanied by rapid expansion of its urban area. Its GDP reached \$3.78 × 10^9 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 U.S. 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 5060 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, and was purchased using income obtained from tourism, transfer payments from the U.S. federal government, investment activities, and retirement benefits from the large population of retired citizens who live in this region (Woithe 1995). We could not find GDP data for 1990, but its GDP had reached \$7.15 × 10^9 in 2003 (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 the 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 is 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 for the city alone, but in 1992, the GDP of Puerto Rico was \$39.8 × 10^9 (Doherty 1995).

Table 2.5 compares the main emergy indicators for Macao with those of the four other cities. The comparison of the trade emergy and net emergy are shown in Fig. 2.7. We found that all five cities had a positive net emergy (i.e., they imported more emergy than they exported), and were therefore expanding. Taipei imported the most emergy and also had the highest net emergy.

Table 2.5 Comparison of the emergy indices for Macao, Taipei (China Taiwan), Zhongshan (China), Miami-Dade County (USA), and San Juan (Puerto Rico)

Index	Expression	Macao (2004)	Taipei (2002)	Zhongshan (2000)	Miami-Dade County (1990)	San Juan (1992)
Area	A (km^2)	22.75	2325.00	1800.00	5060.00	537.00
Population	P ($\times 10^6$)	0.47	6.30	1.34	1.94	1.71
Renewable emergy flows	R ($\times 10^{20}$ sej)	0.32	5.02	2.52	23.1	0.39
Non-renewable emergy flows[a]	N ($\times 10^{20}$ sej)	3.53	11.20	2.58	0.07	0.00
Imported emergy flows	F ($\times 10^{22}$ sej)	2.42	11.8	2.69	6.38	3.76
Emergy used (U)	$R + N + F$ ($\times 10^{22}$ sej)	2.46	11.9	2.74	6.61	3.76
Exported emergy (Y)	$P_1 E_3 + B + N_2$ ($\times 10^{22}$ sej)	1.80	2.92	1.88	0.05	1.43
Emergy yield ratio (EYR)	Y/F	0.743	0.249	0.699	0.082	0.380
Emergy exchange ratio (EER)	F/Y	1.35	4.02	1.43	121.90	2.63
The percentage of total emergy use accounted for by renewable resources (%Ren)	$(R/U) \times 100$ %	0.13	0.42	0.92	3.50	0.10
Proportion of total emergy use accounted for by purchased emergy	F/U	0.984	0.986	0.981	0.965	0.999

Table 2.5 (*Continued*)

Index	Expression	Macao (2004)	Taipei (2002)	Zhongshan (2000)	Miami-Dade County (1990)	San Juan (1992)
Proportion of total emergy use accounted for by free emergy	$(R + N_0)/U$	0.0157	0.0055	0.0186	0.0351	0.0010
Emergy investment ratio (EIR)	$F/(R + N)$	6.27	7.24	5.27	2.75	96.41
Emergy density	U/A ($\times 10^{13}$ sej m^{-2})	89.39	5.12	1.52	1.31	7.01
Emergy use per person	U/P ($\times 10^{16}$ sej person^{-1})	5.28	1.89	2.05	3.41	2.20
Environmental loading ratio (ELR)	$(F + N)/R$	743	234	108	27.6	964
E_m/\$ ratio	U/GDP ($\times 10^{12}$ sej \$$^{-1}$)	2.39	0.56	7.25	1.60	1.64
% of emergy use accounted for by electricity	(ELE/U) × 100 %	5.06	15.51	11.43	51.30	11.80
Fuel use per person	Fuel/P ($\times 10^{15}$ sej person^{-1})	3.63	1.6	2.59	4.38	7.75
Emergy sustainability index (ESI)	EYR/ELR ($\times 10^{-3}$)	1.00	4.30	6.50	0.30	0.39
Net emergy (NE)	$R + F - Y$ ($\times 10^{22}$ sej)	0.63	8.88	0.83	6.56	2.33
Net emergy ratio (NER)	$(R + F - Y)/U$	0.25	0.75	0.30	0.99	0.62
Waste emergy ratio	W/U	0.12	0.15	0.18	–	–

[a] Non-renewable resources (N) can be divided into three parts: N_0 is the dispersal into the rural environment, N_1 is concentrated use, and N_2 is direct exports (H. T. Odum 1996)

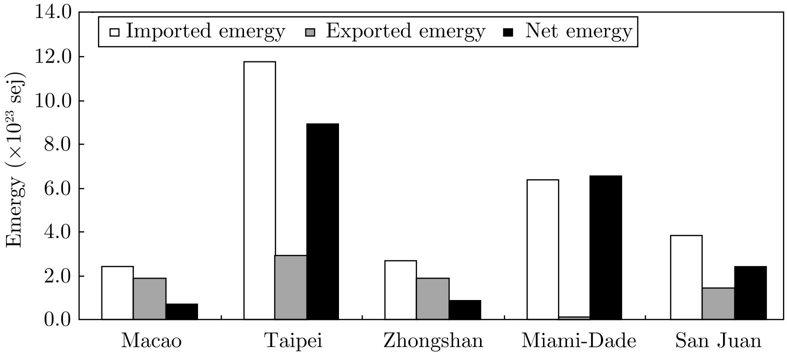


Fig. 2.7 A comparison of the import and export of emergy (and the resulting net emergy) of the five cities

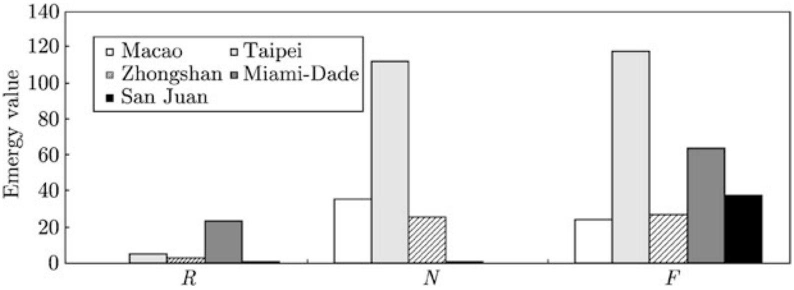


Fig. 2.8 Comparison of the renewable (R), non-renewable (N), and purchased emergy flows (F) for the five cities. *Note*: The three parameters use different units on the *y-axis*. R ($\times 10^{20}$ sej), N ($\times 10^{19}$ sej), F ($\times 10^{21}$ sej)

2.3.1 Comparison of the Emergy Components

Figure 2.8 visually compares the emergy components shown in Table 2.5. Because of a lack of local resources, all five cities imported most (more than 95 %) of the emergy they used (U). The proportion of U accounted for by purchased emergy ranged from 96.5 % (Miami-Dade County) to 99.9 % (San Juan), indicating that all five cities imported most of their used emergy.

2.3.2 Emergy Density, Emergy Use, and Fuel Use per Person

Figure 2.9 compares the emergy density, emergy use, and fuel use per person of the five cities. Macao's emergy use per person in 2004 (5.28×10^{16} sej; Table 2.5) was the highest of the five cities by a considerable margin (Fig. 2.9). Macao has one of the highest population densities in the world (Maritime Administration 2005),

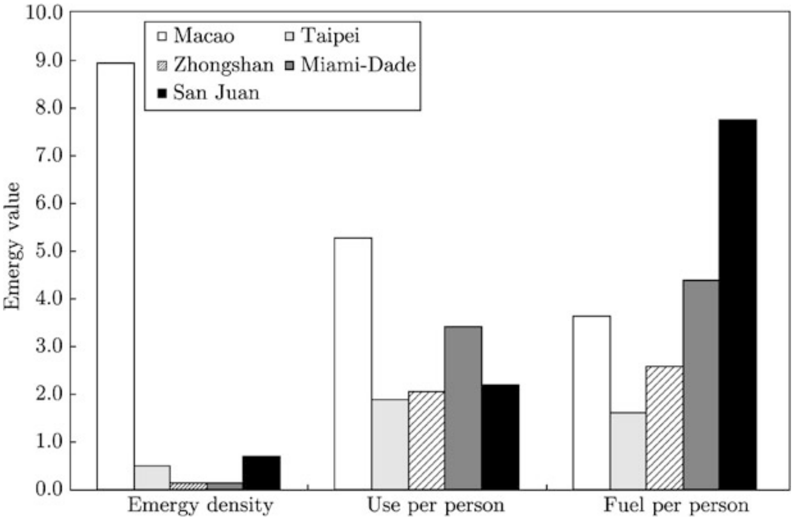


Fig. 2.9 Comparison of the emergy density and the per capita emergy and fuel use for the five cities. *Note*: The three parameters use different units on the *y-axis*. Emergy density ($\times 10^{14}$ sej/m^2), emergy use per person ($\times 10^{16}$ sej/person), fuel per person ($\times 10^{15}$ sej/person)

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 Miami-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 per capita fuel emergy use (7.75×10^{15} sej person^{-1}) of the five cities. Macao also had the highest emergy use per person. The large number of tourists consume many materials and services, thereby increasing the imported emergy. However, in contrast with the approach described in Chap. 1, this consumption was calculated by adding the average emergy consumption by local residents in order to use the same approach as in the other four studies and make the results comparable.

2.3.3 E_m/\$ Ratio and Emergy Investment Rate (EIR)

The E_m/\$ ratio represents the relationship between the emergy used and GDP, and it can thus indicate the levels of development and industrialization of a city (Table 2.5). A higher ratio implies that more resources would be consumed to produce the same GDP. Macao's E_m/\$ ratio in 2004 was 2.39×10^{12} sej \$$^{-1}$, which was lower than that of Zhongshan (7.25×10^{12} sej \$$^{-1}$) but higher than that of Miami-Dade County (1.60×10^{12} sej \$$^{-1}$), San Juan ($1.64 \times 10^{12}$ sej \$$^{-1}$), and Taipei ($0.56 \times 10^{12}$ sej \$$^{-1}$). In 2000, Zhongshan had experienced rapid industrial

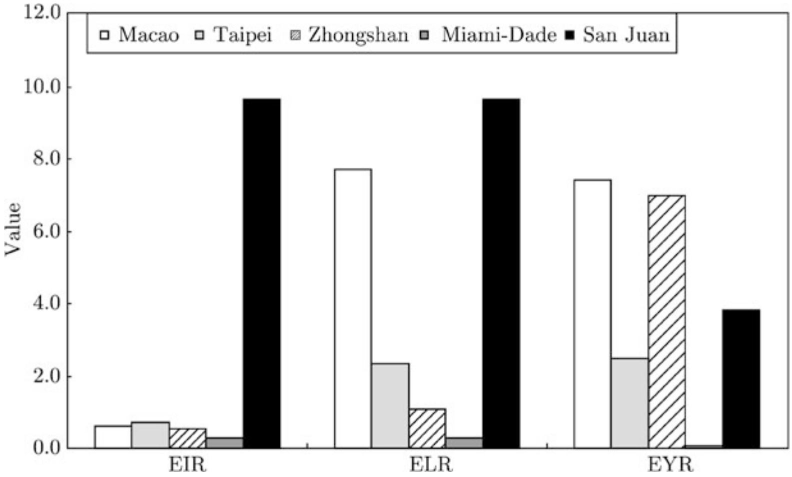


Fig. 2.10 Comparison of the emergy investment ratio (EIR), emergy yield ratio (EYR), and environmental loading ratio (ELR) of the five cities. *Note*: The three parameters use different units on the *y-axis*. ELR and EIR ($\times 10^2$), EYR ($\times 10^{-1}$)

development accompanied by intense use of a rich supply of natural resources, so its $E_m/\$$ ratio was the highest of the five cities. The high $E_m/\$$ ratio 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.

EIR equals the flows of imported emergy (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, ranging from 2.75 (Miami-Dade County) to 96.41 (San Juan).

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 a 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 of output to the market outside the system. Miami-Dade County had the lowest ratio (0.08) of the five cities (Fig. 2.10).

2.3.4 Emergy Exchange Ratio (EER)

Emergy is an appropriate measure for evaluating the benefits to a nation from all types of international exchange (H. T. 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 2.5 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 emergy 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 exported 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.

2.3.5 Renewable Resources Proportion (%Ren), Emergy Sustainability Index (ESI), and Net Emergy Ratio (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). %Ren is the proportion (%) of the total energy driving a process that is derived from renewable sources (i.e., $\%\text{Ren} = (R/U) \times 100\ \%$). In the long run, only processes with high %Ren are sustainable (Brown and Ulgiati 1997). %Ren 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 (H. T. Odum 1996). Table 2.5 and Fig. 2.11 show that %Ren ranged from 0.1 % (San Juan) to 3.5 % (Miami-Dade County). Because these values are so small, comparing the cities based exclusively on %Ren would be ineffective because it would neglect the enormous emergy input that plays such an important role in these cities.

The ESI values of all five cites were well below 1, ranging from 0.3×10^{-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 2.5, Fig. 2.11). The NER values 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. However, 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.

2.4 Time Series for Macao's Emergy and Emergy-Based Indices

Emergy accounting can also be used to examine how a system's use of resources changes over time. Table 2.6 summarizes the changes in Macao's key emergy components and indicators from 1983 to 2004. In the remainder of this section, we will

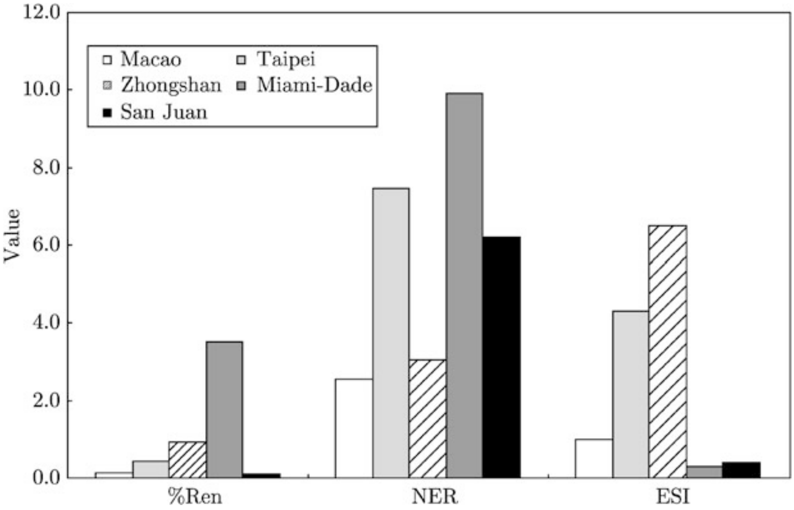


Fig. 2.11 Comparison of the proportion of renewable emergy (%Ren), the net emergy ratio (NER), and the emergy sustainability index (ESI) of the five cities. *Note*: The three parameters use different units on the *y-axis*, NER ($\times 10^{-1}$), ESI ($\times 10^{-3}$)

discuss the trends for individual emergy components and indicators during this period.

2.4.1 The Components of Emergy Use

Figure 2.12 presents the variations of the components of Macao's total emergy use (U) from 1983 to 2004. The emergy of raw materials was the largest imported item for Macao, and it increased as Macao's economy grew. The emergy of minerals was the second-largest imported item from 1985 to 1993, when food became the second-largest import. Table 2.6 summarizes the emergy components and indicators used for the years under study.

Figure 2.13 presents the variations in emergy flows in Macao's renewable and non-renewable resources and in water, electricity, and fuel consumption from 1983 to 2004. The non-renewable resources declined from 7.2×10^{20} sej in 1983 to 5.4×10^{20} sej in 1988, then decreased to 3.60×10^{20} sej in 1990 due to decreasing excavation of marble, and then remained at roughly the same level until 2004. The water and electricity consumption increased slowly throughout this period as the population increased. Fossil fuel consumption increased every year, from 4.98×10^{20} sej in 1983 to 16.70×10^{20} sej in 2004.

Figure 2.14 presents the variations in Macao's imports of minerals, raw materials, goods, food, and services from 1983 to 2004. The imports of food and services rose slowly during this period as the population increased. The emergy of goods fluctuated within a narrow range, but increased from 21.70×10^{20} sej in 1983 to

Table 2.6 Changes in Macao's emergy components and emergy-based indicators from 1983 to 2004

Item	Equation	1983	1985	1988	1990	1993	1995	1997	2000	2004
Renewable emergy ($\times 10^{20}$ sej)	R	0.274	0.264	0.258	0.253	0.270	0.266	0.286	0.286	0.271
Non-renewable emergy ($\times 10^{20}$ sej)	N_0	7.20	7.20	5.40	3.60	3.60	3.60	3.60	3.60	3.60
Imported emergy ($\times 10^{20}$ sej)	F	92.98	111.04	149.07	184.88	243.15	213.44	192.65	183.72	241.34
Total emergy used ($\times 10^{20}$ sej)	U	100.45	118.50	154.73	188.73	247.02	217.31	196.54	187.60	245.21
Exported emergy ($\times 10^{20}$ sej)	Y	71.44	92.06	118.29	133.07	132.94	120.00	107.17	135.62	178.03
Waste emergy ($\times 10^{20}$ sej)	W	8.74	8.95	9.76	10.30	21.00	21.70	25.08	26.50	49.42
%Ren	$(R/U) \times 100$	0.27	0.22	0.17	0.13	0.11	0.12	0.15	0.15	0.11
ESR (%)	$[(R+N_0)/U] \times 100$	7.44	6.30	3.66	2.04	1.57	1.78	1.98	2.07	1.58
EIR	$F/(R+N)$	12.4	14.9	26.3	48.0	62.8	55.2	47.0	47.3	62.3
ELR	$(N+F)/R$	366	448	598	745	915	817	687	655	904
Emergy density ($\times 10^{14}$ sej m^{-2})	U/area	6.47	7.00	9.14	10.90	12.80	10.35	9.16	7.39	8.92
Per capita emergy use ($\times 10^{14}$ sej person^{-1})	U/P	355.15	409.03	489.65	563.43	643.32	530.92	465.73	428.80	526.96
Per capita electricity use ($\times 10^{14}$ sej person^{-1})	Electricity/P	8.23	8.31	11.01	13.14	17.00	17.87	19.28	20.71	31.17
Per capita fuel use ($\times 10^{14}$ sej person^{-1})	Fuel/P	17.60	16.04	22.55	23.11	25.36	24.59	26.11	26.79	35.88
E_m/\$ ratio ($\times 10^{12}$ sej \$$^{-1}$)	U/GDP	8.76	8.66	6.64	5.78	4.36	3.18	2.66	3.03	2.38
EYR	Y/F	0.77	0.83	0.79	0.72	0.55	0.56	0.56	0.74	0.74
ESI ($\times 10^{-3}$)	EYR/ELR	2.10	1.85	1.33	0.97	0.60	0.69	0.81	1.13	0.82
Net emergy ($\times 10^{20}$ sej)	$F+R-Y$	21.81	19.23	31.04	52.06	110.49	93.70	85.77	48.39	63.58
Net emergy ratio	Net emergy/U	0.217	0.162	0.201	0.276	0.447	0.431	0.436	0.258	0.259

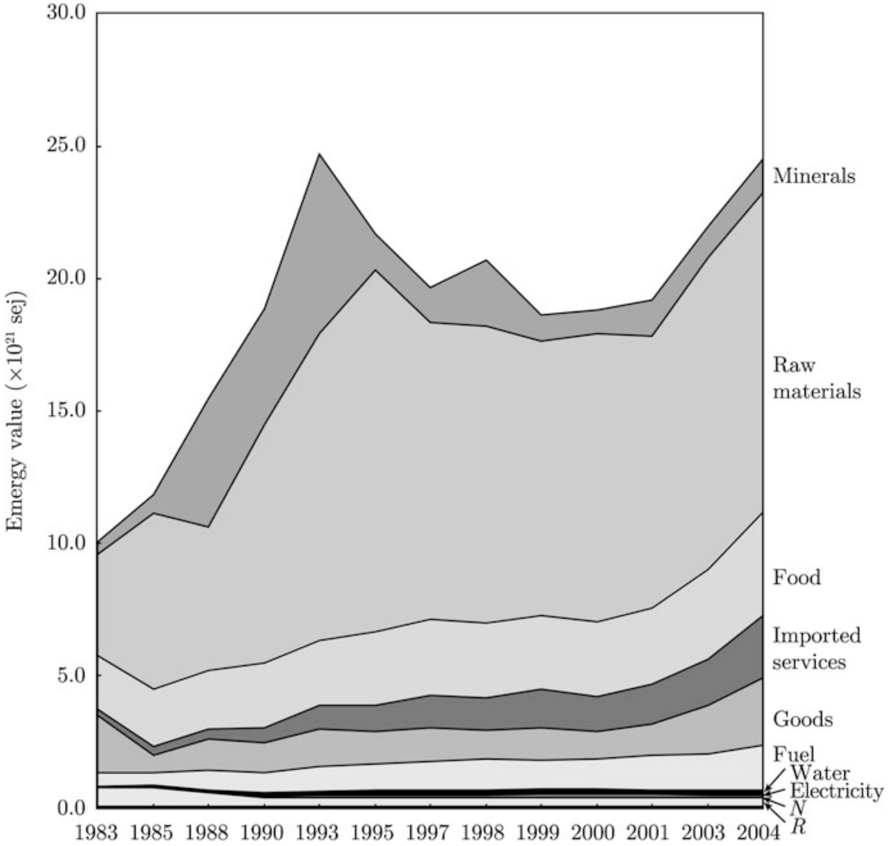


Fig. 2.12 Changes in the components of Macao's emergy use from 1983 to 2004

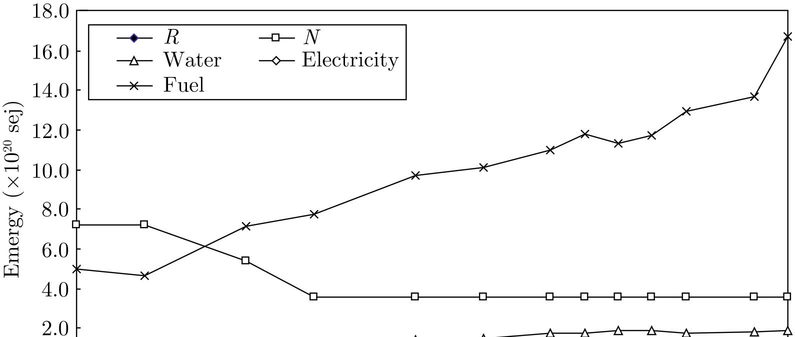


Fig. 2.13 The trends in emergy components (R, renewable resources; N, non-renewable resources; and water, electricity, and fuel) from 1983 to 2004

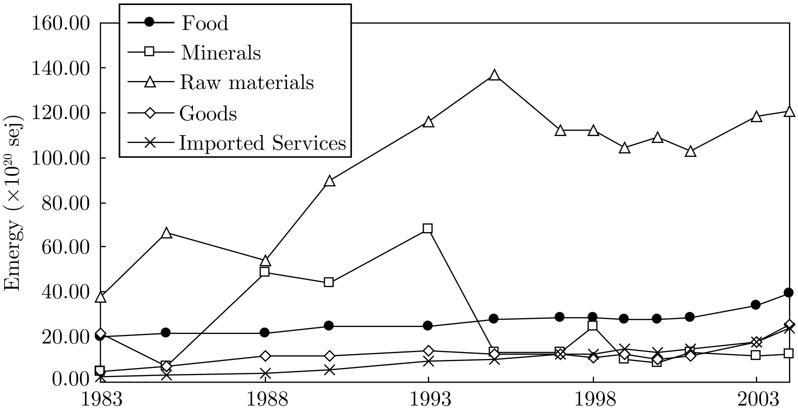


Fig. 2.14 Trends in Macao's imported emergy components from 1983 to 2004

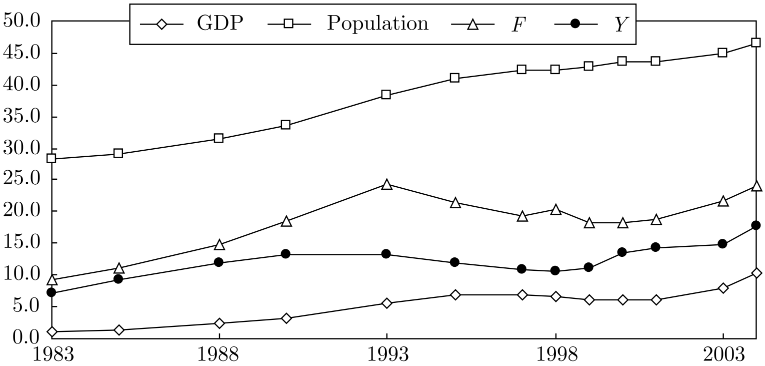


Fig. 2.15 Trends in Macao's GDP, population, imported emergy (F), and exported emergy (Y) from 1983 to 2004. *Note*: The four parameters use different units on the *y-axis*. GDP ($\times 10^9$ \$), Population ($\times 10^4$ persons), the other two parameters ($\times 10^{21}$ sej)

25.66×10^{20} sej in 2004, whereas the emergy of imported food rose from 20.00×10^{20} sej to 39.15×10^{20} sej.

The emergy of raw materials increased from 38.20×10^{20} sej in 1983 to a peak of 137.00×10^{20} sej in 1995, then decreased to 120.77×10^{20} sej in 2004. The emergy of minerals fluctuated during the study period, especially from 1985 to 1993, which was a period when infrastructure development and land reclamation were booming. The peak of Macao's development occurred in 1993, when mineral imports reached 50.93×10^{12} g, which was 5.28 times the 1992 value (9.65×10^{12} g) and 37.2 times the 1994 value (1.37×10^{12} g). In terms of the emergy value of these minerals, the value in 1993 (67.80×10^{20} sej) was 1.6 times the 1990 value (43.80×10^{20} sej), and 5.0 times the 1995 value (13.50×10^{20} sej). At that time, the high quantity of mineral imports raised the imported emergy (F), so the amount of emergy used (U) and the imported emergy (F) were also the highest in that year (Fig. 2.15).

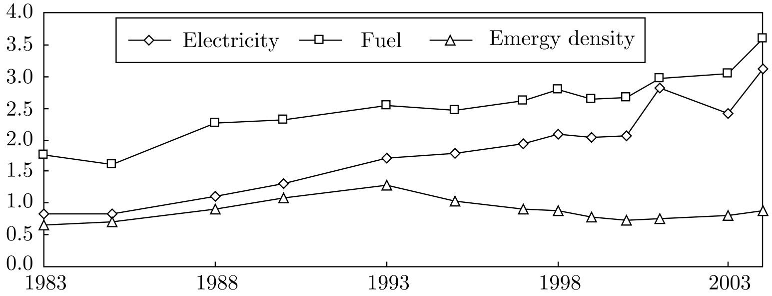


Fig. 2.16 Changes in Macao's per capita electricity and fuel consumption and its emergy density (U/area) from 1983 to 2004. *Note*: Per capita electricity and fuel emergy use the same units ($\times 10^{15}$ sej/person); emergy density uses different units ($\times 10^{15}$ m^{-2})

From 1983 to 1993, the population and GDP increased. During the same period, U, F and Y increased steadily (Fig. 2.15), while emergy density and average emergy also increased. After 1993, U, F, Y and emergy density began to decrease slowly until 2000, and then increased again (Fig. 2.16).

F increased from 92.98 × 10^{20} sej in 1983 to its peak of 243.15 × 10^{20} sej in 1993, decreased until 1999, and finally rose to 241.34 × 10^{20} sej in 2004. Simultaneously, Y increased from 71.44 × 10^{20} sej in 1983 to a peak of 132.94 × 10^{20} sej in 1993, decreased until 1999, and finally rose to 178.03 × 10^{20} sej in 2004. F increased more rapidly than Y, followed by GDP and population.

2.4.2 Per Capita Electricity Emergy, Fuel Emergy, and Emergy Density (*U*/area)

Macao's per capita electricity emergy increased from 8.23 × 10^{14} sej in 1983 to 31.17 × 10^{14} sej in 2004 (Fig. 2.16). During the same period, per capita fuel emergy increased from 17.60 × 10^{14} sej in 1983 to 35.88 × 10^{14} sej in 2004.

Macao's emergy density (U/area) increased from 6.47 × 10^{14} sej in 1983 to 12.80 × 10^{14} sej in 1993, declined to 7.39 × 10^{14} sej in 2000, and finally increased to 8.92 × 10^{14} sej in 2004. During this period, the population density decreased from 18 230 km^{-2} in 1983 to 16 961 km^{-2} in 2004 as a result of land reclamation.

2.4.3 %Ren and Emergy Self-sufficiency Ratio (ESR)

%Ren can be considered 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. For Macao, %Ren decreased steadily from 0.3 % in 1983 to 0.1 % in 2004 (Fig. 2.17). The city's ecosystem has a very low ability to provide sufficient emergy from inside its boundaries. R equaled only 2.71 × 10^{19} sej in

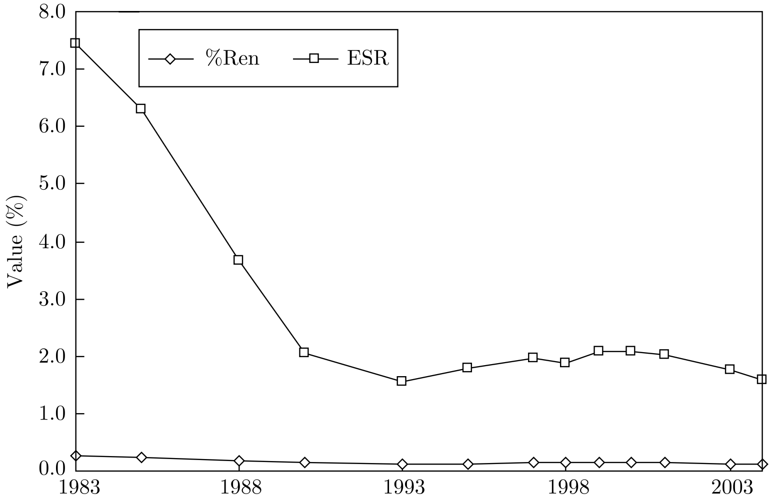


Fig. 2.17 Trends in Macao's proportion of renewable emergy (%Ren) and the emergy self-sufficiency ratio (ESR) from 1983 to 2004

2004. Thus, Macao's ESR, which equals $[(R + N_0)/U] \times 100\ \%$, was about 7.4 % in 1983, and decreased to 1.6 % in 2004.

2.4.4 Emergy Exchange Ratio (EER) and Emergy Yield Ratio (EYR)

EER can express the benefits of exchanges of emergy between Macao and its external environment. The larger the ratio, the more emergy Macao receives for every unit of emergy that it exports. EER varied greatly during the study period, increasing from 1.46 in 1983 to 2.42 in 1998, decreasing to 1.74 in 2001, and increasing to 2.11 in 2004 (Fig. 2.18). Simultaneously, EYR showed relatively little variation, decreasing from 0.77 in 1983 to 0.53 in 1998, then increasing to 0.74 in 2004.

2.4.5 Total Emergy Used (U), Emergy Money Ratio (E_m/\$), Proportion of Waste Emergy (W), and Per Capita Emergy Use

U increased from 1.00×10^{22} sej in 1983 to a peak of 2.47×10^{22} sej in 1993, decreased to 1.88×10^{22} sej in 2000, then increased to 2.45×10^{22} sej in 2004 (Fig. 2.19). The per capita emergy use increased from 3.55×10^{16} sej in 1983 to 6.43×10^{16} sej in 1993, declined to 4.29×10^{16} sej in 2000, and then increased to

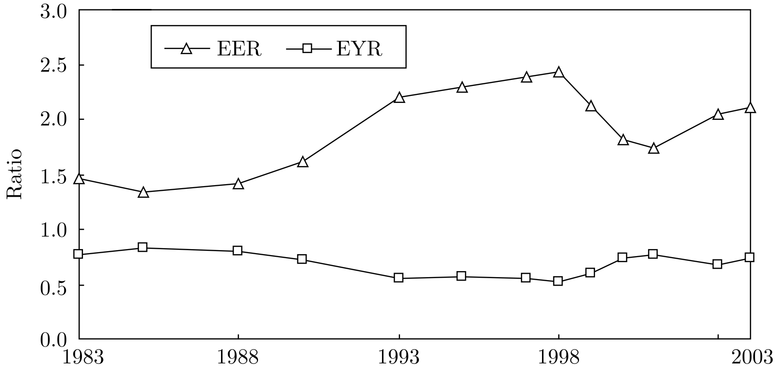


Fig. 2.18 Trends in Macao's emergy exchange ratio (EER) and emergy yield ratio (EYR) from 1983 to 2004

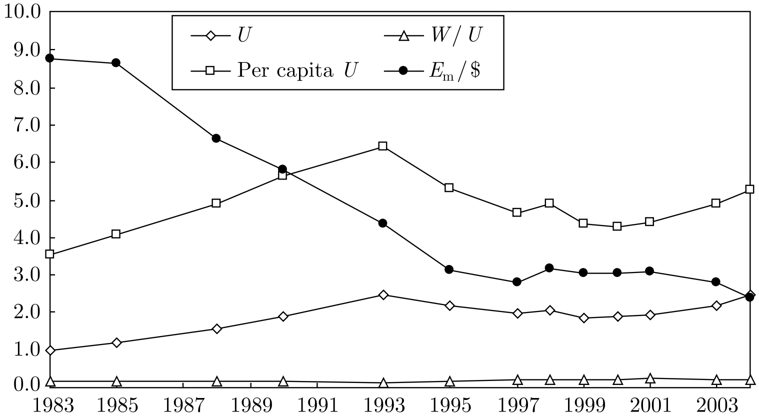


Fig. 2.19 Changes in Macao's total emergy used (U), the ratio of waste emergy to total emergy (W/U), the emergy money ratio ($E_m/\$$), and per capita U from 1983 to 2004. *Note*: The four parameters use different units on the *y-axis*. U ($\times 10^{22}$ sej), per capita U ($\times 10^{16}$ sej person^{-1}), $E_m/\$$ ($\times 10^{12}$ sej/\$ $^{-1}$)

5.27×10^{16} sej in 2004. $E_m/\$$ represents the relationship between the total emergy used and GDP. This ratio decreased steadily from 8.76×10^{12} sej \$$^{-1}$ in 1983 to 2.38×10^{12} sej \$$^{-1}$ in 2004, which was lower than the corresponding ratio for China in 2001 (4.94×10^{12} sej \$$^{-1}$; Zhao 2002) and higher than the ratio for the United States in 2000 (0.78×10^{12} sej \$$^{-1}$; Tilley 2005).

The gradual increase in waste emergy as a proportion of U during the study period (Fig. 2.19) indicated worsening environmental pressure. W/U increased from 0.16 in 1983 to 0.20 in 2004.

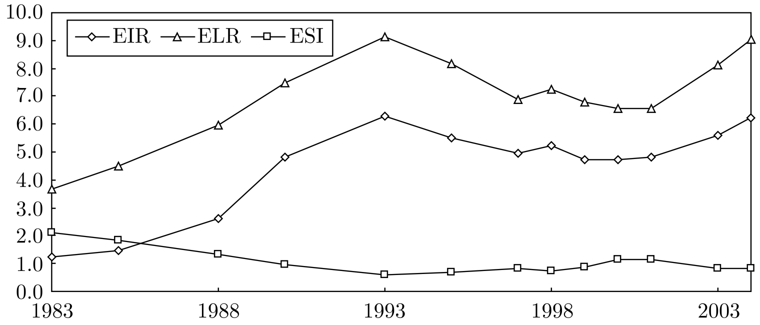


Fig. 2.20 Changes in Macao's emergy investment ratio (EIR), emergy loading ratio (ELR), and emergy sustainability index (ESI) from 1983 to 2004. *Note*: The three parameters use different units on the *y-axis*. EIR ($\times 10$), ELR ($\times 10^2$), ESI ($\times 10^{-3}$)

2.4.6 Emergy Investment Ratio (EIR), Environmental Loading Ratio (ELR), and Emergy Sustainability Index (ESI)

ELR is an indicator of the pressure on the local ecosystem and can be considered a measure of the level of ecosystem stress due to production activities (Ulgiati and Brown 1998). U and ELR fluctuated similarly in Macao during the study period. In the mid-1990s, GDP increased with increasing EIR and increasing ELR. $E_{\mathrm{m}}/\$$ decreased from 8.76×10^{12} sej $\$^{-1}$ in 1983 to 2.38×10^{12} sej $\$^{-1}$ in 2004, which indicates that during this period, GDP increased faster than U, a phenomenon that also occurred in most other countries (Brown and Ulgiati 1997). Macao's per capita emergy used was 3.55×10^{16} sej in 1983, reached a maximum of 6.43×10^{16} sej in 1993, decreased to 4.29×10^{16} sej in 2000, and increased to 5.27×10^{16} sej in 2004. Macao's ESI was very small throughout the study period (less than 0.0021) and decreased from 1983 to 1993. In 1993, EYR remained stable while ELR reached its peak (915), thus ESI decreased to its lowest value (0.0006); thereafter, ESI increased until 2000 (0.0011) and then decreased until 2004 (0.0008; Fig. 2.20, Table 2.6). ESI was only 0.001 in 2004, versus values of 0.036 for Italy (Cialani et al. 2005) and 0.120 for Sweden (Hagström and Nilsson 2005). This comparison clearly indicates that Macao has a highly developed consumer system compared with the other countries. ESI decreased as the economy grew (i.e., as GDP increased) during the study period (Fig. 2.15).

Emergy-based indices are very different in cities than they are in large natural areas, where free renewable resources can be used to support the ecological system (Lan et al. 2002). This can be seen by comparing the value of an index such as ELR for Macao (904 in 2004) with that for the U.S. (5.85 in 2000; Professor Mark Brown, University of Florida, 2005, personal communication). Although the indices for small, dense areas such as Hong Kong, Singapore, and Macao differ from those of countries with vast territories, such as the United States, and are therefore not directly comparable, the magnitude of the difference in these values can still provide

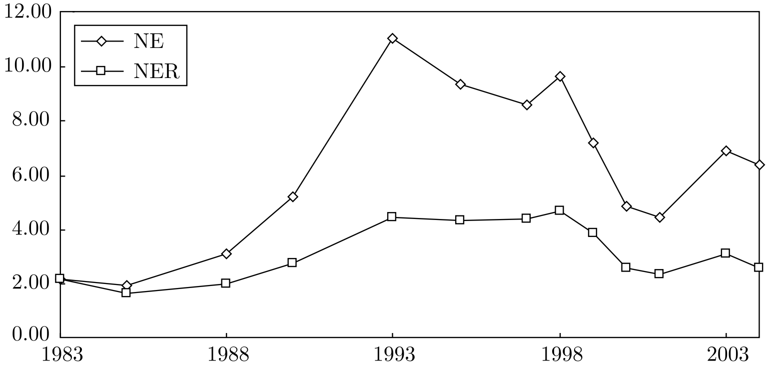


Fig. 2.21 Changes in Macao's net emergy (NE) and net emergy ratio (NER) from 1983 to 2004. The two parameters use different units on the *y-axis*. NE ($\times 10^{21}$ sej), NER ($\times 10^{-1}$)

insights into the relative ecological characteristics of two areas and can guide the development of suitable policies to improve sustainability.

2.4.7 Net Emergy (NE) and the Net Emergy Ratio (NER)

The NER values shown in Table 2.6 are a measure of the overall emergy exchange conditions for a study area. A high NER indicates a system that imports more emergy than it exports, accompanied by increased NE and improved welfare. NE increased from 2.18×10^{21} sej in 1983 to a peak value of 11.05×10^{21} sej in 1993, then decreased to 4.45×10^{21} sej in 2001, and increased again to 6.36×10^{21} sej in 2004 (Fig. 2.21, Table 2.6). These changes represent the benefits due to expansion of tourism and increased emergy imports. During the same time period, NER increased from 0.22 in 1983 to 0.45 in 1993 (Fig. 2.21, Table 2.6), which indicated that Macao earned a large part of its net emergy through international trade. Finally, NER decreased to 0.26 in 2004. In Macao, NER is therefore more an index of locally sustainable production than it is an emergy yield ratio.

Money is not real wealth, since real wealth includes food, minerals, fertile land, housing, information, arts, and other important factors (Ulgiati et al. 2004). Balancing the exchange of emergy between exports and imports may lead to more sustainable development for Macao in the long run (Brown and Ulgiati 2001) and may increase the real wealth of its citizens. The survival of a system depends on having a net emergy surplus (Ulgiati et al. 1995; Lei et al. 2006).

2.5 Time Series for Emergy Flows of Italy, Sweden, and Macao of China

Emergy synthesis can also be employed to evaluate macroeconomic conditions and the environment of regions ranging from cities that cover a large area to entire countries. In this section, we demonstrate this approach by comparing Macao with two other regions, with particular attention on how the emergy indicators changed over time in response to growth of a region's economy. In this comparison, we used research results for Italy (Cialani et al. 2005), Sweden (Hagström and Nelsson 2005), and Macao (our research). Table 2.7 summarizes the data used in this analysis. NE for all three regions remained positive throughout the study period (Figs. 2.22 to 2.27), which means that all three regions obtained more emergy than they exported. The positive NE will be advantageous for a region's development in the long term.

Macao is located on the western coast of China's Pearl River estuary. Although it is currently a special administrative region of China, Macao reflects more than 400 years of cultural exchanges between the western world and China. In 2004, Macao had a population of 465 333 and covered an area of 27.5 km^2 (DSEC 1984–2011, 2005 data). Tourism, manufacturing, the financial and insurance sector, and the construction and real estate sector were the four pillars of Macao's economy. Macao's economy has maintained a robust growth rate for the past three decades, largely due to sustained prosperity from the tourism sector.

Italy covers an area of 301 230 km^2, and had a population of 58 103 033 in 2002. It has a highly diversified modern industrial economy. Because of Italy's small size and high population, most of the raw materials needed by its industries and more than 75 % of its energy requirements are imported.

Sweden is one of the largest countries in Europe, with an area of 447 760 km^2. In 2002, its population was 9 001 774. Throughout the 20th century, Sweden has achieved one of the highest standards of living in the world as a result of its mixture of high technology and extensive natural resources. In particular, the combination of large size and small population make Sweden less dependent on imported emergy than many other countries of comparable size.

The three regions in this case study clearly represent different types of system: Macao is a high-density, high-consumption city, Italy is a developed country with insufficient internal natural resources to support its economy, and Sweden is rich in natural resources and has a small population. Table 2.7 summarizes the emergy indicators of all three countries or region since 1983 (Macao), 1984 (Italy), and 1956 (Sweden).

2.5.1 %Ren

Renewable resources are an important component of any system's sustainability because they will be replaced by natural processes after the passage of sufficient time. However, renewable resources are endangered by socioeconomic develop-

Table 2.7 Comparison of emergy indicators (EYR, emergy yield ratio; ELR, environmental load ratio; ESI, environmental sustainability index) and the net emergy (NE) and net emergy ratio (NER) for Macao of China, Italy, and Sweden. R, emergy in renewable resources; N, emergy in non-renewable resources; F, external inputs; Y, emergy yield ($= R + N + F$); U, total emergy consumption; %Ren, % of total emergy consumption provided by renewable emergy

Countries or region	Year	R ($\times 10^{21}$ sej)	N ($\times 10^{22}$ sej)	F ($\times 10^{23}$ sej)	Y ($\times 10^{23}$ sej)	U ($\times 10^{23}$ sej)	Population ($\times 10^{6}$)	GDP ($\times 10^{10}$ \$)	E_m/\$ ($\times 10^{12}$ sej \$$^{-1}$)
Macao of China	1983	0.03	0.07	0.09	0.06	0.10	0.28	0.12	8.76
	1985	0.03	0.07	0.11	0.09	0.12	0.29	0.14	8.66
	1988	0.03	0.05	0.15	0.12	0.16	0.32	0.23	6.64
	1990	0.03	0.04	0.19	0.13	0.19	0.33	0.33	5.78
	1993	0.03	0.04	0.24	0.13	0.25	0.38	0.57	4.36
	1995	0.03	0.04	0.21	0.12	0.22	0.41	0.69	3.13
	1997	0.03	0.04	0.18	0.11	0.19	0.42	0.70	2.66
	1998	0.03	0.04	0.20	0.11	0.21	0.42	0.65	3.12
	1999	0.03	0.04	0.18	0.11	0.19	0.43	0.61	3.06
	2000	0.03	0.04	0.18	0.13	0.19	0.44	0.62	3.03
	2003	0.03	0.04	0.22	0.15	0.22	0.45	0.79	2.782
Italy	1984	121.00	30.00	5.37	2.36	9.58	56.60	39.00	2.46
	1989	121.00	35.70	7.89	3.12	12.60	56.70	86.60	1.46
	1991	121.00	50.20	8.16	3.09	13.80	56.80	115.00	1.20
	1995	121.00	47.80	10.10	4.56	15.40	57.30	107.00	1.44
	2000	121.00	44.20	16.90	11.40	22.60	57.80	116.00	1.86
	2002	121.00	34.80	16.00	9.30	20.70	57.30	126.00	1.75
Sweden	1956	45.20	30.10	0.86	0.61	1.46	7.34	0.85	17.20
	1972	45.20	50.80	1.71	1.18	2.43	8.13	3.14	7.74
	1988	45.20	28.40	2.21	1.67	2.80	8.46	17.10	1.63
	1996	45.20	30.60	2.60	2.12	3.22	8.84	28.00	1.15
	2002	45.20	30.80	3.06	2.62	3.70	8.94	36.00	1.03

Table 2.7 (*Continued*)

Countries or region	Year	Emergy/capita ($\times 10^{16}$ sej)	EYR	ELR	ESI	%Ren	NE ($\times 10^{22}$ sej)	NER
Macao of China	1983	3.55	0.73	366.09	0.002	0.27	0.31	0.31
	1985	4.09	0.78	448.24	0.002	0.22	0.19	0.16
	1988	4.90	0.80	597.66	0.001	0.17	0.31	0.20
	1990	5.63	0.68	832.21	0.001	0.13	0.52	0.28
	1993	6.43	0.61	972.48	0.001	0.11	1.10	0.45
	1995	5.31	0.70	882.29	0.001	0.12	0.94	0.43
	1997	4.42	0.81	651.62	0.001	0.15	0.77	0.41
	1998	4.91	0.70	726.91	0.001	0.14	0.97	0.47
	1999	4.35	0.78	679.24	0.001	0.15	0.72	0.39
	2000	4.29	0.91	655.19	0.001	0.15	0.53	0.28
	2003	4.90	0.92	812.81	0.001	0.12	0.69	0.31
Italy	1984	1.69	1.78	6.91	0.260	12.63	42.20	0.44
	1989	2.23	1.61	9.47	0.170	9.60	59.60	0.47
	1991	2.44	1.76	10.46	0.170	8.77	62.70	0.45
	1995	2.69	1.59	11.72	0.140	7.86	67.30	0.44
	2000	3.90	1.33	17.65	0.080	5.35	67.10	0.30
	2002	3.60	1.29	16.13	0.080	5.85	78.70	0.28
Sweden	1956	1.99	1.71	2.23	0.765	30.96	5.52	0.38
	1972	2.99	1.42	4.36	0.326	18.60	7.42	0.31
	1988	3.31	1.26	5.19	0.244	16.14	8.63	0.31
	1996	3.64	1.24	6.13	0.203	14.04	7.95	0.25
	2002	4.13	1.21	7.17	0.169	12.22	7.63	0.21

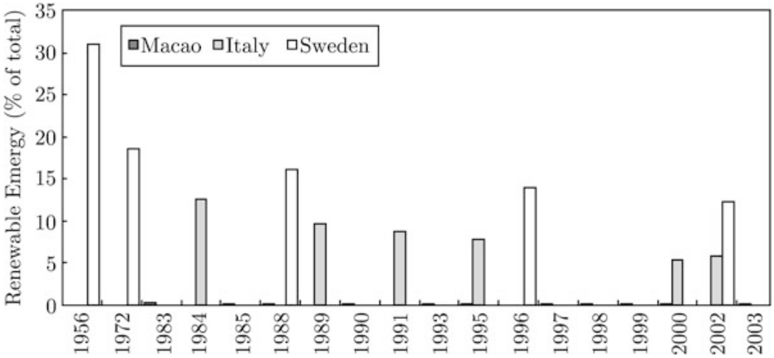


Fig. 2.22 Time series for the proportion of total emergy use in Macao of China, Italy, and Sweden accounted for by renewable emergy (%Ren) (Lei et al. 2012)

ment when the rate of development is greater than the rate of replenishment. These resources must therefore be carefully managed to avoid exceeding the natural environment's capacity to replenish them.

Unlike non-renewable resources such as fossil fuels, which cannot be replenished on human time scales, renewable resources have a sustainable yield if they are used wisely (Lei et al. 2012).

The value of %Ren differed greatly between the three regions (Table 2.7). Sweden is rich in natural resources, so its %Ren has been consistently higher than that of Italy (by more than 200 %), and was two orders of magnitude higher than that of Macao, which has few internal natural resources. These differences persisted throughout the study period (Fig. 2.22). However, %Ren has decreased over time for all three regions, since non-renewable fossil fuels have been the main energy source for modern society.

2.5.2 Emergy Use Per Capita

Figure 2.23 suggests that of the three regions, only Macao has shown a significant decrease in per capita emergy consumption during the study period, largely because of a shift to a non-industrial structure that is focused on the tourism sector. Macao nonetheless consumed more emergy per capita than Italy or Sweden throughout most of the study period.

2.5.3 Emergy Money Ratio ($E_m/\$$)

We found that $E_m/\$$ decreased throughout the study period (Fig. 2.24). Macao has had the highest $E_m/\$$ since about 1983, due to high NE as a result of inflows from tourism (Lei and Wang 2008a).

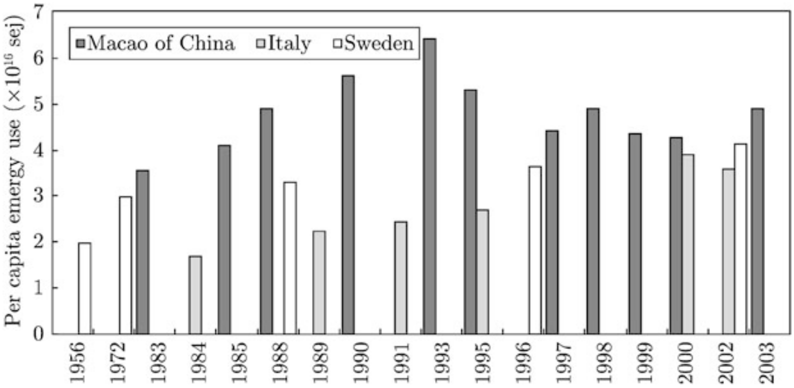


Fig. 2.23 Time series for the per capita emergy use for Macao of China, Italy, and Sweden

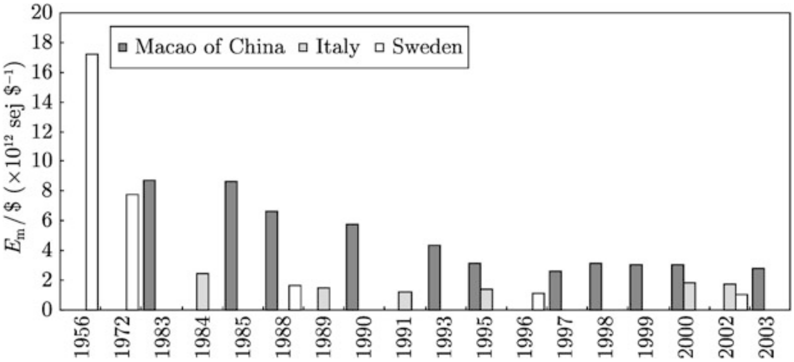


Fig. 2.24 Time series for the $E_m/\$$ for Macao of China, Italy, and Sweden

2.5.4 Integrated Emergy Index: The Environmental Sustainability Index (ESI)

The ESI of all three regions was considerably less than 1 throughout the study period (Table 2.7, Fig. 2.25), indicating that they are all highly developed consumer-oriented economies according to the criteria of Brown and Ulgiati (1997). In addition, ESI has declined throughout the study period for all three regions, as each economy depended on increasing flows of non-renewable emergy from outside the system, supported by increased imports of purchased energy and materials. Nonetheless, because ESI focuses mainly on the ecological aspects of a system, it has been criticized by economists as providing a weaker assessment of socioeconomic development than $E_m/\$$ (Hau and Bakshi 2004). Economists point out two shortcomings of ESI: First, ESI has declined rapidly in recent decades as economies have become increasingly dependent on flows of non-renewable emergy and on imports of purchased emergy and materials, thereby making the meaning of ESI unclear and

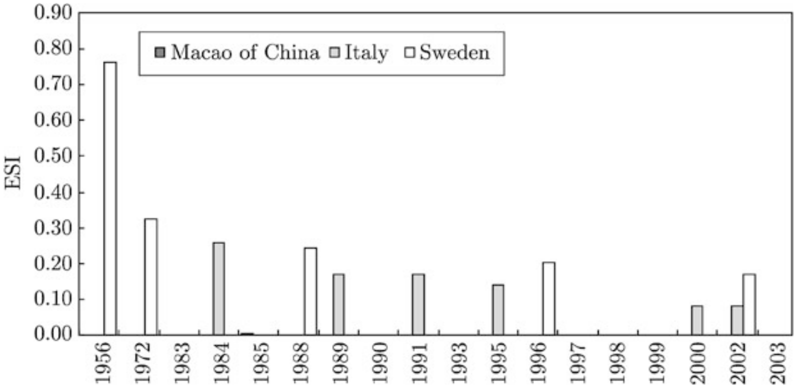


Fig. 2.25 Time series for the environmental sustainability index (ESI) for Macao of China, Italy, and Sweden (Lei et al. 2012)

implicit. Second, differences in scale between regions make it difficult to compare emergy flows between regions.

Figure 2.25 and Table 2.7 show that Macao's ESI is tiny compared with those of Italy and Sweden, and has declined starting in about 1983. This decline occurred because EYR remained steady while ELR increased (Lei et al. 2012). The ESI for Italy declined from 0.26 in 1984 to 0.08 in 2002. The ESI for Sweden's economy declined from 0.77 in 1956 to 0.17 in 2002.

At least two aspects of an analysis based on ESI must be improved to permit an adequate evaluation of a system's sustainable development: First, although all of a system's outputs are valuable from an ecological perspective in emergy accounting, we do not yet know how to make full use of these outputs. Thus, not all the system's outputs can be adequately valued in our analysis. Some are currently harmful and have negative impacts, such as waste and pollution, but this may change when improved technology lets us recover and reutilize these outputs. Because of limitations on current technology, not all systems with a high EYR are beneficial or promote sustainable development. Second, market prices of purchased inputs are influenced by many factors, such as market forces, cultural differences, ethical considerations, and the location of a system. Therefore, the same EYR value can have different consequences for a system because of differences in market factors (Lu et al. 2005). Third, the meaning of a specific ESI value is not clear; although a value closer to 1.0 is clearly more sustainable than a value closer to 0, the number alone does not tell us whether the system is sustainable in an absolute sense.

For these reasons, simplistic comparisons of ESI between systems can produce misleading results. At a national scale, ELR would be small when mostly renewable resources are used, but at a city scale, ELR is usually high due to large imports of renewable resources from outside the urban system, leading to a small ESI. However, for a region such as Sweden that is rich in natural resources, the imports of renewable emergy from outside a given city may be sustainable. Macao is a highly developed consumer-oriented economy with tremendous consumption of non-renewable

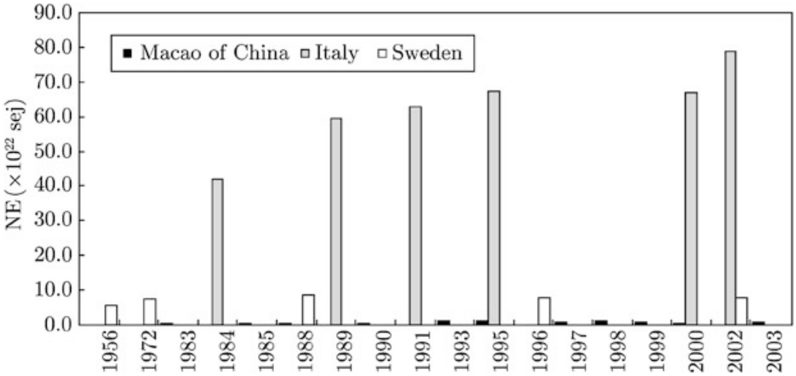


Fig. 2.26 Time series for the net emergy (NE) of Macao of China, Italy, and Sweden (Lei et al. 2012)

resources. These results show that ESI is an unsuitable index because of its limitations for describing the complexity of a system: it conceals too many differences between regions and between scales.

2.5.5 Storage Indices: NE and NER

The net emergy (NE) increased for all three regions during the study period (Fig. 2.26, Table 2.7). The NE was proportional to the population of each region (Table 2.7), so Macao's NE was much lower than those of Sweden and Italy. We found NE $>$ 0 for all three regions throughout the study period, which means that their emergy capital was sustainable based solely on a consideration of the results within each region's boundaries. This is a clearer result than the uncertain results of the ESI analysis.

NER appears to be the most reasonable measure of a system's sustainability in the long term. NER declined from 0.44 in 1982 to 0.28 in 2002 for Italy (Fig. 2.27, Table 2.7). For Macao, NER was 0.31 in 1983, increased to a peak of 0.47 in 1997, then oscillated until it returned to its original level (0.31) in 2003. The NER of Italy and Sweden has decreased in recent decades, though Italy's ELR has remained higher than Sweden's throughout the study period. Decreasing NER means that the accumulation of real emergy wealth is slowing. These results demonstrate that both ESI and NER have followed the same declining trend at a national scale, but that they sometimes followed a different pattern at different scales. The greater NER oscillation of Macao is to be expected, since small systems such as cities tend to oscillate more than large systems such as nations (H. T. Odum 1996).

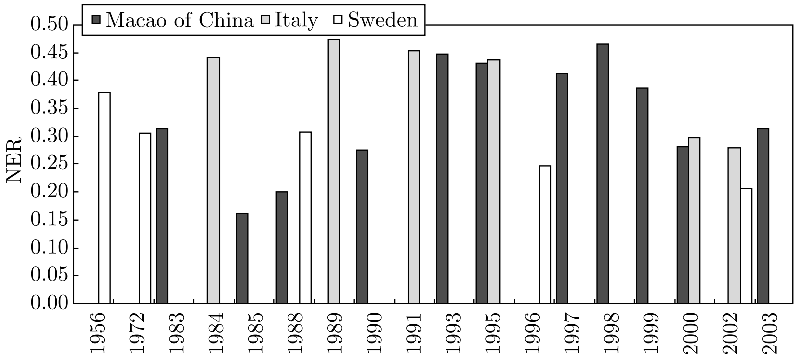


Fig. 2.27 Time series for the net emergy ratio (NER) of Macao of China, Italy, and Sweden (Lei et al. 2012)

2.6 Statistical Analyses of Emergy-Based Indicators of Macao

Table 2.8 shows the results of our correlation analysis between the various emergy statistics that we calculated. In summary:

Significant positive correlations: These combinations represented indicators that both increased over time. The following indicators were positively correlated with development processes: imported emergy, emergy used (U), exported emergy, emergy investment ratio (EIR), environmental loading ratio (ELR), per capita emergy used, per capita electricity emergy used, per capita fossil fuel used, and the ratio of electricity to U.

No significant correlation: The following indicators were not correlated with development processes: the ratio of renewable resources to emergy used, and the ratio of wastes to emergy used.

Significant negative correlations: These indicators represent indices that tend to decrease as development progresses. The following indicators were negatively correlated with development: the $E_{\mathrm{m}}/\$$ ratio, the emergy yield ratio (EYR), ESI, and net emergy (NE).

2.7 Conclusions

Compared with mature ecosystems, limited urban ecosystems are relatively immature due to their rapid growth and inefficient use of resources. In addition, cities rely more strongly on ecosystems beyond the city limits than is the case for more self-contained natural ecosystems. As cities draw more and more resources from distant areas, they also accumulate large amounts of materials, including wastes discharged into the surrounding systems. Odum has observed that cities are among the most heterotrophic ecosystems in the biosphere, and this also appears to be true in all of the cities we studied (Macao, Zhongshan, Taipei, Miami-Dade County, and San Juan).

Table 2.8 The results of correlation analysis (Pearson's correlation coefficient) for the primary emergy components and indicators for Macao (Lei and Wang 2008a)

No.	Emergy-based indicators	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Imported emergy (*F*)															
2	Emergy used (*U*)	++														
3	Exported emergy (*Y*)	++	++													
4	Ratio of renewable resources (*R*) to *U*	0	0	0												
5	EIR	++	++	++	0											
6	ELR	++	++	++	0	++										
7	Ratio of wastes (*W*) to *U*	0	0	0	0	0	0									
8	Per capita emergy used	++	++	+	0	++	++	−								
9	Per capita electrical emergy	++	++	++	0	++	+	+	0							
10	Per capita fuel emergy	++	++	++	0	++	++	0	0	++						
11	E_m/$ ratio	−−	−−	−	0	−−	−−	0	0	−−	−−					
12	EYR	0	0	0	0	0	0	0	0	0	0	0				
13	Ratio of electricity emergy to *U*	0	0	+	0	−	0	++	0	++	++	−−	0			
14	ESI	−−	−−	−	0	−−	−−	0	−−	−	−	++	0	0		
15	NE	0	0	0	0	0	0	0	0	0	0	0	−−	0	−−	

Notes: −− and −, significant negative correlations at $P < 0.01$ and $P < 0.05$, respectively (two-tailed test). 0, no significant correlation. ++ and +, significant positive correlations at $P < 0.01$ and $P < 0.05$, respectively (two-tailed test)

From the point of view of systems ecology, cities are self-regulating systems and may be seen as super-organisms that were created for the benefit of human beings and for sustaining their livelihood.

Our research demonstrated that by relying on an imbalance between imports and exports, Macao has absorbed large amounts of emergy through inflows of negative entropy to support not only its survival, but also its booming development. EER has proven to be a useful indicator for studying emergy exchanges; an EER value of more than 1 means that the exchange brings an emergy surplus to the system, and this surplus can also be used in Macao's tourism industry. The imported emergy (F), emergy density, fuel and electricity emergy, and ELR of cities are much higher than those of natural systems. Dense cities usually have a very high ELR due to their lack of internal natural resources available for use. For a micro-ecosystem such as that of a small city, oscillations in emergy can always be found (H. T. Odum 1996); this variability reflects the instability and fragility of the system. Macao is now getting richer in emergy, but further studies will probably show that this has had a high environmental cost: local environmental resources have decreased greatly, and the need to import large quantities of emergy from surrounding regions may have had serious negative impacts on these regions.

We investigated the evolution of Macao's system from 1983 to 2004 by means of ecological energy accounting. Time-series analyses helped to reveal the dynamics of Macao's ecological economy. This approach can be applied to any country or region, provided that reliable data is available, and this highlights the importance of updating national analyses yearly to ensure the detection of long-term trends. An agreed-upon, standardized, and homogeneous procedure for emergy analysis is necessary to allow a reliable evaluation of a region's performance over time, as well as comparisons among different regions (e.g., using relevant emergy indicators such as ESI, NE, NER, ELR, and $E_{\mathrm{m}}/\$$). The comparison between Macao, Italy, and Sweden showed that emergy accounting significantly improves our understanding of the performance of a regional economy over time, and it reveals differences in the patterns for a given region.

We also employed correlation analysis to reveal that some of the emergy-based indicators that we used in the present study were positively and negatively correlated, whereas others showed no significant correlation.

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Chapter 3
Emergy Synthesis and Simulation for Macao

System dynamics was developed as a field of study in the 1950s by Jay W. Forrester of the Sloan College of the Massachusetts Institute of Technology. It is a methodology and a mathematical modeling technique for framing, understanding, and discussing complex issues and problems (Sterman 2000). System dynamics helps to conceptualize and rationally analyze the structure, interactions, and modes of behavior of complex systems and sub-systems, thereby allowing researchers to explore, assess, and predict the impacts of these systems in an integrated, holistic manner. The most famous and most widely read application of system dynamics is presented in *The Limits to Growth* (Meadows 1972), which was commissioned by the Club of Rome to model the interactions of five global variables: the world's population, industrialization, pollution, food production, and resource depletion. The book used the system dynamics method to simulate the consequences of interactions between the Earth's natural and human systems. The goal was to explore the possibility of a sustainable feedback pattern that would be achieved by altering trends in the growth of the five variables and simulating the future world, and the approach echoed worldwide concerns about sustainable development in a way that would balance socioeconomic and environmental concerns.

A system dynamics analysis is performed by defining feedback loops, variables that describe flows along the loops, and equations that quantify the flows. In this approach, a feedback loop is defined as a closed chain of cause and effect. The researcher defines three kinds of variables: level variables that accumulate a flow over a continuous time period; rate variables that represent a flow during given time period; and auxiliary variables that identify rate variables. The three kinds of variables are linked by integral, differential, or other types of equations (Ford 1999). The elements of system dynamics diagrams are feedbacks, accumulations of flows into stocks, and time delays. Most computer simulation applications based on system dynamics models rely on the use of the Vensim software (www.ventanasystems.com) or the STELLA software (Isee Systems 2012), both of which can handle the mechanisms of system dynamics.

System dynamics provides a way of thinking (a paradigm) and associated communication and computer simulation tools that will help us design policies that pro-

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vide durable solutions to our problems. In the policy-design cycle, system dynamics lets researchers compare competing policies through simulations rather than directly, in a real-world environment where experimentation would be dangerous and unethical. Researchers can then use the results of the policy simulation experiments to inform real-world policy choices (Meadows et al. 1992).

As previous chapters have shown, Macao is a tourist city with a dense population and a shortage of natural resources. It is therefore the kind of system that can be described well by system dynamics models. Macao has experienced six periods of land reclamation since 1866, supported by large-scale imports of sand and rock from China. By simulating the emergy trends using the STELLA dynamic modeling software, we have predicted the evolution of trends in Macao's development for more than 22 years (starting in 2003) as a result of past and future land reclamation. In 2025, the city's economy is estimated to be 15 times its current size as a result of Macao's territorial expansion. The city's emergy exports will increase slowly and then gradually stabilize, the population will reach about 600 000, and the area covered by Macao will expand to nearly 40 km^2.

Note: Because of the large number of parameters defined in this book, we have provided a summary of all parameters and their definitions in Appendix C.

3.1 Introduction to Ecological Emergy Accounting in a System Dynamics Context

Modeling and simulation offer quantitatively rigorous ways of connecting theories with reality, and help us to understand how systems are organized and how they function. Howard Odum and Odum (2000) provided guidance that has helped many researchers to improve their models, and have particularly provided tools to help researchers account for the periodic oscillations that occur in most ecosystems. Costanza and Gottlieb (1998, 2001) have also developed many kinds of models using STELLA, which is an icon-based programming language specifically designed to support the modeling of dynamic ecological and socioeconomic systems. Huang and Chen (2005) successfully used Odum's system model (H. T. Odum and Odum 2000) to simulate the temporal and spatial distribution of Taipei's land use as part of their analysis of the city's urban hierarchy and developmental trends. Their preliminary findings indicated that intensive and diversified emergy sources were used to build the structure and enhance the metabolism of Taipei's urban area (Huang and Chen 2005). In our study of Macao, we applied H. T. Odum and Odum's (2000) emergy accounting approach to investigate Macao's socioeconomic and environmental emergy changes from 1983 to 2003, then used the STELLA software to create a model for forecasting Macao's emergy changes during the land reclamation that is predicted to occur during the period from 2003 to 2025.

Urban ecosystems function as the habitat for a large number of people living in close proximity. They also serve as centers for residential and commercial activities. Urban ecosystems have the same basic kinds of interactions (i.e., resource flows within the system and between the system and its external environment) as other ecosystems, but no urban ecosystem is ecologically self-contained or self-sufficient. In particular, all cities are sustained by biophysical processes that occur mainly outside the boundaries of the city. As a result of the flow of materials and energy from rural areas to suburban areas and from suburban areas to the urban area, energy is concentrated within the dense urban area. The energy and materials that provide Macao's life-support system are provided by areas outside the city, and particularly by mainland China.

3.2 Simulation Methodology Using the STELLA Modeling Software

The STELLA software (Costanza and Gottlieb 1998, 2001) can create dynamic visual models for studying a wide variety of problems. The software allows for "real-time" analysis and provides a simulation environment in which researchers can gain insights into complex systems (Meadows et al. 1992). We created a dynamic model of Macao in STELLA and used regression analysis, performed using the SPSS statistical software (SPSS Inc., Chicago, IL), to simulate the emergy trends for Macao. For a regression equation expressed in the following form (Shun 1999):

$$y = f(x) \tag{3.1}$$

where x is the independent variable, y is the dependent variable, and the simulation error μ_i for every value of y (y_i) is given by

$$\mu_i = y_i - \overline{y_i} \tag{3.2}$$

where y_i represents the actual value and $\overline{y_i}$ is the simulated value. The mean simulation error can be obtained by

$$\overline{\mu} = \frac{\sum u_i f_i}{\sum f_i} \quad (i = 1, 2, \ldots, n) \tag{3.3}$$

where f_i is the frequency of error μ_i. This mean error $\overline{\mu}$ should be added to $\overline{y_i}$ to calibrate the final result (Shun 1999), as described in Sect. 3.4 of the present chapter. The actual emergy values in various categories (obtained during our study) were used to calibrate $\overline{\mu}$.

Most of the data used in this chapter were provided by DSEC (http://www.dsec.gov.mo/Home.aspx?lang=en-US) and the Environment Council of Macao (ECM 2004).

3.3 Land Use and Reclamation in Macao

The history of Macao (Macao Information Bureau 2008) can be traced back to the Qin Dynasty (221 to 206 BC), when the region now called Macao came under the jurisdiction of Panyu County, in Nanhai Prefecture (present-day Guangdong). The first recorded inhabitants of the area were people seeking refuge from invading Mongols during the Southern Song Dynasty from 1127 to 1229 AD (Ng and Yang 2005). Under the Ming Dynasty (1368 to 1644 AD), fishermen migrated to Macao from Guangdong and Fujian provinces.

Macao did not develop as a major settlement until the Portuguese arrived in the 16th century (Chan 2000). In 1535, Portuguese traders obtained the rights to anchor their ships in Macao's harbors and to carry out trading activities, though not the right to stay onshore. Around 1552–1553, they obtained temporary permission to erect storage sheds onshore in order to dry out goods drenched by sea water. The Portuguese soon built rudimentary stone houses around the area now called Nam Van (Fung 1999). At this time, Macao was an island, but a sandbar gradually connected the island to the mainland via a narrow isthmus. Land reclamation in the 17th century made Macao and its isthmus into a peninsula, and a barrier gate was built to mark the separation between the peninsula and mainland China. Pre-colonial records show that Macao's area totaled only 2.78 km^2, but the city began to expand rapidly as a result of Portuguese settlement.

By the late 17th century, Macao had already become an internationally renowned commercial port, and was undergoing non-stop urban development. During the 17th century, some 5000 slaves lived in Macao, in addition to 2000 Portuguese and 20 000 Chinese (Hao 2011). The Portuguese continued to pay an annual tribute to China until 1863 in order to stay in Macao.

Following the Opium War (1839 to 1842), Portugal occupied Taipa (in 1851) and Coloane (in 1864). Macao officially became a territory under Portuguese administration shortly thereafter (Ng and Yang 2005).

Land growth as a result of reclamation accelerated during the last quarter of the 20th century. The land reclamation has been most rapid in the Taipa and Coloane areas. In the mid-19th century, Macao underwent urbanization, transforming from a fishing village into a city, and the gradual development of Macao's central district at that time led to high demand for land reclamation. Macao has experienced six major periods of land reclamation since 1866.

Table 3.1 summarizes the changes in Macao's area as a result of land reclamation since 1840. The earliest reclamation on the Macao peninsula began in 1863, when the bay opposite the Macao Governor's house was filled in. The bays along the western shore were then filled in from 1866 to 1910, followed by the Inner Harbor near the western shore of Macao from 1919 to 1924 and finally the eastern and the southern shores of the Macao peninsula from 1923 to 1938. In 1919, two small islands (Taipa Grande and Taipa Pequena) were combined through reclamation. The reclamation of Coloane occurred between the 1930s and the 1970s and after 1992, mainly in the northwestern corner of Coloane. After 1980, the government conducted the reclamation at the southeastern Macao Peninsula and Taipa. In addition, a project began in 1992 to expand the city's area by 1.9 km^2 and to establish two artificial lakes in Nam Van. The lands of Macao International Airport and the Macao Jockey Club were also produced by land reclamation. In Coloane, the Concordia Industrial Park, with a total area of 0.33 km^2, appeared after 1992 as the result of several years of reclamation (Ng and Yang 2005).

Table 3.1 The main land reclamation periods in Macao's history

Period	Macao Peninsula	Taipa	Coloane
1863	Reclamation of the bay opposite the Macao Governor's house		
1866 to 1910	Reclamation of the bays on the western shore		
1919 to 1924	Reclamation of the Inner Harbor near the western shore	Reclamation resulted in combining of two small islands, Taipa Grande and Taipa Pequena	
1923 to 1938	Reclamation of the eastern and southern shores of the Macao peninsula		
1930 to 1970			Reclamation mainly of the northwestern corner of Coloane
1980 to 1990	Reclamation of the southeastern Macao Peninsula	Reclamation near Taipa	
Since 1992	A project began in 1992 to expand the area by 1.9 km^2 and create two artificial lakes	The land of Macao International Airport and the Macao Jockey Club was formed by land reclamation	The Concordia Industrial Park, with a total area of 0.33 km^2, was created after several years of reclamation

Table 3.2 shows how Macao's area expanded from 2.78 km^2 in 1840 to 16.92 km^2 in 1986 (Miao et al. 1988). The latest reclamation period happened from 1986 to 1996, and increased the city's area by 4.48 km^2. Most of Macao's current land area is the result of a string of land reclamation projects that were launched back in the early 20th century. In 1986, Macao's land area stood at just 16.92 km^2. It reached 27.50 km^2 in 2004. Historical records showed that sand and rock imports increased tremendously during these reclamation periods (DSEC 1986–1995).

3.4 Simulation Results and Analyses

Figure 3.1 is a concise emergy-flow diagram of Macao's environment and economy that summarizes the main emergy flows (Lei and Wang 2008b).

Current predictions suggest that Macao will reclaim even more land in the coming years to satisfy its development needs (Macao Daily News 2006). In 2010, plans were announced for an additional 3.5 km^2 of land reclamation in Macao, to be carried out over 5 years and divided into six phases. These new areas will cover an area

Table 3.2 The change in Macao's total area since 1840 (Ng and Yang 2005)

Year	Area (km^2)				
	Macao Peninsula	Taipa	Coloane	Cotai	Total area
1840	2.78	–	–	–	2.78
1851	2.78	2.30	–	–	5.08
1864	2.78	2.30	5.90	–	10.98
1912	3.40	2.30	5.90	–	11.60
1936	5.20	2.60	6.00	–	13.80
1957	5.50	3.30	6.30	–	15.10
1986	6.00	3.80	7.10	–	16.92
1991	6.50	4.00	7.60	–	17.32
1996	7.70	5.80	7.60	–	21.40
1999	7.80	6.20	7.60	–	23.80
2001	8.50	6.20	7.60	3.50	25.80
2003	8.70	6.20	7.60	4.70	27.30
2004	8.80	6.40	7.60	4.70	27.50

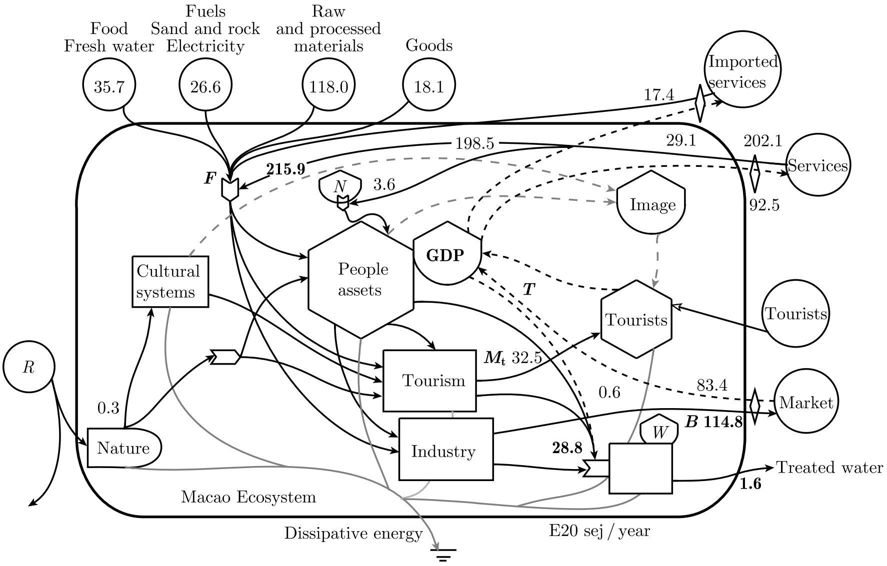

Fig. 3.1 A concise emergy-flow diagram for the Macao ecosystem in 2003 (all values are $\times 10^{20}$ sej). *Image* represents reputation and other information that attracts tourists. B = exported production, F = imported emergy, M_t = emergy consumed by tourists, N = non-renewable resources, R = renewable resources, T = number of tourists, W = waste emergy. ——, material emergy flow; - - - -, monetary emergy flow; – – –, image flow that attracts tourists (Lei and Wang 2008b)

east of the Outer Harbour Ferry Terminal, an area south of Avenida Sun Yat Sen, and the northern side of Taipa Island (Secretary for Transport and Public Works 2011).

For the system dynamics analysis of Macao described in this chapter, we chose the period from 2003 to 2025 for our simulation. The materials used for reclamation are mainly large-scale imports of sand, rocks, and other construction materials from China. Using the SPSS software, we analyzed the per capita trends for the main emergy categories between 1983 and 2003 (Table 3.3). First, we correlated the main emergy categories during this period with time and population to detect any long-term trends (Table 3.4), and then we selected the independent variable (time or population) with the best fit (Table 3.5). The exceptions were for raw and processed materials, sand and rock, and food. For these categories, we assumed that time was inherently a more reasonable independent variable and could be easily defined as the simulation factor. Next, we performed multiple regressions to determine which of several equation forms provided the best fit to the available data; we have provided only a single example, for fuel emergy, to illustrate typical results of this analysis (Table 3.6). We selected the best regression equations according to two criteria: first, the equation had to be logical (i.e., it had to provide a plausible causal explanation for an observed trend), and second, it had to have a high goodness of fit (i.e., R^2). Table 3.7 provides the final results of the regressions that we retained based on these criteria, and Table 3.8 summarizes the error analysis (i.e., the difference between the actual and predicted values).

Table 3.7 presents the final regression equations that we used in our simulation of Macao's future emergy trends using the dynamic STELLA model and the equations that resulted from our analysis of the results in Tables 3.4 to 3.6. We found that the per capita fuel emergy, imported services emergy, and area were strongly and significantly correlated ($R^2 > 0.869$) with the year, and were thus correlated with the booming tourism and expanding urban area, both of which increased during the study period and both of which increased imports and consumption. Our results also show that Macao imported increasing amounts of labor and services during the study period. The per capita raw and processed materials emergy, goods emergy, and exported emergy (Y) were also significantly but less strongly correlated ($|r| > 0.585$) with the year, which shows that the trade in raw and processed materials and in goods was influenced by the scale of the manufacturing industry (Lei and Wang 2008a). In contrast, water and electricity emergy both increased with increasing population. Table 3.7 also reports the calibration value that must be added to the simulated results produced using Eq. 3.3. The last column of the table reports the results of the correlation analysis between the real and simulated values. We assumed in this analysis that the indigenous renewable and non-renewable resources remained constant. If the resulting correlation was not satisfactory (i.e., if $|r| < 0.58$), then we used the t-test to evaluate the results. Results that were significant on this basis are labeled "pass" (Lei and Wang 2008b).

Table 3.8 shows the results of a typical error analysis that compares the real versus the simulated per capita emergies (here, for fuel). The difference between the two was not significant ($P = 0.736$; two-tailed t-test); thus, the logarithmic model that we developed provided a realistic simulation of the observed values. The equa-

Table 3.3 Emergy values in the main categories for Macao from 1983 to 2003 for 11 representative years (Lei and Wang 2008b)

Year	Emergy per capita (sej)										
	Renewable	Non-renewable	Food	Water	Electricity	Fuel	Sand and rock	Raw materials	Goods	Imported services	Exported emergy
1983	9.67×10^{13}	25.46×10^{14}	7.07×10^{15}	2.10×10^{14}	0.41×10^{14}	1.76×10^{15}	1.72×10^{15}	1.35×10^{16}	7.67×10^{15}	0.92×10^{15}	0.62×10^{22}
1985	9.11×10^{13}	25.46×10^{14}	7.49×10^{15}	2.25×10^{14}	0.95×10^{14}	1.61×10^{15}	2.44×10^{15}	2.30×10^{16}	2.39×10^{15}	1.13×10^{15}	0.92×10^{22}
1988	8.18×10^{13}	18.64×10^{14}	6.96×10^{15}	2.99×10^{14}	0.72×10^{14}	2.26×10^{15}	15.4×10^{15}	1.71×10^{16}	3.77×10^{15}	1.28×10^{15}	1.18×10^{22}
1990	7.55×10^{13}	11.39×10^{14}	7.35×10^{15}	3.37×10^{14}	1.67×10^{14}	2.31×10^{15}	13.1×10^{15}	2.69×10^{16}	3.40×10^{15}	1.67×10^{15}	1.33×10^{22}
1993	7.02×10^{13}	10.75×10^{14}	6.49×10^{15}	3.67×10^{14}	1.88×10^{14}	2.54×10^{15}	17.7×10^{15}	3.02×10^{16}	3.59×10^{15}	2.33×10^{15}	1.33×10^{22}
1995	6.49×10^{13}	9.38×10^{14}	6.71×10^{15}	3.69×10^{14}	2.49×10^{14}	2.47×10^{15}	3.30×10^{15}	3.35×10^{16}	3.03×10^{15}	2.44×10^{15}	1.20×10^{22}
1997	6.77×10^{13}	8.80×10^{14}	6.83×10^{15}	4.10×10^{14}	2.39×10^{14}	2.61×10^{15}	3.11×10^{15}	2.66×10^{16}	2.92×10^{15}	2.95×10^{15}	1.06×10^{22}
1998	6.74×10^{13}	8.53×10^{14}	6.70×10^{15}	4.19×10^{14}	2.36×10^{14}	2.79×10^{15}	5.92×10^{15}	2.65×10^{16}	2.53×10^{15}	2.96×10^{15}	1.07×10^{22}
1999	6.39×10^{13}	8.52×10^{14}	6.49×10^{15}	4.33×10^{14}	2.61×10^{14}	2.63×10^{15}	2.28×10^{15}	2.42×10^{16}	2.84×10^{15}	3.33×10^{15}	1.11×10^{22}
2000	6.53×10^{13}	8.38×10^{14}	6.45×10^{15}	4.37×10^{14}	2.56×10^{14}	2.67×10^{15}	2.00×10^{15}	2.49×10^{16}	2.35×10^{15}	3.04×10^{15}	1.31×10^{22}
2003	6.02×10^{13}	8.23×10^{14}	7.56×10^{15}	4.12×10^{14}	2.30×10^{14}	3.05×10^{15}	2.65×10^{15}	2.63×10^{16}	4.04×10^{15}	3.88×10^{15}	1.47×10^{22}

Table 3.4 Pearson's correlation coefficient (r) for the relationships between the main emergy categories (per capita values) and the year and between these categories and the population. The correlations were calculated for the period from 1983 to 2003

Emergy category	Correlation coefficient (r)	
	Year	Population
Renewable	0.527	0.586
Food	−0.340	−0.454
Water	0.954*	0.963*
Electricity	0.917*	0.951*
Fuel	0.944*	0.928*
Sand and rock	−0.258	−0.264
Raw and processed materials	0.570	0.629
Goods	−0.501	−0.494
Imported services	0.987*	0.974*
Exported emergy	0.653	0.595

Values followed by an * are statistically significant ($p < 0.05$)

Table 3.5 The independent variables selected by the analysis of correlation coefficients in Table 3.4

Emergy category	Correlation coefficient (r)	Independent variable with the best fit
Fuel	0.944	Year
Imported services	0.987	Year
Water	0.963	Population
Raw and processed materials	0.570	Year
Goods	−0.501	Year
Sand and rock	−0.258	Year
Food	−0.340	Year
Electricity	0.951	Population
Exported emergy	0.653	Year
Area	0.968	Year
Waste emergy	0.983	Population

tions for all other parameters also showed no significant difference between the predicted and actual values, and were therefore retained in our analysis.

Table 3.9 shows the equations and the flows in the model that we created in STELLA. Table 3.10 shows the simulated trends from 2003 to 2025 (Lei and Wang 2008b).

Figure 3.2 presents the system diagram created for use in the STELLA simulation. The top rectangle represents the population of Macao, which is influenced by

Table 3.6 The regression curve forms and their goodness of fit (R^2) values for the example of per capita fuel emergy (y) as a function of the year (x) from 1983 to 2003. All regressions were significant at $p < 0.001$

Regression method	R^2	d.f.	F	b_0	b_1	b_2
Linear	0.891	9	73.72	1.6×10^{15}	6.2×10^{13}	–
Logarithmic	0.886	9	70.05	8.7×10^{14}	6.3×10^{14}	–
Inverse	0.746	9	26.42	2.9×10^{15}	-4.0×10^{15}	–
Quadratic	0.903	8	37.24	1.4×10^{15}	9.6×10^{13}	-1.0×10^{12}
Compound	0.857	9	53.78	1.6×10^{15}	1.0280	–
Power function	0.884	9	68.34	1.2×10^{15}	0.2836	–
Sigmoidal	0.765	9	29.29	35.6123	−1.9185	–
Growth	0.857	9	53.78	35.0309	0.0276	–
Exponential	0.857	9	53.78	1.6×10^{15}	0.0276	–

the birth rate, death rate, and immigration rate. The emergy values are expressed with respect to either the year or the population, depending on the results of our analysis in Table 3.7.

Running the STELLA model from 2003 to 2025 produced the simulated results shown in Table 3.11 and Fig. 3.3. When large amounts of sand and rock are imported periodically during land reclamation, the total emergy consumed by the system (U) and imported emergy (F) reach their peak, and the emergy density and emergy used per capita will fluctuate simultaneously. In 2025, U is predicted to reach 3.49×10^{22} sej, F will reach 3.45×10^{22} sej, and the exported emergy (Y) will reach 1.40×10^{22} sej as Macao's territory expands. Y will increase slowly and will reach a steady level, the population will reach 593 185, and the area of Macao will expand to 38.91 km^2. The waste emergy will reach 0.413×10^{22} sej. Macao will import more resources to support the needs of its population, and the per capita emergy used will gradually increase to 5.89×10^{16} sej, about 1.2 times the level in 2003. The emergy density will decrease slowly because the land area will increase faster than the U (Lei and Wang 2008b).

Brown and Ulgiati (1997) note that for a steady-state system the input emergy must equal the output (exported) emergy (i.e., $Y = R + N + F$), whereas Huang and Chen (2005) note that for an expanding system, the output emergy should be less than the input emergy (i.e., $Y < R + N + F$) and the emergy storage should increase. Our simulation results (Table 3.11) support these predictions. On the other hand, for a degrading system, it is reasonable to predict that the outflow emergy will exceed the inflow emergy ($Y > R + N + F$). Whether a system is expanding or shrinking thus depends on its emergy balance (Lei and Wang 2008b).

Since the gross emergy storage is not easy to calculate accurately for an urban system such as Macao, the emergy increase since 1983 can only be estimated by adding the emergy storage in each year, which provides a total value of 32.6×10^{22} sej by 2025, which equals 3.78 times the value in 2003 and 14.82 times the total emergy used (U) in 2003. The increased emergy storage comes from the construc-

Table 3.7 The regression parameters and calibration values for the models that we developed. The calibration value is the value produced using Eq. 3.3 that must be added to the simulated results. Results with an unsatisfactory regression coefficient ($R^2 < 0.58$) were further examined using the t-test; those that were significant ($p < 0.05$) are labeled “pass”

Emergy category	Curve form	Equation	Regression coefficient (R^2)	Calibration value	Correlation or t-test
Fuel	Logarithmic	$8.73661 \times 10^{14} + 6.29244 \times 10^{14} \ln(\text{Year} - 1980)$	0.886	-1.516×10^{13}	Pass
Imported services	Logarithmic	$-1.16307 \times 10^{15} + 1.42582 \times 10^{15} \ln(\text{Year} - 1980)$	0.869	-8.538×10^{13}	Pass
Water	Inverse	$7.92247 \times 10^{14} - (1.61151 \times 10^{20}/\text{Population})$	0.953	$+3.02 \times 10^{11}$	0.982
Raw and processed materials	Sigmoidal	$e^{37.96596291-[2.30734742603792/(\text{Year}-1980)]}$	0.636	$+7.216 \times 10^{14}$	Pass
Goods	Inverse	$2.13816 \times 10^{15} + 1.292 \times 10^{16}/(\text{Year} - 1980)$	0.585	-1.173×10^{14}	Pass
Sand and rock	Compound	$1.544 \times 10^{16} \sin^2(\text{Year}/6) \times \text{Round}[\sin^2(\text{Year} - 3)/6] + 4.66 \times 10^{13} \times (\text{Year} - 1983)$	–	Rise 0.022 % yearly	Near pass
Food	Compound	$7.07 \times 10^{15} \times 1.003356155^{(\text{Year}-2003)}$	–	Rise 0.336 % yearly	Pass
Electricity	Inverse	$6.11875 \times 10^{14} - (1.57825 \times 10^{20}/\text{Population})$	0.920	-3.402×10^{13}	0.943
Exported emergy	Sigmoidal	$e^{51.01696117-2.332783727/(\text{Year}-1980)}$	0.753	$+4.226 \times 10^{20}$	Pass
Area	Linear	$12\,772\,065.03 + 582\,995.3 \times (\text{Year} - 1980)$	0.937	-9.488×10^{4}	Pass
Waste	Linear	$-2.94049 \times 10^{21} + 1.28296 \times 10^{16} \times \text{Population}$	0.967	−5.37129E+20	Pass

Table 3.8 A typical example of the results of our error analysis, using the example of the real and simulated (using the logarithmic equation from Table 3.3) per capita fuel emergy from 1983 to 2003

Year	Per capita fuel emergy ($\times 10^{15}$ sej person^{-1})		Error terms		
	Real	Simulated	Error	Error/Real value	Error/Simulated value
1983	1.7607	1.56	1.96×10^{14}	0.11	0.13
1985	1.6051	1.89	-2.80×10^{14}	−0.18	−0.15
1988	2.2564	2.18	7.42×10^{13}	0.03	0.03
1990	2.3107	2.32	-1.20×10^{13}	−0.01	−0.01
1993	2.5366	2.49	4.89×10^{13}	0.02	0.02
1995	2.4676	2.58	-1.10×10^{14}	−0.04	−0.04
1997	2.6115	2.66	-4.50×10^{13}	−0.02	−0.02
1998	2.7942	2.69	1.02×10^{14}	0.04	0.04
1999	2.6304	2.73	-9.60×10^{13}	−0.04	−0.04
2000	2.6743	2.76	-8.40×10^{13}	−0.03	−0.03
2003	3.0547	2.85	2.08×10^{14}	0.07	0.07
Mean value	–	–	9.5	−0.005	0.01

tion of new roads, buildings, and other urban infrastructure. Most of the net emergy storage comes from China in the form of imported materials and energy (Lei and Wang 2008a). China also strongly supports Macao's net emergy storage by exporting large quantities of emergy-rich materials and resources, and will continue to perform this role in the future. Without these rich inputs of emergy from the surrounding environment, Macao's urban expansion will be unable to continue (Lei and Wang 2008b).

3.5 Conclusions

Cities lack sufficient resources to sustain themselves and must instead rely on the ecosystems beyond the city limits for their survival. As cities draw ever more resources from more distant areas, they also accumulate large amounts of materials (Huang and Hsu 2003), including discharged wastes. As is the case for other cities, Macao's development exhibits weak sustainability because its resource use is sustained only by large imports of emergy from outside its ecosystem to make its economy sustainable. For this reason, Huang and Hsu observed that cities are equivalent to heterotrophic organisms, and that from the perspective of systems ecology, they are self-regulating systems that resemble super-organisms that have been created for the benefit of human beings and for sustaining human livelihood. Howard Odum (1994) observed that a system that is far from equilibrium (a dissipative structure) can exist only as long as the system is maintained in its non-equilibrium state by

Table 3.9 The simulation equations and processes used in the STELLA layers. The format matches the output from the STELLA model

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$\text{Emergy storage}(t) = \text{Emergy storage}(t - \mathrm{d}t) + (\text{Inflow emergy} - \text{Outflow emergy} - \text{Waste emergy})\mathrm{d}t$

INIT Emergy storage $= 0$

INFLOWS:

Inflow emergy $= F$

OUTFLOWS:

Outflow emergy $= Y$

Waste emergy $= -2.9942 \times 10^{22} + 1.28296 \times 10^{16}$Population

$\text{Population}(t) = \text{Population}(t - \mathrm{d}t) + (\text{Immigrants} + \text{Birth} - \text{Death})\mathrm{d}t$

INIT Population $= 2.6374 \times 10^{5}$

INFLOWS:

Immigrants = Immigrants rate × Population

Birth = Population × Birth rate

OUTFLOWS:

Death = Population × Death rate

Area $= 12\,677\,185 + 582\,995.3(\text{Year} - 1980)$

Birth rate $= 2 \times 10^{67} \exp(-0.0798\,\text{Year})$

Death rate $= 0.0049\,\text{Year}^{-0.1547}$

Density $= U/\text{Area}$

Electricity per capita $= 5.77855 \times 10^{14} - (1.57825 \times 10^{20}/\text{Population})$

$F = \text{Population} \times F$ per capita

Food per capita $= 7.07 \times 10^{15} \times 1.003356155^{(\text{Year}-2003)}$

Fuel per capita $= 8.58498 \times 10^{14} + 6.29244 \times 10^{14}\,\text{LOGN}(\text{Year} - 1980)$

F per capita = Food per capita + Fuel per capita + Goods per capita + Imported services per capita + Minerals per capita + Raws materials per capita + Water per capita + Electricity per capita

Goods per capita $= 1.96816 \times 10^{15} + [1.292 \times 10^{16}/(\text{Year} - 1980)]$

Immigrants rate $= 0.009292389$

Imported services per capita $= -1.07769 \times 10^{15} + 1.42582 \times 10^{15}\,\text{LOGN}(\text{Year} - 1980)$

Sand and rock per capita $= 1.544 \times 10^{16}\{\sin[(\text{Year} - 3)/6]\}^{2} \times \text{Round}\{[\sin([\text{Year} - 3]/6)]^{2}\} + 4.66 \times 10^{13}(\text{Year} - 1983) - 6.936 \times 10^{14}$

$N = 3.6 \times 10^{20}$

$R = 1.34352 \times 10^{12}\,\text{Area}$

Raws materials per capita $= \exp\{37.96596291 - [2.30734742603792/(\text{Year} - 1980)]\} + 7.22 \times 10^{14}$

$U = F + N + R$

U per capita $= U/\text{Population}$

Water per capita $= 7.23847 \times 10^{14} - 1.61151 \times 10^{20}/\text{Population}$

$Y = \exp\{51.01696117 - [2.332783727/(\text{Year} - 1980)]\} + 4.22596 \times 10^{20}$

Year = TIME

Table 3.10 Simulated trends in Macao's emergy from 2003 to 2025

Emergy category (per capita values)	Curve	Trends
Fuel	Logarithmic	Increase
Imported services	Logarithmic	Increase
Water	Inverse	Increase
Raw and processed materials	Sigmoidal	Increase
Goods	Inverse	Almost steady
Sand and rock	Compound	Increase but oscillating
Food	Compound	Increase
Electricity	Inverse	Increase
Wastes	Linear	Increase
Area	Linear	Increase

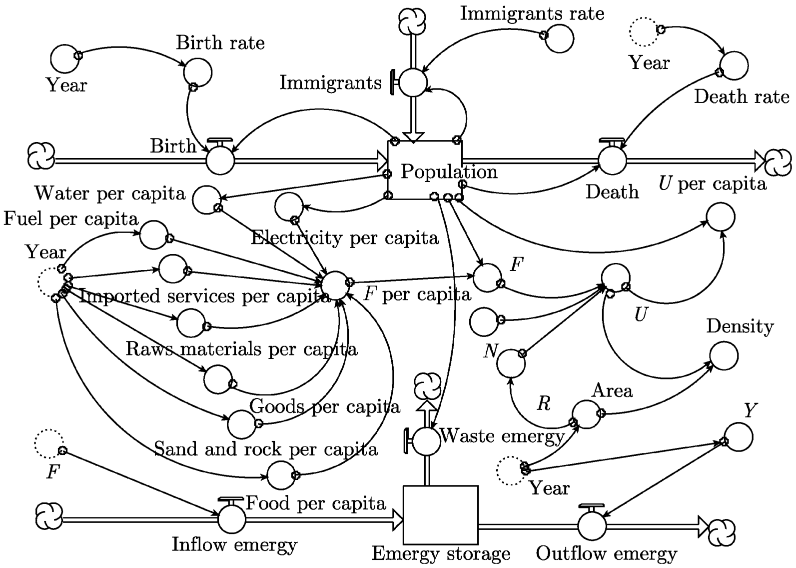


Fig. 3.2 The simulation variables and their relationships for Macao's main emergy flows. $B =$ exported production, $F =$ imported emergy, $M_t =$ emergy consumed by tourists, $N =$ non-renewable resources, $R =$ renewable resources, $T =$ number of tourists, $U =$ total emergy used by the system, $W =$ waste emergy, $Y =$ exported emergy (Lei and Wang 2008b)

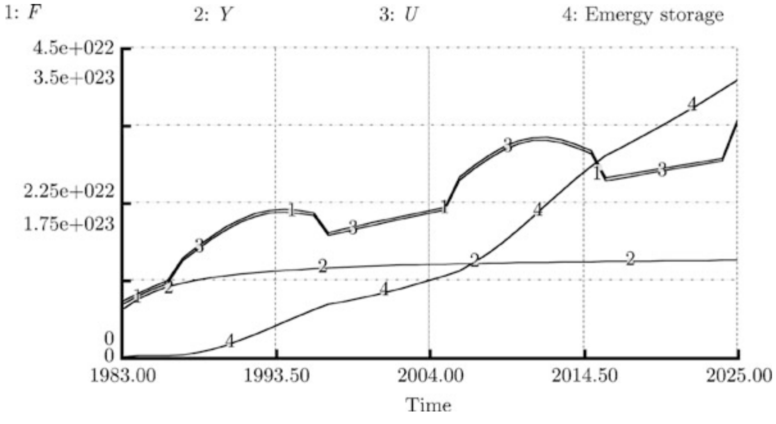
a continuous inflow of energy, matter, or both (i.e., negative entropy) throughout the system. Our research demonstrated that by relying on its tourism industry and an unfairly advantageous emergy trade with China, Macao has absorbed large amounts of emergy (i.e., has exhibited a negative entropy) to do more than just survive; the city has undergone explosive development because of the large size of the imbalance between imports and exports.

Table 3.11 Summary of the simulated changes in the characteristics of Macao's development from 2003 to 2025

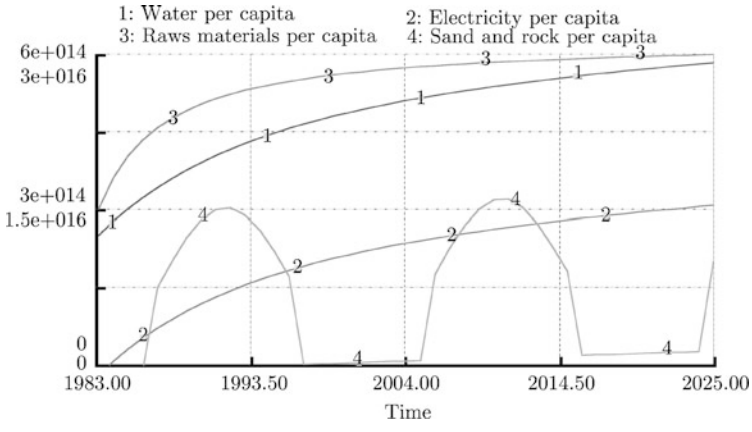
Category	2003 actual value	2025 simulated value	Ratio of the 2025 value to the 2003 value	Trends during development
Population (persons)	448 495	593 185	1.32	Increase
Area (km^2)	27.3	38.91	1.43	Increase
Imported emergy (F, $\times 10^{22}$ sej)	2.16	3.45	1.60	Increase and fluctuation
Total emergy use (U, $\times 10^{22}$ sej)	2.20	3.49	1.59	Increase and fluctuation
Exported emergy (Y, $\times 10^{22}$ sej)	1.47	1.40	0.95	Slow decrease, then reaches a steady level
Renewable resources emergy (R, $\times 10^{19}$ sej)	2.70	5.24	1.94	Increase with increasing area
Non-renewable resources emergy (N, $\times 10^{20}$ sej)	3.60	3.60	1.00	Constant
Emergy density ($\times 10^{14}$ sej m^{-2})	8.05	8.98	1.12	Slow increase and fluctuation
Emergy per capita ($\times 10^{16}$ sej person^{-1})	4.90	5.89	1.20	Increase and fluctuation
Waste emergy (W, $\times 10^{22}$ sej)	0.288	0.413	1.43	Increase
Emergy storage ($\times 10^{22}$ sej)	8.63	32.61	3.78	Increase

Compared with other ecosystems, urban systems are relatively immature because of their rapid growth and inefficient use of resources and the resulting lack of equilibrium; in contrast, mature ecosystems tend to be in a state of equilibrium or near-equilibrium. Urban development involves both the import and the export of raw materials. The purchased (imported) emergy (F), emergy density, and the environmental load ratio [$\text{ELR} = (U - R + F)/R$] of cities thus tends to be much higher than those of natural systems. Denser cities usually have a very high ELR value due to a lack of indigenous natural resources that are available for use. Lei and Wang (2008a) found that in 2003, the ELR of Macao was 813, which was considerably higher than that of the United States (5.85), Italy (16.1), and Sweden (13.6).

To determine the net emergy benefits that result from purchases of environmental products (H. T. Odum 1996), the emergy benefit to the purchaser can be inferred by calculating the "benefit ratio", which equals the emergy in the product divided by that in the buying power represented by the money that was paid for that resource. For example, H. T. Odum (1996) suggested that this ratio for purchased oil equaled 13.1. By using Odum's methods, we calculated the benefit ratio for sand and rock



(a)



(b)

Fig. 3.3 Predicted trends in the main emergy indicators for Macao from 1983 to 2025 using the STELLA model. **a** Imported emergy (F), exported emergy (Y), emergy used by the system (U), and emergy storage. **b** Per capita consumption of water, electricity, raw materials, and sand and rock. **c** Per capita consumption of fuel, goods, food, and imported services. **d** Population, area, waste emergy (W), emergy density, and U per capita

imported by Macao, and found that the ratio equaled 40. Natural sand comprises the majority of these imports, and its benefit ratio equaled 181 (Table 3.12). These results mean that Macao obtained a large net emergy benefit from each land reclamation action that used these resources, and that this net emergy was an important part of the engine driving the city's expansion. Nonetheless, if a city develops without any regard to balancing its net emergy, it may import external resources and services at an unsustainable rate that leads to unsustainable development of the regions surrounding the city, and possibly even more distant regions (Lei and Wang 2008b).

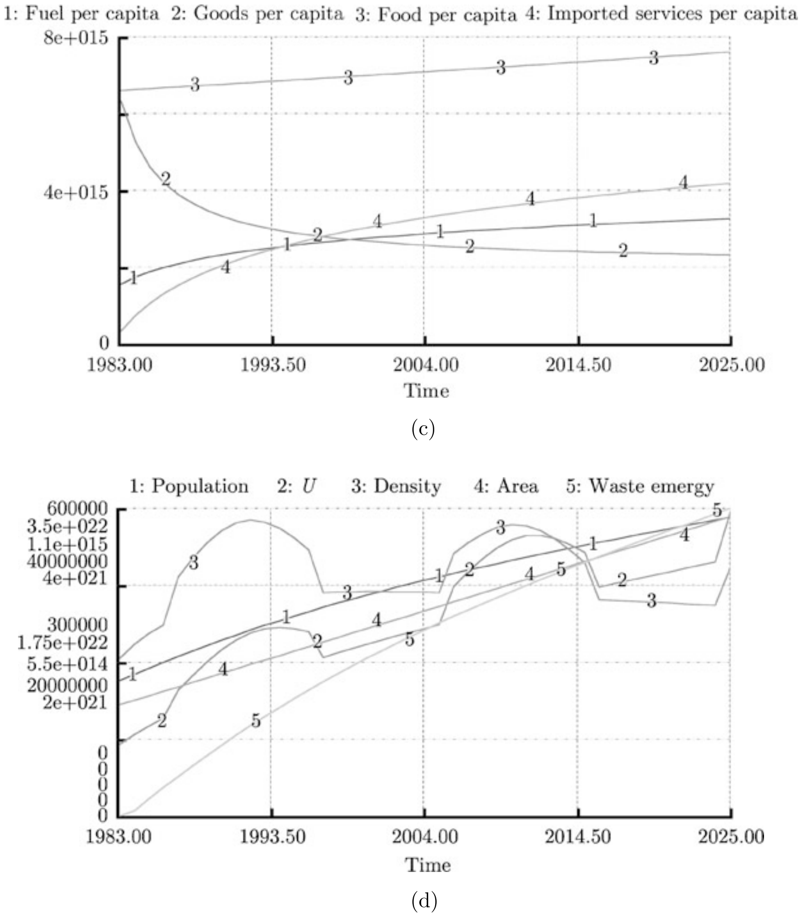


Fig. 3.3 (*Continued*)

Sustainability is defined as preserving the ability of humans to meet their needs (Hjorth and Bagheri 2006). Howard Odum (1994) envisioned sustainability as the process of adapting to the oscillations that occur in natural capital, recognizing that such unstable states are “possibly the most general patterns in nature”. For a limited ecosystem such as that of a small city, emergy fluctuations can usually be seen, and smaller systems fluctuate more frequently than larger systems (H. T. Odum 1996); these changes reflect the instability and fragility of such a small system. Because systems exhibit variation at various temporal and spatial scales, the emergy flows, emergy storage, and various related indices also fluctuate.

The boom in tourism development and in Macao’s economy has increased the demand for facilities and services. Unfortunately, Macao has little available land area, so the government has been forced to reclaim land to provide additional space to support all sectors of society. In Macao, periodic reclamation can add to the land

Table 3.12 Emergy benefit ratio of imported natural sands and of sand and rock for Macao in 2003

Item	Emergy in the product (sej)	Money paid to acquire the product ($)	Emergy paid to acquire the product (sej)	Emergy benefit ratio (product emergy divided by emergy paid)
Natural sand	2.692×10^{20}	535 089	1.4883×10^{18}	181
Sand and rock	1.19×10^{21}	10 645 264	2.96088×10^{19}	40

Note: Natural sand is a component of the imported sand and rock, and is mainly imported from China

stock and provide land for use in coming years, although there will be an environmental cost for this reclamation that has not yet been quantified. For example, Macao's expansion has narrowed the surrounding sea, leading to maritime traffic jams. The reclamation process has also benefited from a decrease in sea levels at the western side of the Pearl River estuary, and this has brought more sand to Macao's coast, leading to a net emergy flow into Macao. Through these natural and artificial processes, the area of Macao has increased during the past 150 years to 9.8 times its size in 1840 (Lei and Wang 2008b).

During the simulation period, the emergy used by Macao will increase along with increasing urban development and population growth, and the area occupied by Macao will expand while the city continues to accumulate emergy storage. We propose the following policies to help improve the sustainability of Macao's development during its future growth: (1) Steady, sustainable reclamation of new land would be advantageous, but excessive reclamation will damage the city's ecological health and weaken its sustainability. Thus, future reclamation should be carefully assessed from both environmental and sustainability perspectives, not from a purely socioeconomic perspective. (2) Sustaining a good relationship with regions external to the city, and especially with mainland China, will also be very important because it will help to sustain the net emergy inflow that Macao requires to sustain its current system and its future growth. In particular, Macao should find ways to ensure that its imports of external resources do not cause serious economic or environmental consequences for the providers of those resources. Such damage may lead the providers to limit the flows of these crucial resources (Lei and Wang 2008b).

It would be helpful to obtain more and better data to permit more exact results from modeling such as that conducted during the present study. Using the limited data that is currently available makes predictions about the future difficult, and the results of simulations may be inaccurate; however, even such inaccurate results provide a good starting point for future studies. In addition, the accuracy of the data provided by the government would also influence the results of our simulations. Macao is a tourism-driven city, yet the resources provided to tourists only amounted to about 15 % of total emergy use (U). However, our analysis in the current chapter did not separate the emergy that tourists consumed from the emergy consumed by Macao residents; therefore, the increase in the per capita emergy produced an inflated estimate.

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Chapter 4
Emergy Analysis for Tourism Systems: Principles and a Case Study for Macao

4.1 Introduction to Ecological Emergy Accounting for Tourism

As one of the world's largest and fastest growing industries, tourism is placing great stress on biologically diverse habitats and indigenous cultures, which are often used to support large-scale tourism activities. The governments and tour operators who are engaged in promoting sustainable tourism are sensitive to these dangers and seek to protect tourist destinations from unsustainable use so they can protect their tourism industry. To permit sustainable tourism, environmental integrity and economic development should be assessed using a suitable measurement system. Since human systems (and especially cities) concentrate materials and energy obtained from outside the system boundaries (i.e., human socioeconomic systems are rarely self-sustaining), one of the earliest modern ecological approaches to urban systems was an assessment of the biogeochemical budgets of whole cities (E. C. Odum and Odum 1980). For a tourism city, the large exchanges of materials and energy with the external environment are accompanied by large flows of money to sustain tourists, tourism equipment and infrastructures, and tourist services.

The World Tourism Organization defines sustainable tourism development as "Tourism that takes full account of its current and future economic, social and environmental impacts, addressing the needs of visitors, the industry, the environment and host communities" (UNEP and WTO 2005). Since 2000, emergy synthesis has been introduced to measure the sustainability of tourism systems (Abel 2000, 2003; Brown and Ulgiati 2001; Lei and Wang 2008a; Vassallo et al. 2009; Lei et al. 2010). Abel (2000, 2003) addressed the problem of emergy synthesis for ecotourism on Bonaire Island in the Caribbean. Brown and Ulgiati (2001) studied resorts in Mexico and Papua New Guinea. In our previous research (Lei and Wang 2008a), we studied the tourism industry of Macao, and found that tourist consumption could be quantified using emergy accounting, and could be calculated as a proportion of the total emergy use by the host country (Lei et al. 2006). Vassallo et al. (2009) used the tourism area life cycle model to investigate the emergy flows related to tourists and residents for an Italian coastal resort region, and found that emergy synthesis could be used to assess a tourist region's sustainability. We have also studied (Lei et al.

K. Lei et al., *Ecological Emergy Accounting for a Limited System: General Principles and a Case Study of Macao*, Springer Environmental Science and Engineering,
DOI 10.1007/978-3-642-45170-6_4,

2010) the use of emergy accounting to assess the main branch of tourism in Macao, namely the gambling sector, by following the food, tickets, services, water, electricity, equipment, labor, and other services that consumed large quantities of materials and energy. In this chapter, we discuss the different approaches that have been used in emergy accounting, and discuss their relative suitability, key characteristics, and the sustainability of tourism based on these approaches (Lei et al. 2011).

Note: Because of the large number of parameters defined in this book, we have provided a summary of all parameters and their definitions in Appendix C.

4.2 Methodology

4.2.1 Approaches Used in Tourism Emergy Accounting

Tourism is an industry with high consumption of energy and other natural resources. As a result, many tourist destinations operate at a lower ecological efficiency than the global average (Gössling et al. 2005). Sustainable tourism has thus become an increasingly important concern, and there is broad consensus that the industry's environmental impacts can no longer be ignored (Hunter and Green 1995). Ecotourism projects seem more environmentally benign, but since they are often assessed purely at a local level (i.e., ignoring external inputs into the system), even ecotourism may not be sustainable from a broader perspective. An advantage of the concept of emergy proposed by H. T. Odum (1996) is that this approach explicitly attempts to measure flows into and out of the ecological and socioeconomic components of a system. Emergy quantifies energy, materials, and environmental and human services within a common framework while accounting for differences in the quality of the energy and the resources that are consumed. Another advantage of emergy analysis is that it explicitly places a value on the services provided by the environment, which were traditionally considered to be free and outside the monetary economy that is emphasized in conventional economics (Brown and Ulgiati 2001).

There have been four main approaches used in emergy analysis for tourism, with different scopes of applicability and different analytical tradeoffs (Table 4.1). In our previous research (Lei et al. 2006, 2008, 2011; Lei and Wang 2008a), we studied tourism emergy for Macao using the emergy accounting approach. Here, we will discuss the relevance of four approaches, using data from our previous studies supplemented by new data from 2007 in the emergy calculations (Lei et al. 2011). The resulting analysis does a better job of accounting for the unique characteristics of tourism.

Approach 1: Conversion of Money Flows into Emergy

In recent research, most authors have treated the monetary flows from tourism as an income source (Ulgiati et al. 1994; Huang and Odum 1996; Brown and Ulgiati 2001;

Table 4.1 Summary of the approaches used for tourism emergy analysis

Approach	Applicability	Emergy accounting	Problems	Advantage
1	A country or region. Detailed statistical data is available	Simply convert the money flows into emergy flows by multiplying the money by a conversion factor ($E_{\mathrm{m}}/\$$)	There is debate over which $E_{\mathrm{m}}/\$$ conversion factor should be employed	Easy to calculate
2	A single resort. Detailed data is available	Emergy accounting	A single resort provides limited insight into the problems of larger-scale systems	Easy to calculate
3	Two or more resorts in a small area. Detailed data is available	Emergy accounting	A small number of resorts may still provide limited insights into larger-scale systems	Easy to calculate
4	Many resorts distributed throughout a region. Aggregate data is available for the region	The proportion of total emergy use accounted for by tourist consumption is multiplied by the total emergy that is consumed by the system	The weight used for the tourist consumption factor[a] must be determined from statistics and surveys of the relative emergy consumption by the average tourist and the average local resident	Suitable for analysis at larger scales (e.g., systems or countries)

[a] r varies among countries and regions as a result of different consumption styles. In Macao, r is about 1.9 (Lei and Wang 2008a)

Lan et al. 2002; Jiang et al. 2008; L. X. Zhang et al. 2009), and have treated these incomes as a kind of external input (i.e., an investment) for a regional ecosystem (Fig. 4.1, Approach 1). The solar emergy (E_{m}) of the tourism system is simply calculated by multiplying the quantity of money involved in a flow by a conversion factor ($E_{\mathrm{m}}/\$$) specific to the system being studied. The imported emergy of tourism (T_{m}) is calculated as follows:

$$T_{\mathrm{m}} = (E_{\mathrm{m}}/\$)C_{\mathrm{t}} \tag{4.1}$$

where $E_{\mathrm{m}}/\$$ is an emergy conversion factor for the emergy (E_{m}) of monetary flows (\$) and C_{t} is the income from tourism. Since the concept of tourism emergy has been expressed differently by different researchers, it is important to define emergy in terms of emergy-exchange processes (Fig. 4.2), as described in the following paragraphs.

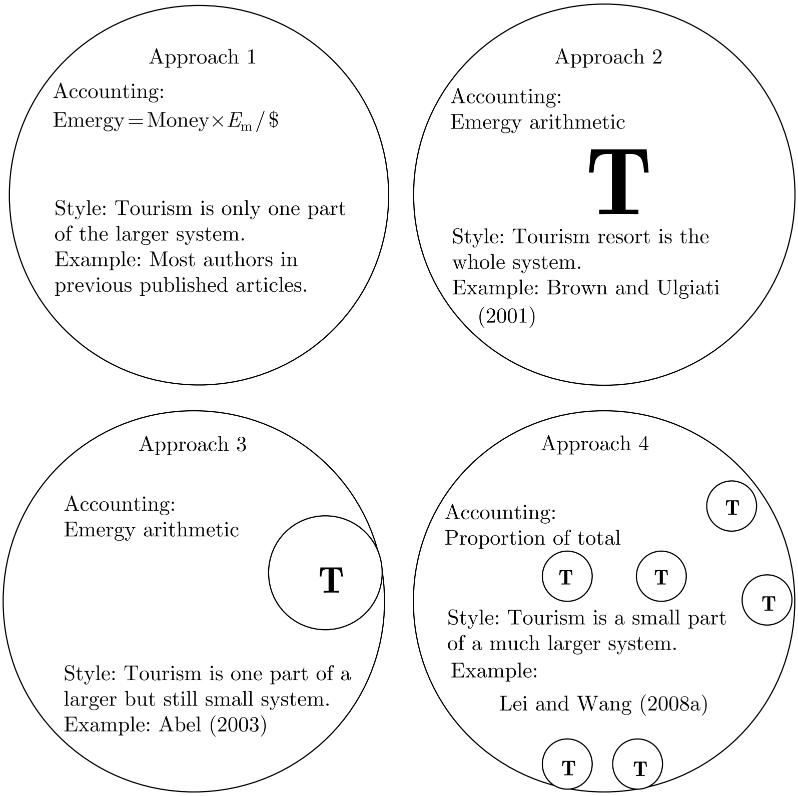

Fig. 4.1 The four main approaches used in tourism emergy accounting (Lei et al. 2011): (*T* represents tourist resorts)

Embodied Emergy of the Tourist (i.e., the Emergy Imported from the Tourist's Home Country) Brown and Ulgiati (2001) proposed that the E_m/\$ ratio from a tourist's home country should be included in the analysis. When tourists visit a host country, the embodied emergy that they bring with them corresponds to their country's technology and the condition of its resources. Although we agree with their logic, we have employed the global E_m/\$ ratio in our research on Macao because tourists typically come from many countries with very different E_m/\$ ratios, and there is insufficient data available to let us calculate a weighted-average emergy value for the tourists who came to Macao in each year of our study period; this is a particular problem for Macao, which is the subject of our case study later in this chapter, because most tourists come from China, and emergy data for China is generally lacking.

The Emergy Consumed by Tourists (i.e., the Emergy Supplied by the Host Country) The previous paragraph accounts for emergy imports that accompany tourists when they enter a host country, but we must also account for the emergy

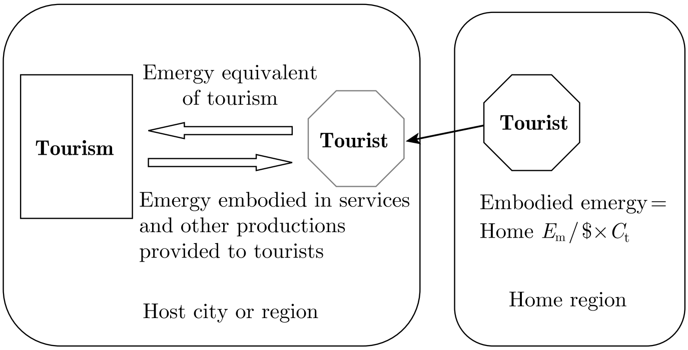

Fig. 4.2 An emergy-exchange diagram for a tourist resort and its host city or region

of the goods and services they consume during their stay in their host country. By accounting for the quality of each good and service and for the real (emergy) value of the environmental services that sustain tourism, resources are not valued solely by their cost or by society's willingness to pay, and the environmental externalities that are often ignored by purely economic analyses are implicitly included in the analysis, thereby making it possible to account for the environmental consequences of the economic activities (Baumgärtner and Quaas 2010).

The Conversion of Monetary Expenditures by Tourists into Emergy and the Problem of "Double Counting" This aspect of emergy should be distinguished in emergy accounting to avoid "double counting", since the money is used to purchase energy, goods, and services from outside the system being studied, and these purchases may have already been accounted for when flows of these inputs into a tourism system were calculated (Lei et al. 2008).

Some authors treat tourism as an emergy export (Huang and Odum 1996; H. T. Odum 1996; Abel 2000), since the goods and services eventually leave the host region and are exported to the tourist's home region; on this basis, tourism emergy can be depicted as another "export industry". Goods and services provided by a host region are purchased by foreigners who use hotel facilities, eat in restaurants, and buy goods (Abel 2000), and these aspects of consumption can therefore be thought of as the exported emergy (Fig. 4.2) of tourism (Lei et al. 2008). However, it's important to note that this description may be too simplistic. Some emergy is clearly *not* exported (e.g., money lost during gambling remains within the host region) and some is clearly exported (e.g., goods that are purchased as souvenirs and that are returned to the tourist's home country). In future research, it would be helpful to develop methods to distinguish between the two categories of emergy.

Approach 2: Emergy Synthesis for a Single Resort

Brown and Ulgiati (2001) studied tourism resorts in Papua New Guinea and Mexico. The first study was of a small diving resort on the Island of New Britain; the second was of a large hotel resort complex in the city of Puerto Vallarta. They proposed that sustainable tourism development was related to the net emergy benefits for the host region, and that sustainability resulted from a positive emergy balance. Their paper outlined a method for determining the carrying capacity for economic investments based on an emergy evaluation using tourism development data for the two host regions (Fig. 4.1, Approach 2).

The total annual resource use (E_{m}) by the tourist resorts and the economies in which they were embedded was calculated and converted into emergy units, mostly using materials and energy terms and with limited use of money emergy. They used the following equation:

$$E_{\mathrm{m}} = T_r E_{\mathrm{n}} \tag{4.2}$$

where E_{n} is the available energy or mass and T_r is the transformity, which represents a conversion factor between the available resource and its equivalent emergy.

Approach 3: Emergy Synthesis for a Small Area

Abel (2000, 2003) performed an emergy synthesis analysis for ecotourism as part of an interdisciplinary study conducted on the island of Bonaire in the Netherlands Antilles. Abel (2003) modeled ecotourism development on Bonaire in terms of emergy perturbations of a complex combined human–ecological system. New emergy flows associated with ecotourism fueled transformations of the island's ecology and of its sociocultural system. Tourism emergy inflows included the following: transportation, which is an essential ingredient because tourists could not reach the island without it; local services, in both direct and indirect forms, that were required to maintain and promote the hotel industry; imported goods, including the emergy of shipping and foods, that were present in the emergy inflows from the retail subsystem; and labor, since tourists require a large amount of support from tourism staff, and the emergy inflow from this labor is substantial. Abel considered the sum of these emergy inputs to represent the emergy exports of tourism, which flow to the tourists, although exchange processes may occur within the host region (Fig. 4.1, Approach 3; Fig. 4.3). Vassallo et al. (2009) performed a similar case study for an Italian coastal resort region and obtained results similar to those of Abel (2000).

Approach 4: Tourism Emergy as a Proportion of Total Emergy Use

In some cases, detailed statistics on flows of energy, materials, and money are available for a region, and this abundance of data allows researchers to calculate the overall emergy use in that region. If insufficient amounts of detailed data are available for the tourism sector, its emergy flows can sometimes be approximated satisfactorily if the proportion of the overall emergy flows accounted for by tourism can be estimated (Fig. 4.1, Approach 4). For example, Macao is a tourism-dominated city with a large number of tourists. Since the resources of such tourism cities are

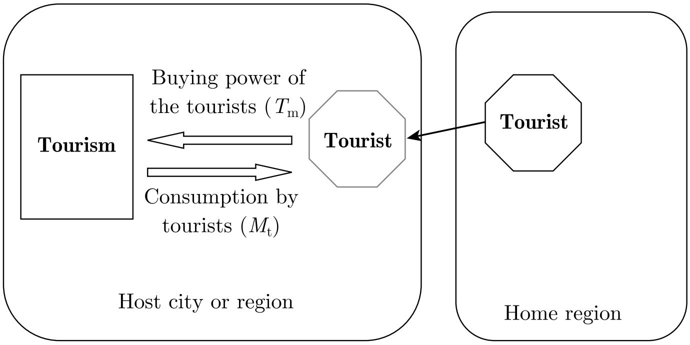

Fig. 4.3 An emergy-exchange diagram for a small tourist resort region composed of multiple resorts

shared by both local residents and tourists, consumption by the tourists can be accounted for as a proportion of the total emergy used by the host region (Lei et al. 2006, 2008). Therefore, the emergy consumed by tourists (M_t) can be estimated as follows:

$$M_t = R_t U \tag{4.3}$$

where R_t is the proportion of total emergy use (U) that is consumed by tourists. R_t can be calculated as follows:

$$R_t = Tdr/(Tdr + 365P) \tag{4.4}$$

where T represents the total number of tourists, d is the average number of days that a tourist stays in the host region, r is the consumption factor for the tourists (i.e., the ratio of consumption by a tourist to consumption by a resident), and P represents the population of Macao. In our previous research (Lei et al. 2008), we estimated an r value of 1.9 for Macao, which means that a tourist consumes 1.9 times the emergy consumed by a local resident. In our updated 2007 study of Macao, the resulting R_t was 0.267.

This approach recognizes the fact that tourism destinations are shared by local residents and tourists, and that tourist consumption represents a calculable proportion of the total emergy used by the host region (Lei et al. 2006, 2011; Lei and Wang 2008a).

4.2.2 Two Emergy Flows for Tourism: What You Paid for and What You Got

It can be shown that the emergy of the money that tourists spend in the host region does not equal the emergy they consume (Lei et al. 2008). To express the difference between spending and consumption in the emergy-exchange processes between the tourism sector and the tourists (Fig. 4.2), we have proposed a more reasonable method for calculating the emergy consumed by tourists (M_t). The buying-power emergy represents what the tourists spend (T_m), and what the tourists consume (M_t) represents a different quantity (Fig. 4.3); the two flows travel in opposite directions and can have very different values (Lei et al. 2008), but the advantage of our method is that it accounts for both flows.

4.3 Emergy Analysis and Discussion: A Case Study of Tourism in Macao

4.3.1 Introduction to Tourism in Macao

Because of its unique mixture of Portuguese and Chinese cultures, Macao makes an interesting destination for tourists from around the world. Although Macao's rising reputation as a gambling heaven, spurred by the development of ever larger and grander casinos, is a major attraction for many, there are also beaches, historical sites (fortresses, churches, temples, and gardens), and excellent museums to explore. Since 2005, Macao has been officially listed as a World Cultural Heritage Site (Government of Macao 2012).

Tourism is a vital part of Macao's economy, accounting for \$1.449 $\times$ 10^9 in 2007, which amounted to about 75.7 % of its GDP (DSEC 2008). (Unless otherwise noted, all monetary values are in U.S. dollars.) The tourism sector has become Macao's main source of revenue, as the city's other industries have declined due to competition from neighboring regions since 1992. Tourism employed more than 40 % of the working population in 2007 (DSEC 2008).

4.3.2 Emergy Accounting for Macao's Tourism Sector

To focus on the core features of tourism emergy, we obtained extensive data on the flows of energy, money, and materials into and out of Macao's socioeconomic and environmental systems. This data is provided in Tables B.1 through B.7 in Appendix B. Here, we have only presented the most relevant data in the form of summary tables. Table 4.2 summarizes the renewable (R) and indigenous non-renewable (N) resources. In our research, we used the most recent emergy baseline for Earth's geobiosphere, namely 15.8×10^{24} sej year^{-1}, but we did not modify the transformities of the items included in our analysis because the new baseline produced only minor changes in the transformities (Brown and Ulgiati 2010). Table 4.3 summarizes the emergy exchanges (imports versus exports) and Table 4.4 summarizes the main emergy flows for Macao in 2007 (Lei et al. 2011).

In Macao, tourism is the economy's main engine, and it can be thought of as an emergy-earning industry. In 2007, nearly 27 million tourists visited Macao; this

Table 4.2 Annual emergy flows for renewable (R) and non-renewable (N) resources for Macao in 2007 (Lei et al. 2011)

Categories	Item	Raw units	Transformity (sej unit^{-1})	Emergy (sej)	Emdollars (em$)	Source of transformity
Renewable	1. Sunlight	1.50×10^{17} J	1	1.50×10^{17}	8.22×10^{4}	H. T. Odum (1996)
	2. Wind, kinetic	6.86×10^{13} J	663	4.55×10^{16}	2.50×10^{4}	Campbell et al. (2005)
	3. Rain, chemical	2.12×10^{14} J	18 199	3.85×10^{18}	2.11×10^{6}	Campbell et al. (2005)
	4. Rain, geopotential	4.20×10^{13} J	10 488	4.40×10^{17}	2.41×10^{5}	Campbell et al. (2005)
	5. Tide	1.17×10^{13} J	16 842	1.97×10^{17}	1.08×10^{5}	Campbell et al. (2005)
	6. Waves	1.17×10^{15} J	30 550	3.59×10^{19}	1.97×10^{7}	H. T. Odum (1996)
	7. Earth cycles	4.23×10^{13} J	34 377	1.46×10^{18}	7.99×10^{5}	Campbell et al. (2005)
	Total $(3 + 6 + 7)$	1.23×10^{15} J		3.75×10^{19}		
Non-renewable	1. Stone	3.60×10^{11} g	1×10^{9}	3.60×10^{20}	1.98×10^{8}	H. T. Odum (1996)
	2. Topsoil loss	1.90×10^{9} g	62 500	1.19×10^{14}	6.52×10	H. T. Odum (1996)
	Total $(1 + 2)$	3.62×10^{11} g		3.98×10^{20}	1.98×10^{8}	

Table 4.3 Emergy evaluation for Macao's imports and exports in 2007 (Lei et al. 2011)

Item	Raw units (g)	Raw units (J, g or $)	Transformity (sej unit^{-1})	Source of transformity	Emergy ($\times 10^{20}$ sej)	Emdollars ($\times 10^{7}$ em$)
Imports						
1. Foods	4.18×10^{11}	5.27×10^{15}	23 categories[b]	Summary of food in Table B.1	30.34	268.53
2. Fresh water	7.46×10^{13}	3.69×10^{14}	660 000	Lan et al. (2002)	2.43	21.53
3. Electricity[a]	–	6.06×10^{15}	160 000	H. T. Odum (1996)	9.70	85.81
4. Fuels	7.38×10^{11}	3.07×10^{16}	54 000	H. T. Odum (1996)	16.48	145.87
5. Minerals	3.79×10^{12}	3.79×10^{12}	6 categories[b]	Summary of minerals in Table B.2	45.33	401.14
6. Raw materials	7.65×10^{11}	3.65×10^{15}	38 categories[b]	Summary of raw materials in Table B.3	96.34	852.54
7. Goods	1.11×10^{12}	8.08×10^{11}	13 categories[b]	Summary of goods in Table B.4	45.07	398.86
Total (1 to 7)	8.14×10^{13}	4.60×10^{16}			245.69	2174.28
Exports						
1. Foods	7.00×10^{9}	1.01×10^{14}	19 categories[b]	Summary of foods in Table B.5	0.51	2.78
2. Fuels	1.01×10^{8}	3.379×10^{12}	54 000	H. T. Odum (1996)	0.002	0.01
3. Cement	1.13×10^{9}	1.135×10^{9}	2.07×10^{9}	Brown and Buranakarn (2003)	0.02	0.125
4. Raw materials	2.30×10^{11}	2.409×10^{15}	35 categories[b]	Summary of raw materials in Table B.6	140.82	772.71
5. Goods	2.04×10^{11}	1.266×10^{11}	13 categories[b]	Summary of goods in Table B.7	22.61	124.08
Total (1 to 5)	4.43×10^{11}	2.514×10^{15}			163.96	899.70

Table 4.3 (*Continued*)

Item	Raw units (g)	Raw units (J, g or \$)	Transformity (sej unit^{-1})	Source of transformity	Emergy ($\times 10^{20}$ sej)	Emdollars ($\times 10^{7}$ em\$)
Service imports and tourism exports \$			$E_{\mathrm{m}}/\$$		Emergy	Emdollars
1. Service imports ($P_2 I_3$)		2.54×10^9	3.91×10^{12}	Y. Zhang et al. (2008)	99.33	545.06
2. Tourism (T_{m})		1.45×10^{10} \$	1.13×10^{12}	Brown and Bardi (2001)	163.47	1446.63
3. Tourist consumption (M_{t})	Tourists consumed 0.267[c] of the total emergy used (U)				93.03	510.48

[a] The electricity purchased from China totaled 1683 GW · h, for an equivalent energy of 6.06×10^{15} J

[b] We have presented the raw data used to calculate certain values in this table in Appendix B

[c] R_t was calculated using Eq. 4.4

Table 4.4 Summary of the main emergy flows for Macao in 2007

Variable	Description	Energy or mass or money	Solar emergy ($\times 10^{20}$ sej)	Emdollars ($\times 10^{9}$ em\$)
R	Renewable resources	1.23×10^{15} (J)	0.38	0.02
N	Non-renewable resources	3.62×10^{11} (g)	3.6	0.20
Fuel	Imported fuels and minerals	3.67×10^{16} (J)	71.51	3.92
G	Imported foods, goods, and raw materials	9.29×10^{15} (J)	174.19	9.56
$P_2 I_3$	Imported services	2.54×10^{9} (\$)	99.33	5.45
F (imported)	Imported emergy ($\text{Fuel} + G + P_2 I_3$)	4.60×10^{16} (J)	345.03	18.93
U	Emergy used ($R + N + F$)	4.73×10^{16} (J)	349.00	19.15
B	Exported production	2.51×10^{15} (J)	163.96	9.00
Y (exported)	Exported emergy ($B + M_t$)	1.51×10^{16} (J)	256.99	14.10
ELE	Electricity (3136.9 GW · h)	1.13×10^{16} (J)	18.07	0.99

is about 51.3 times its population (Table 4.5). The majority of tourists came from Mainland China (55.1 %), Hong Kong (30.3 %), and Taiwan (5.3 %). The average spending by tourists was $203.70, and the average duration of their stay was 1.36 days. In 2007, tourism brought in a gross income of $14.5 billion. Revenue from gambling was $10.2 billion, which was 70.4 % of the total annual tourism revenues (DSEC 2008). Tourism contributed an estimated 75.7 % of the GDP in 2007 (Lei et al. 2011).

The data from DSEC (2008) show that the mean duration of a tourist's stay in Macao has slowly decreased, but spending on non-gambling activities has also gradually increased. In 1983, there were only 4.1 million tourists, but that total reached nearly 27 million in 2007 (an increase to nearly 6.6 times the 1983 value). The number of tourists amounted to 14.5 times Macao's population in 1983, but this ratio increased to 51.3 in 2007 (Table 4.5). The tourism indicators increased steadily from 1983 to 2007 (Fig. 4.4), except between 1997 and 1999. Since 2000, the economy of Macao has grown more rapidly than during previous periods, primarily as a result of growth in the gambling and tourism industries (Lei et al. 2011).

During the 1980s, the manufacturing industry contributed important benefits to Macao's economy, particularly after China opened its doors to the world market. However, this sector lost this advantageous situation after 1990 due to competition from Chinese and southeast Asian rivals. As a result, gambling and tourism became increasingly important to Macao's economy and accounted for an increasingly large proportion of the government's revenues. Figure 4.4 shows the trends in GDP, tourism income, gambling income, government revenues, and gambling tax revenues from 1983 to 2007; all five curves show parallel changes, with only slight differences in the slopes of the curves. The proportion of GDP accounted for by gambling taxes increased from between 18.3 % in 1983 and 30.1 % in 1995 to 53.3 % in 2007 (Lei et al. 2011). The GDP increased slowly at first, from $\$1.15 \times 10^9$ in 1983 to $\$7.01 \times 10^9$ in 1997. After a brief decrease to $\$6.19 \times 10^9$ in 2000, it increased rapidly to $\$19.15 \times 10^9$ in 2007 (Table 4.5).

The proportions of GDP accounted for by Macao's tourism and gambling industries have increased in parallel with increases in their proportions of total emergy use (Fig. 4.5). In monetary terms, only man-made capital is accounted for, so the proportions of tourism and gambling income were higher in monetary terms (as a proportion of GDP) than in emergy terms (as a proportion of U). The emergy synthesis analysis for tourism fully accounts for both environmental resources and economic services, and therefore provides a more fair and reasonable accounting than simply accounting for monetary values. However, both proportions of the total increased steadily from 1983 to 2004, except for a brief period between 1997 and 1999. The percentage of GDP accounted for by tourism increased from 44.0 % in 1983 to 75.7 % in 2007; during the same period, the proportion of GDP accounted for by gambling revenues rose from 18.3 % to 53.3 %. On an emergy basis, the proportion of total emergy use (U) accounted for by tourism rose from 11.1 % in 1983 to 46.8 % in 2007, versus a corresponding increase for the gambling component from 4.6 % to 33.0 % (Lei et al. 2011).

These results can be explained by changes in the components of different industries and their development during this period. Tourism, manufacturing, finance and

Table 4.5 Changes in Macao's emergy and tourism-related indicators from 1983 to 2007. (The dollar values were adjusted for inflation)

Indicators	1983	1985	1988	1990	1993	1995	1997	1999	2000	2003	2004	2007
Population	282 843	289 704	315 997	334 961	383 984	409 300	422 000	429 600	437 500	448 495	465 333	525 800
GDP ($\times 10^9$ \$)	1.15	1.37	2.33	3.26	5.67	6.94	7.01	6.1	6.19	7.9	10.31	19.15
Tourists ($\times 10^6$)	4.1	4.18	5.54	5.94	6	5.99	7	7.44	9.16	11.89	16.67	26.99
Mean duration of visit (days)	1.9	1.8	1.7	1.7	1.6	1.5	1.4	1.4	1.3	1.2	1.13	1.36
Tourism income ($\times 10^9$ \$)[a]	0.5	0.53	0.91	1.46	2.48	3.15	3.16	2.7	3.28	5.21	8.1	14.49
Gambling income ($\times 10^9$ \$)[a]	0.218	0.23	0.44	0.87	1.77	2.09	2.16	1.63	1.99	3.58	5.36	10.2
World emergy/\$ ($\times 10^{12}$ sej \$$^{-1}$)[b]	2.2	2.22	2	2	1.98	1.98	1.98	1.98	1.66	1.66	1.66	1.13
Macao's emergy/\$ ($\times 10^{12}$ sej \$$^{-1}$)[c]	8.76	8.66	6.64	5.78	4.36	3.13	2.66	3.06	3.03	2.78	2.38	1.82
Emergy used ($\times 10^{20}$ sej)[c]	100.45	118.5	154.73	188.73	247.02	217.31	196.54	186.82	187.6	219.73	245.21	349.00
Service imports ($\times 10^{20}$ sej)[c]	2.61	3.28	4.05	5.6	8.93	10	12.45	14.34	13.25	17.4	23.77	99.33
Imported emergy ($\times 10^{20}$ sej)[c]	92.98	111.04	149.07	184.88	243.15	213.44	192.65	182.94	183.72	215.86	241.34	345.03

Table 4.5 (*Continued*)

Indicators	1983	1985	1988	1990	1993	1995	1997	1999	2000	2003	2004	2007
Exported emergy ($\times 10^{20}$ sej)[c]	61.84	92.06	118.29	133.07	132.94	120	106.09	111.08	131.25	147.34	178.03	256.99
T_m ($\times 10^{20}$ sej)[c]	11.05	11.77	18.24	29.21	49.09	62.43	62.63	53.43	54.49	86.5	134.56	163.47
Gambling income ($\times 10^{20}$ sej)[c]	4.61	5.11	8.87	17.4	35	41.4	42.7	32.4	33.1	59.4	89.03	115.03
Tourist consumption ratio (R_t)[c]	0.096	0.095	0.113	0.114	0.102	0.096	0.108	0.112	0.124	0.148	0.174	0.267
M_t ($\times 10^{20}$ sej)[c]	9.56	11.28	17.54	21.61	25.24	20.94	21.2	20.95	23.29	32.54	42.60	93.03
T_m/GDP (%, $ basis)[c]	44	38.7	39.1	44.8	43.7	45.4	45.1	44.2	53	65.9	78.6	75.7
T_m/U (%, sej basis)[c]	11.1	10	11.7	13.8	18.7	26.6	33.5	28.6	29	39.3	54.9	46.8
Gambling/GDP (%, $ basis)[c]	18.3	16.8	19.0	26.6	31.1	30.1	30.8	26.8	32.1	45.3	52.0	53.3
Gambling/U (%, sej basis)[c]	4.6	4.3	5.7	8.2	13.3	17.6	22.8	17.3	17.6	27	36.3	33.0

[a] Data obtained from DSEC (2008)

[b] Data from Y. Zhang et al. (2008)

[c] Data sources: Indicators before 2003 are from Lei and Wang (2008a), indicators from 2004 are from Lei and Wang (2008b), and indicators from 2007 are from Lei et al. (2011)

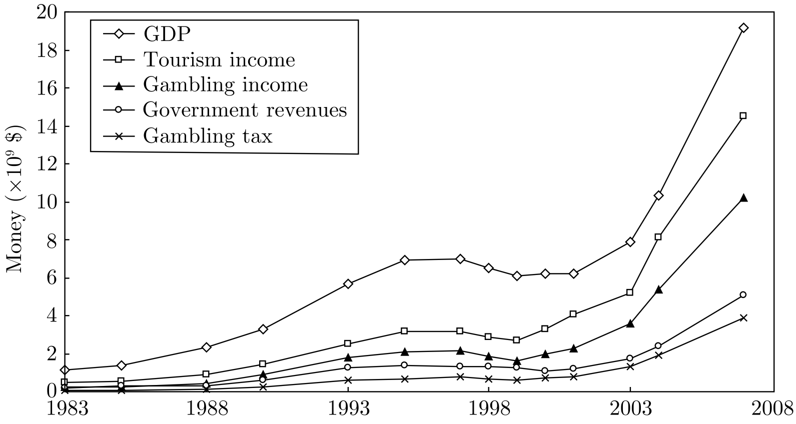

Fig. 4.4 Monetary flows for Macao from 1983 to 2007 (Lei et al. 2011)

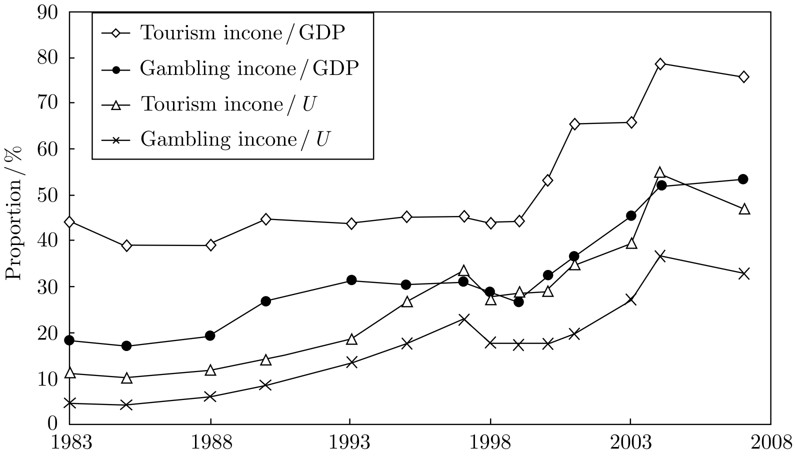

Fig. 4.5 The proportions of GDP accounted for by the tourism and gambling industries, and the corresponding proportions of total emergy use (U) from 1983 to 2007 (Lei et al. 2011)

insurance, and construction and real estate had been thought of as the four pillars of Macao's economy in the 1980s (Miao et al. 1988). However, Macao has become a consumer society since 1990, following the abandonment of agriculture and the decline of the local fishing industry. Moreover, the manufacturing sector migrated to southern China around this time. From 1997 to 2000, the GDP decreased in response to a decrease in gambling income and tourism as a result of increased criminal activity and a corresponding decrease in tourist interest in visiting the city (Lei et al. 2011). Since 2000, Macao's economy has experienced robust growth as a result of a more holistic view that has emphasized other aspects of the economy (e.g., the city's cultural and natural heritage), combined with more effective public security and the

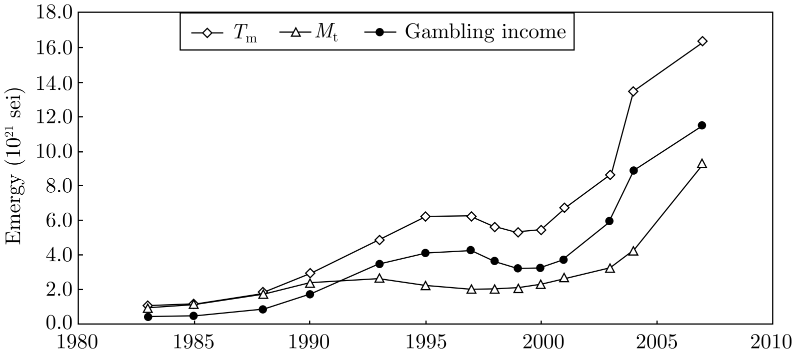

Fig. 4.6 Emergy trends for T_m, M_t, and gambling income from 1983 to 2007 (Lei et al. 2011)

sustained prosperity of China, leading to increases in tourist visits from China (Lei et al. 2011).

Figure 4.6 shows the changes in T_m, M_t, and gambling income from 1983 to 2007. Both T_m and M_t peaked between 1995 and 1997, decreased briefly, then increased once more. The emergy received from Macao's tourism industry represents the emergy converted from the monetary income provided by tourism (T_m), and the emergy of tourist consumption is the emergy provided to the tourists (M_t). The emergy of tourism (T_m) increased from 11.1×10^{20} sej in 1983 to 163.5×10^{20} sej in 2007. During the same period, M_t increased from 9.56×10^{20} sej to 93.03×10^{20} sej. Gambling income peaked between 1995 and 1997, decreased briefly, and then began to increase again. The proportion of total emergy use (U) that was consumed by tourists (R_t) increased steadily, from 0.096 in 1983 to 0.267 in 2007 (Table 4.5).

This analysis has shown that more emergy wealth is imported than exported in Macao's tourism industry. The tourism-related emergy flows, storage, and indices all changed to follow the rapid changes in Macao's socioeconomic system. Accompanying the sustained growth of tourism from mainland China and the construction of new casinos, the expenditures of non-gambling tourism increased (Figs. 4.4, 4.5), mainly as a result of two factors: First, Macao is a port where people, cargo, and capital are generally allowed to flow freely. The lower tax rates and prices for gold, jewelry, and cosmetics compared with Mainland China attracts many Chinese visitors, who spend large amounts of money on these and other goods. Second, Chinese visitors also spend large amounts of money consuming the services provided by Macao (DSEC 2008).

4.4 Conclusions

Ecological tourism appeals to ecologically and socially conscious individuals. It typically involves travel to destinations where the flora, fauna, and cultural heritage are the primary attractions, although visitors motivated by the latter attraction are often referred to as "cultural heritage tourists" rather than ecotourists. Cultural attractions are an important part of tourism at levels ranging from global highlights to the lesser attractions that underpin a local culture's identity (Richards 2001). However, culture has increasingly been rediscovered as an important marketing tool to attract travelers who are interested in a region's heritage. Responsible ecotourism includes programs that minimize the negative aspects of conventional tourism on the environment and enhance the cultural integrity of local peoples. This would have the additional beneficial effect of diversifying Macao's tourism economy, making it more resistant to recessions or changes in tourist preferences.

In Macao, our data show that visitors were strongly attracted by gambling, and spent a large proportion of their money on gambling and related activities. Gambling has been legal in Macao since the 1850s, when the Portuguese government legalized the activity in their colony. However, the gambling industry has also been a source of instability in Macao's economy, as the nature of the gambling business does not appear to be susceptible to technological advancement or productivity growth. The gambling business also depends strongly on the prosperity of other Asian economies, especially those of China and Hong Kong.

Sustainable tourism development depends on the wise use of resources and an understanding of the flows of energy embodied in these resources (i.e., the emergy flows). Due to a lack of data on services and imports from other regions, we used the world $E_m/\$$ ratio for all imported services. This approach undervalues the labor and service imports, since (for example) China's $E_m/\$$ value is higher than the global average (Lei and Wang 2008a), and using this higher value in our accounting would decrease the net emergy for Macao. Adopting the real $E_m/\$$ value for Macao and the regions that exchange emergy with the city would therefore increase the net emergy of Macao's system. However, determining that real value of $E_m/\$$ will be a challenge for future research.

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Chapter 5
Ecological Energy Accounting for the Gambling Sector: A Case Study in Macao

5.1 Introduction to Macao's Gambling Sector

In recent decades, the field of ecological economics, which integrates systems ecology with classical economics, has provided an innovative approach to understanding the interdependent relationships between the environment and man (Costanza et al. 1997). The emergy evaluation model developed by Odum has proven to be a useful tool for measuring the environment's contribution to human welfare (Ulgiati et al. 1994; H. T. Odum 1996; Huang 1998; Ulgiati and Brown 1998; Brown and Ulgiati 1999; Huang and Hsu 2003). Emergy analysis considers all systems to be networks of energy flows, and determines the value of these streams in emergy units. "Emergy is a universal measure of real wealth of the work of nature and society made on a common basis" that allows direct comparisons between flows of money, energy, and materials despite the different units used to measure these flows (Ulgiati and Brown 2009; H. T. Odum and Odum 2001). The characteristics and advantages of the emergy analysis method were concisely stated by Hu et al. (2009) and Li and Wang (2009).

Gambling and related tourism activities represent a special form of economic and societal activity (Wikipedia 2012). Since 2000, the framework of emergy analysis has been used to analyze tourism (Abel 2000; Brown and Ulgiati 2001). In these and other studies, emergy inflows from tourism have been accounted for in the following areas: (1) transportation, since the tourists must be brought to the study area and must move around once they have arrived; (2) local services, such as those provided by the hotel industry, since these are consumed directly and indirectly to maintain and promote the industries that support tourists during their stay; (3) imported goods (including the emergy of shipping and foods), since these emergy inflows into the retail subsystem also sustain tourist activities; and (4) labor, since tourism is supported by a large labor force that embodies a substantial emergy inflow. The sum of these categories of imports represents the total emergy *exports* of tourism, since tourists take these benefits with them when they leave the study system, even though the exchange processes happen within the host region (Abel 2000). Brown and Ulgiati

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(2001) have studied tourism resorts in Mexico and Papua New Guinea, and proposed that economic development is related to the net emergy benefits created by tourism, and that these net benefits represent a positive net trade in emergy.

Despite these previous studies, the emergy accounting method has not been used to analyze the gambling sector, which is a crucial component of cities such as Macao. In the present chapter, we use emergy accounting to illustrate the emergy flows within Macao's gambling sector. To do so, we analyze the emergy flows through this sector and calculate several emergy-based indicators for the sector to let us analyze the functioning and efficiency of this sector.

Note: Because of the large number of parameters defined in this book, we have provided a summary of all parameters and their definitions in Appendix C.

5.2 An Overview of Macao and Its Gambling Sector

Macao had a population of 465 333 in 2005. This special administrative region lies between the longitudes of 111°31′33″E and 111°35′43″E and the latitudes of 22°06′39″N and 22°13′06″N, at the western side of the Pearl River estuary. Macao's annual temperature averages 22.3 °C (Maritime Administration 2005) due to its location within the southern edge of the northern tropics. The region covered 27.5 km^2 in 2004, including the Macao Peninsula, Taipa Island, Coloane Island, and the Cotai Reclaimed Land (Lei et al. 2010).

Macao's gambling sector can be traced back to the 16th century, when Macao first opened its harbor to visitors (McCartney 2005). After Hong Kong's sovereignty was ceded to the British in 1842, Macao was gradually replaced as an important trading port by Hong Kong. In an effort to fill its depleted coffers and diversify its economic activities, Macao's Portuguese government legalized gambling for the first time in 1847. At the time, Macao was renowned as "the Monte Carlo of the Orient".

In 2002, Macao's government ended its monopoly on gambling and granted three (later six) casino operating concessions and subconcessions to six local and international gambling companies. In May 2004, the first Asian casino project in which an American company invested, the Venetian Casino Company's Sands Casino Macau, was opened. This was also the first gambling investment project developed by an American company in Asia. In the same year, Galaxy's first project (Casino Waldo) also commenced operations. By the end of 2004, 17 casinos were operating in Macao (DSEC 2005).

Gambling plays an important role in Macao's economy. The gambling activities can be divided into three main categories: casino games (Table 5.1), horse racing, and greyhound racing (Table 5.2). In addition, sports betting and a number of lotteries are available, and provide a significant contribution to the economy. The casino industry, which accounts for about 95 % of gambling revenues, is viewed by many as harmful to society because of its high social and economic costs for gamblers who come from nearby regions. A high crime rate also resulted from these economic conditions, and became one of the biggest problems faced by Macao's society. Since

Table 5.1 Changes in the numbers of gaming tables, slot machines, and pachinko machines from 2002 to 2004

Game categories	2002	2003	2004
Gaming tables	339	424	1092
Slot machines	808	814	2254
Pachinko machines	188	188	188

Source: Gaming Inspection and Coordination Bureau of Macao (2012)

Table 5.2 Gross revenues from Macao's main gambling activities from 2002 to 2004

Gaming item	Revenues ($\times 10^7$ \$)		
	2002	2003	2004
Games of chance	268.22	347.18	521.74
Greyhound racing	0.95	0.92	1.09
Horse racing	6.71	12.50	20.33
Chinese lotteries	0.05	0.04	0.06
Instant lotteries	0.01	0.001	0.001
Sports lotteries—football (soccer)	7.74	6.18	5.57
Sports lotteries—basketball	0.67	0.62	0.45
Total	284.35	367.47	549.25

Source: Gaming Inspection and Coordination Bureau of Macao (2012)

Macao's return to Chinese rule in 1999, the public security situation has markedly improved (Lei and Wang 2008a).

Gambling remains a pillar of Macao's economy. Information from DSEC (2005) indicates that the real GDP reached \$10.31 billion in 2004 (all values in U.S. dollars). In 2004, gambling taxes generated an estimated 78.8 % of the Macao Special Administrative Region's total fiscal revenues (Gaming Inspection and Coordination Bureau of Macao 2012). The success of Macao's gambling sector is primarily due to its official support by the government, robust investments by entrepreneurs, and the gambling preferences of Asians (Lei et al. 2010).

5.3 Study Methodology

We used the conventional emergy synthesis method of H. T. Odum (1996) to study the flows of materials, energy, and money using a single metric. To account for the emergy of labor, we have proposed a quantitative method that is introduced in Sect. 5.4. Unless otherwise indicated, all data used in the present analysis were provided by Macao's DSEC (2005).

The buying power (H. T. Odum 1996) of money imported by visitors (T_{m}) differs from the monetary value consumed by visitors ("service exports", abbreviated as M_t) and flows in the opposite direction. Since the services of a tourism city such as Macao are shared by local residents and visitors, we used a proportional approach (see Eqs. 1.14 and 1.15 in Chap. 1, and Sect. 4.2.1 in Chap. 4) to calculate the service exports and emergy consumption by visitors (Lei et al. 2006; Lei and Wang 2008a, 2008b).

The emergy of labor in the gambling sector (E_g) was measured by multiplying the population of employees in the gambling sector (N_g) by the per capita emergy of employees, which equals the ratio of the city's total emergy (U) to its total employed population (N_e)

$$E_g = N_g \times (U/N_e) \tag{5.1}$$

We have also used the following emergy-based indicators in our analysis (Lei and Wang 2008a) of Macao's gambling sector (all of which are defined in Chap. 1): renewable resources (R), imported emergy (F), exported emergy (Y), the emergy exchange ratio (EER), the emergy yield ratio (EYR), net emergy ($= R + F - Y$), and the net emergy ratio (NER $=$ net emergy/total emergy used [U]).

5.4 Results and Discussion

The case study in this chapter used data from 2002 to 2004, a period in which Macao's gambling and tourism industry grew rapidly. The data were provided by DSEC (2005) and the Gaming Inspection and Coordination Bureau of Macao (2012). The emergy data were obtained from our calculations and from previously published results (Lei and Wang 2008a). We adopted the 9.26×10^{24} sej planetary baseline for annual emergy imports (Campbell et al. 2005). The results of our calculations appear in Table 5.3 (emergy flows) and Table 5.4 (emergy indicators). Figure 5.1 summarizes the emergy flows through Macao's gambling sector. The imports (F) represent purchased resources (food, water, electricity, equipment rent, and materials), labor, and operating services. The exports (Y) represent the profit of the casino companies and government taxes. Renewable resources emergy (R, including sunlight, wind, and beautiful sights) and non-renewable resources emergy (N, including sand, stone, winds, and materials used to construct the casinos) were also consumed by the gambling sector, but because it was not possible to find data on these emergies specifically for this economic sector, we assumed that the total emergy used (U) equaled the imports (F) by the gambling sector, and we have omitted data on these specific emergy types from Fig. 5.1. The services and recreation emergy consumed by gambling are consumed by gamblers during the betting process.

Macao is a tourism-dominated city, with a huge number of tourists arriving every day; the emergy consumed by the gambling sector accounted for about 37.2 % of the city's total emergy use in 2004 (Table 5.4). Table 5.4 shows that the EER (emergy exchange ratio) of tourism for Macao increased from 1.16 in 1983 to 3.22 in 2004 (Table 5.4). A high ratio means that the system captures more emergy wealth through the services it provides to tourists. Table 5.5 summarizes the emergy synthesis for food and beverage imports and consumption in Macao's gambling sector in

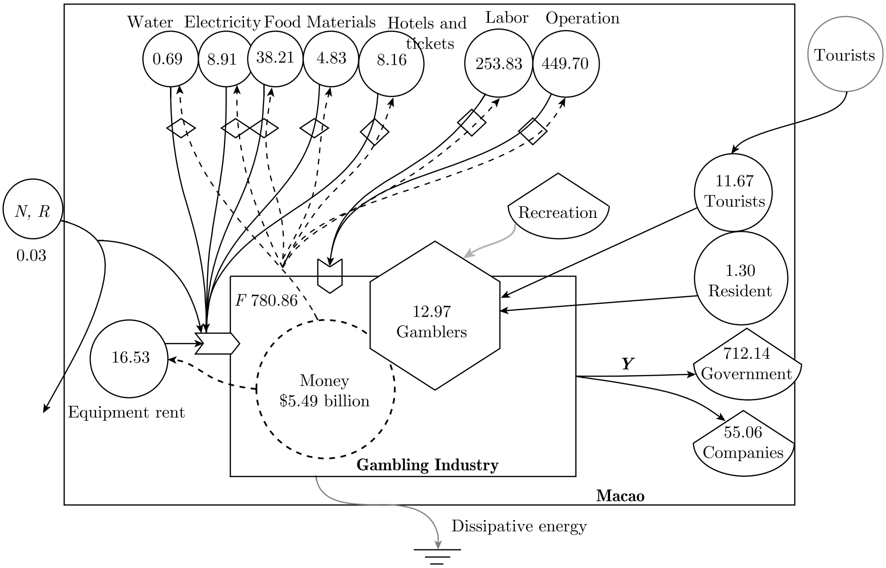

Fig. 5.1 A summary of the emergy flows through Macao's gambling sector. All emergy values are $\times 10^{19}$ sej, except for gamblers, tourists, and residents, which are $\times 10^{6}$ sej (Lei et al. 2010)

Table 5.3 Summary of the emergy flows for Macao in 2004

Variable	Meaning	Value (J, g, $)	Solar emergy ($\times 10^{20}$ sej)	Emdollars ($\times 10^{9}$ em$)
R	Renewable resources	1.11×10^{15} J	0.27	0.01
N	Non-renewable resources	3.62×10^{11} g	3.60	0.15
Fuel	Imported fuels and minerals	3.16×10^{16} J	30.14	1.28
G	Imported foods, goods, and purchased goods (raw materials)	7.03×10^{15}	187.50	7.86
$P_2 I_3$	Emergy of services from outside the study area	1.43×10^{9} $	23.77	1.00
Imports (F)	Imported emergy: Fuel + $G + P_2 I_3$	3.86×10^{16}	241.34	10.14
U	Emergy used: $R + N + F$	3.97×10^{16}	245.21	10.31
B	Exported production	3.00×10^{15}	136.29	5.73
M_t	Tourist consumption		41.75	1.75
Exports (Y)	Exported emergy ($B + M_t$)		178.04	7.48
ELE	Electricity: 1880 GW · h	7.36×10^{15} J	11.68	0.61
GDP	Gross domestic product ($)	1.03×10^{10} $	–	–
P_2	World emergy/$ ratio	1.66×10^{12}	–	–
P_1	Macao's emergy/$ ratio	2.38×10^{12}	–	–

Table 5.4 Emergy and tourism-related indicators for Macao from 1983 to 2004[a]

Indicators	1983	1993	2003	2004
Population	282 843	383 984	448 495	465 333
GDP ($\times 10^9$ \$)	1.15	5.67	7.90	10.31
Tourists per year ($\times 10^3$)	4101	5998	11 888	16 673
Tourists/population	14.5	15.6	26.5	35.8
Tourism income ($\times 10^9$ \$)	0.50	2.48	5.21	8.10
Gambling income ($\times 10^9$ \$)	0.21	1.77	3.58	5.49
T_m ($\times 10^{20}$ sej)[b]	11.05	49.09	86.50	134.56
M_t ($\times 10^{20}$ sej)[c]	9.56	25.24	32.54	41.70
Emergy/\$ of Macao ($\times 10^{12}$ sej \$$^{-1}$)	8.76	4.36	2.78	2.38
Emergy used (U, $\times 10^{20}$ sej)	100.45	247.02	219.73	245.21
Gambling income[d] ($\times 10^{20}$ sej)	4.61	35.00	59.40	91.24
Emergy exchange ratio (EER) of tourism[e] (T_m/M_t)	1.16	1.83	2.65	3.22
Tourism net emergy[e] ($T_m - M_t$)	1.54	22.22	53.92	91.96
Net emergy ratio (NER) of tourism[e]	0.14	0.45	0.62	0.68
T_m/GDP (%, US\$ basis)	44.0	43.7	65.9	78.6
Gambling taxes (% of government revenues)	38.0	46.2	74.9	78.8
Gambling/GDP (%, US\$ basis)	18.3	31.1	45.3	53.2
Gambling/U (%, sej basis)	4.6	13.3	27.0	37.2

[a] The population, GDP, tourist numbers, and tourism income were provided by DSEC (2005)

[b] T_m is the emergy of tourism income, and was obtained from Lei et al. (2008)

[c] M_t was obtained from Lei and Wang (2008a)

[d] Gambling income was converted from monetary to emergy terms using Eq. 1.9 in Chap. 1

[e] The EER of tourism, the tourism net emergy, and the net emergy ratio of tourism were obtained from Lei and Wang (2008a)

2004. Table 5.6 summarizes the emergy imports and exports for Macao's gambling sector in 2004. These results will be discussed in more detail in the remainder of this section. Figure 5.2 summarizes the overall emergy flows through the gambling sector in 2004 (Lei et al. 2010).

To analyze the emergy of the gambling sector, we must be able to estimate the number of gamblers per year, but there were no officially available data for this specific statistic. The population of gamblers was instead provided by the Sociedade de Jogos de Macau (2006, personal communication), which operated 15 of the 17 of casinos in Macao in 2004. Based on interviews with the managers of these gambling businesses, we estimated that 70 % of the visitors to Macao participate in the gambling sector (70 % × 16 673 000 = 11 671 100), and that this amount accounts for about 90 % of the total gamblers. Thus, in 2004, we estimated that the number of gamblers was about (70 % × 16 673 000)/90 % = 12 967 888. We have used

Table 5.5 Food and beverage imports and consumption in Macao's gambling sector in 2004

Item	Weight ($\times 10^8$ kg)	Spending ($\times 10^8$ \$)	Total emergy ($\times 10^{19}$ sej)	Emergy per kg ($\times 10^{12}$ sej kg^{-1})
Imported food[a]	3.363	4.029	392.14	11.659
Imported beverages[a]	0.925	1.237	3.02	0.326
Food, bottled water, and other beverages in casinos[b]	1.474	1.765	38.21	–
Food in casinos[c]	0.295	–	34.36	–
Bottled water and other beverages in casinos[c]	1.179	–	3.85	–

[a] The imported food and beverages represent totals from the data provided by DSEC (2005)

[b] *Source*: Gaming Inspection and Coordination Bureau of Macao (2012)

[c] The calculation processes are discussed in Sect. 5.4.3

Table 5.6 Summary of the emergy flows in Macao's gambling sector in 2004

Categories	Items	Energy ($\times 10^{13}$ J)	Money ($\times 10^8$ \$)	Transformity (sej unit^{-1})	Emergy ($\times 10^{19}$ sej)
Imports[a] (F)					779.73
	1. Water	1.04		6.60×10^5	0.69
	2. Electricity	55.70		1.60×10^5	8.91
	3. Food		1.77		38.16
	3. Equipment rent		0.69	2.38×10^{12}	16.53
	4. Materials		0.29	1.66×10^{12}	4.83
	5. Hotel and tickets		0.34	2.38×10^{12}	8.16
	6. Labor	22 567 casino employees		1.12×10^{17}	252.75
	7. Operating services		18.90	2.38×10^{12}	449.70
Exports (Y)					767.20
	1. Company profits		3.87	1.42×10^{12}	55.32
	2. Government taxes		50.09	1.42×10^{12}	712.14
Income	Gambling and other receipts		54.93	1.66×10^{12}	912.37
P_3	$E_m/\$$ of gambling sector	Imports/Income		1.42×10^{12}	
Gamblers					12.97×10^6

[a] In Macao's gambling sector, we assumed that the total emergy used (E_m) equaled the imports (F)

this quantity for our analysis of emergy consumption by the gambling sector in the following sections (Lei et al. 2010).

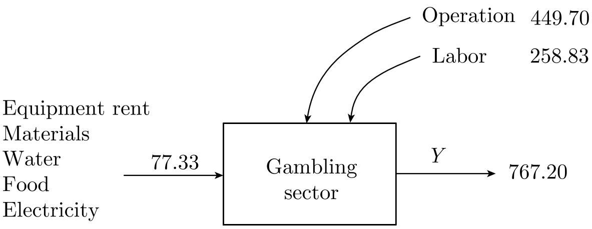

Fig. 5.2 Overall emergy summary diagram for Macao in 2004 (all emergy values are $\times 10^{19}$ sej year^{-1}) (Lei et al. 2010)

5.4.1 *Water Emergy*

Water is an important resource in the gambling sector. It is used for spraying (e.g., in fountains), cleaning, toilet flushing, restaurants, hotels, drinks, and other uses. In 2004, the water cost was \$1.154 × 10^6 (Gaming Inspection and Coordination Bureau of Macao 2012). At a price of \$0.547 m^{-3}, we used an estimated water consumption (based on the purchase data) of 2.11×10^6 m^3, which is equivalent to an emergy of 1.04×10^{13} J.

The emergy of the used water

$$= 2.11 \times 10^6\ \mathrm{m}^3 \times 1\ \mathrm{t\,m}^{-3} \times 1\,000\,000\ \mathrm{g\,t}^{-1} \times 4.94\ \mathrm{J\,g}^{-1} \times 660\,000\ \mathrm{sej\,J}^{-1}$$
$$= 0.688 \times 10^{19}\ \mathrm{sej}$$

By dividing this emergy by the number of gamblers in 2004 (12.97×10^6), the average water emergy consumption per tourist would be 0.53×10^{12} sej (Lei et al. 2010).

5.4.2 *Electricity Emergy*

Electricity is an important resource in the gambling sector. It powers the air conditioning, lights the casinos, and runs the slot machines and other equipment, as well as the hotel machinery and other equipment required to support tourism. In 2004, the gambling sector paid for \$2.14 × 10^7 of electricity at an average price of \$0.13834 $\mathrm{kW \cdot h}^{-1}$.

The emergy of the used electricity

$$= \left(2.14 \times 10^7 / 0.13834\right) \times 1000 \times 3600\ \mathrm{J} \times 160\,000\ \mathrm{sej\,J}^{-1}$$
$$= 8.91 \times 10^{19}\ \mathrm{sej}$$

By dividing this quantity by the number of gamblers in 2004 (12.97×10^6), the average electricity emergy consumption per tourist would be 6.87×10^{12} sej (Lei et al. 2010).

5.4.3 Food and Beverage Emergy

The gambling sector provides visitors with food and beverages. The sector's spending on these materials in casinos in 2004 totaled \$1.77 × 10^8, with a total materials weight of about 1.47 × 10^8 kg (Table 5.5). After consulting the managers of these businesses, we estimated that 80 % of the total by weight was beverages and bottled water, and 20 % was foods.

To calculate the emergy of these foods, bottled water, and other beverages, we used the average emergy per kg of Macao's foods and beverages separately. Since the bottled water includes the emergy of the labor required to create the product and the emergy of the plastic materials, we estimated the emergy of these two components as equal to the emergy of beverages.

Food consumption:

$$\begin{aligned}\text{Value} &= 20\,\% \times \text{Food and beverages in casinos} \times \text{Emergy per kg food}\\ &= 20\,\% \times 1.474 \times 10^{8}\ \text{kg} \times 11.659 \times 10^{12}\ \text{sej}\,\text{kg}^{-1} = 34.28 \times 10^{19}\ \text{sej}\end{aligned}$$

Beverage consumption:

$$\begin{aligned}\text{Value} &= 80\,\% \times \text{Food and beverages in casinos} \times \text{Emergy per kg beverages}\\ &= 80\,\% \times 1.474 \times 10^{8}\ \text{kg} \times 0.326 \times 10^{12}\ \text{sej}\,\text{kg}^{-1} = 3.88 \times 10^{19}\ \text{sej}\end{aligned}$$

Thus, the emergy of food and beverages consumed in casinos

$$= 34.28 \times 10^{19}\ \text{sej} + 3.88 \times 10^{19}\ \text{sej} = 38.16 \times 10^{19}\ \text{sej}$$

By dividing this quantity by the number of gamblers in 2004 (12.97 × 10^6), the average emergy of food and beverages consumption per tourist would be 29.44 × 10^{12} sej (Lei et al. 2010).

5.4.4 Labor Emergy

The total employed population of Macao was 218 013 in 2004; of these workers, 22 567 worked in the gambling sector (DSEC 2005). According to Eq. 5.1 (and the data in Table 5.6):

$$\begin{aligned}\text{Transformity per employee} &= U/N_{\mathrm{e}} = 2.452 \times 10^{22}/218\,013\\ &= 11.248 \times 10^{16}\ \text{sej per worker}\end{aligned}$$

$$\begin{aligned}\text{Labor emergy in the gambling sector} &= E_{\mathrm{g}} = N_{\mathrm{g}} \times (U/N_{\mathrm{e}})\\ &= 22\,567 \times 11.248 \times 10^{16}\\ &= 252.75 \times 10^{19}\ \text{sej}\end{aligned}$$

By dividing this quantity by the number of gamblers in 2004 (12.97 × 10^6), the average emergy labor per tourist would be 194.87 × 10^{12} sej.

The method used to evaluate the human contribution to emergy flows has been one of the major differences among emergy analysts. Some researchers omit the labor category to avoid the question of how to evaluate this service on the same basis as the other imports (e.g., H. T. Odum 1996). Others report the hours of labor without assigning an energy or emergy value (e.g., Lan et al. 2002). Still others calculate the energy of a person's daily metabolism, which produces a relatively small value of about 1.70×10^{16} sej year^{-1} (Brandt-Williams 2001). Ulgiati et al. (1994) evaluated the emergy consumption by labor in industrial production based on two main assumptions: untrained labor and accounting for all emergy required to support this labor. Based on this approach, Ulgiati et al. calculated the transformity for labor as 2.20×10^{16} sej year^{-1} per worker in Italy. In Macao, the equivalent per-worker emergy calculated using this method was 11.2×10^{16} sej year^{-1} in 2004, which was 5.1 times Italy's value in 1994 (Lei et al. 2010). Thus, the emergy efficiency was much higher than that of Italy, although the time periods, industries, and other assumptions differ between these analyses (Lei et al. 2010).

5.4.5 E_m/$ Ratio

Gamblers bring money into gambling establishments for recreation as they attempt to win money. These establishments provide gamblers with food, tickets, services, water, electricity, equipment, labor, and other operating services. The gamblers gain pleasure and recreation from their activities, while mostly losing their money. The balance of imports of emergy in the form of money and exports of emergy in the form of services is summarized in Table 5.6.

Based on the principle of conservation of energy that is assumed by the conventional method of emergy accounting, the emergy used in the casino equals the total emergy imports. In 2004, the $E_{\mathrm{m}}/\$$ ratio for the gambling sector was 1.42×10^{12} sej $\$^{-1}$ (Table 5.7), which was lower than that of Macao as a whole (2.38×10^{12} sej $\$^{-1}$; Lei and Wang 2008b).

5.4.6 Emergy Yield Ratio

The emergy yield ratio (EYR) represents the emergy of exports divided by the emergy of the imports required to produce those exports (Ulgiati et al. 1994). This ratio indicates whether a process can serve as a primary emergy source for an economy. The ratio for competitive sources of fuels has typically been assumed to be greater than 1 (H. T. Odum 1988), but for an urban system, a lower ratio means more net emergy transferred into the city (Lei et al. 2008). The emergy imported by Macao's gambling sector equals the total imports by casinos and other gambling establishments, whereas the exported emergy (Y) equals the government revenues

Table 5.7 Summary of the emergy flows in Macao and in its tourism and gambling sectors in 2004

Index	Expression	Macao[a]	Gambling sector	Tourism
Imports (sej)	F	2.41×10^{22}	779.73×10^{19}	1.35×10^{22}
Emergy used (sej)	U	2.45×10^{22}	779.73×10^{19}	1.35×10^{22}
Exports (sej)	Y	1.78×10^{22}	767.20×10^{19}	0.426×10^{22}
Emergy yield ratio (EYR)	Y/F	0.738	0.984	0.320
Proportion of imported services	Imported services$/U$	0.097	0.901	
Emergy use per person	$U/$population	5.27×10^{16}	6.01×10^{14}	8.14×10^{14}
$E_\mathrm{m}/\$$ ratio, P_1 (sej $\$^{-1}$)	$U/$GDP	2.38×10^{12}	1.42×10^{12}	
Ratio of electricity to emergy use	Electricity$/U$	0.059	0.011	
Average electricity per capita	Electricity$/P$	3.12×10^{15}	6.87×10^{12}	
Net emergy (sej)	$R + F - Y$	6.36×10^{21}	13.69×10^{19}	9.20×10^{21}
Net emergy ratio (NER)	Net emergy$/U$	0.26	0.02	0.68

[a] *Source*: Lei and Wang (2008b)

and profits from this sector. Table 5.7 shows that the EYR value for gambling sector in 2004 equals:

$$\mathrm{EYR} = \left(7.67 \times 10^{21}\right)/\left(7.80 \times 10^{21}\right) = 0.983$$

This value was higher than the EYR for Macao as a whole (0.74) due to the large amount of profits that were taxed by the government and called "franchise revenues", and it was much higher than the EYR of tourism as a whole ($0.320 =$ Exports/Imports $= M_\mathrm{t}/T_\mathrm{m} = 42.6 \times 10^{20}/134.56 \times 10^{20}$). Macao's tourism sector therefore receives net emergy that supports the region's society and other industries (Lei et al. 2010).

5.4.7 *Emergy Used per Gambler*

The emergy used per gambler can be obtained by dividing the imported emergy (Table 5.7) by the number of gamblers:

$$\begin{aligned}\text{Imports/Gamblers} &= \left(779.73 \times 10^{19}\right)/\left(12.97 \times 10^{6}\right)\\ &= 6.01 \times 10^{14}\ \text{sej per gambler}\end{aligned}$$

This value equaled only 1.1 % of the value for a Macao resident (Table 5.7), and equaled 74.0 % of that for a tourist (8.14×10^{14} sej per tourist). This means that gamblers only received a small part of the services compared with the amounts received by residents and tourists when the gamblers stayed in casinos and consumed there (Lei et al. 2010).

5.4.8 The Per Capita Electricity Emergy

The electricity emergy per capita expresses the level of consumption of energy resources, and thus, reflects the environmental pressure created by this consumption. The electricity emergy per gambler (Table 5.7) was 6.87×10^{12} sej, which was much less than that of Macao (3.12×10^{15} sej). The ratio of the electricity emergy to total emergy used by the gambling sector was only 1.1 %, which was much lower than that of Macao as a whole (5.9 %; Lei et al. 2010).

5.4.9 The Ratio of Imported Services to Emergy Used

In the gambling sector, the dense concentrations of labor and services focus on the gambler's activities (Table 5.6):

$$\begin{aligned}\text{Imported services} &= \text{Operating services} + \text{Labor}\\ &= 449.70 \times 10^{19}\ \text{sej} + 253.83 \times 10^{19}\ \text{sej} = 703.53 \times 10^{19}\ \text{sej}\end{aligned}$$

The ratio of imported services to emergy used ($U = \text{Imports} = 779.73 \times 10^{19}$) is high (0.901, versus about 0.097 for Macao as a whole). Gambling requires substantial labor and services. The newly opened casinos absorbed a large number of employees, resulting in a labor shortage for other sectors. In the near future, the gambling sector will continue to compete with other industries for the limited supply of local labor (Lei et al. 2010).

5.4.10 Net Emergy and Net Emergy Ratio

The net emergy of the gambling sector (i.e., $R + I - Y$) was 13.69×10^{19} sej (Table 5.7), and its net emergy ratio $=$ net emergy$/U = 13.69 \times 10^{19}/779.73 \times 10^{19} = 0.018$.

In 2004, the net emergy ratio for the gambling sector was much lower than that of Macao (0.26) and of tourism (0.68). Most of the net emergy wealth received in gambling was transferred to the government in the form of taxes to sustain the region's society; evidently, this outflow of emergy decreased the net emergy of the gambling sector (Lei et al. 2010).

5.4.11 Emergy Exchange Ratio

The emergy exchange ratio (EER) is always expressed relative to one or the other trading partners to indicate the relative trade advantage of one partner over the other.

Table 5.8 Summary of the emergy exchange ratio (EER) of Macao and of its tourism and gambling sectors in 2004

Item	Received (sej)	Given (sej)	EER
Macao	2.41×10^{22}	1.78×10^{22}	1.35
Tourism	13.46×10^{21} (T_m)	4.17×10^{21} (M_t)	3.23
Tourists	4.17×10^{21} (M_t)	13.46×10^{21} (T_m)	0.31
Gambling sector	912.37×10^{19}	779.73×10^{19}	1.17
Gamblers	779.73×10^{19}	912.37×10^{19}	0.85

[a] Emergy flows of Macao and its tourism were obtained from Lei and Wang (2008a) and Lei et al. (2008)

According to H. T. Odum (1996), an EER value greater than 1 means that the received emergy exceeds the emergy that is given away during the exchange process. Many technologically and financially developed countries have emergy imports that are much higher than their emergy exports; for example, Italy had an EER of around 2.5 in 1994 (Ulgiati et al. 1994).

Table 5.8 summarizes the EER values for Macao in 2004. The EER of the gambling sector was 1.17; as a result, the gambling sector received more emergy than the exports of emergy. The EER value was less than that of Macao as a whole (1.36). On the other hand, the EER of gamblers was only 0.86, and although this was higher than that of the tourists (0.32), an EER value less than 1 indicates that the gamblers and tourists are contributing their emergy to the gambling sector when they lose money in a casino or spend money on other tourist activities.

5.5 Conclusions

Traditionally, the emergy of labor has been obtained by multiplying the payments to workers (salaries) by a region's emergy/\$ ratio (H. T. Odum 1996). Because gambling activities include special recreation values that are attractive to gamblers, the conventional calculation method (Eq. 5.1) undervalues the relative emergy involved. Here, we developed a new equation by using the transformity per person (employee) to provide a more reasonable value for the emergy of the services consumed by gambling activities. In Macao, the transformity of an employee in 2004 (11.2×10^{16} sej per worker) was much higher than that of a worker in Italy (2.20×10^{16} sej per person; Ulgiati et al. 1994).

Our results also reveal the differences between gambling and other economic activities. In the gambling sector, the proportion of imported service emergy (0.901) was higher than that of Macao as a whole (0.097), but the net emergy ratio (NER) was lower (0.02) than that of Macao as a whole (0.26) because government taxation of this sector is too high. The majority of the earned emergy is exported as taxes, and these exports become an inflow for the government (Lei et al. 2010).

In the gambling sector, emergy exchange processes are simpler than in a broader system such as Macao. The concentrated emergy and currency flows in this narrow realm usually create a lower emergy/\$ ratio (e.g., for gambling in Macao, 1.42×10^{12} sej $\$^{-1}$) than that of a city or region (e.g., for Macao as a whole, 2.38×10^{12} sej $\$^{-1}$).

Some foods and related materials that support the gambling sector were imported from mainland China, and their emergy has been undervalued in our calculations when we adopted the lower emergy/\$ ratio of Macao (2.38×10^{12} sej $\$^{-1}$) instead of using a different ratio for resources imported from China (2.89×10^{12} sej $\$^{-1}$; Lei et al. 2008), leading to some errors in our estimates. This problem must be solved in future research (Lei et al. 2010).

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Chapter 6
Emergy Synthesis for Waste Treatment in Macao

6.1 Introduction to Waste Treatment in Macao

From the perspective of systems ecology, cities are self-regulating systems similar to super-organisms, but they have been created for the benefit of human beings and to sustain our livelihood. Like other organisms, cities cannot survive without maintaining stable links with the surrounding areas from which they draw energy, food, and materials and into which they release their wastes (Huang and Hsu 2003). To make urbanization sustainable, we must first understand how our cities consume and dispose of resources. As in the case of a living organism's metabolism, the physical and biological processes that characterize a city transform inflows of energy and materials into useful products and services, as well as into wastes, which are generally not considered a useful resource. As the consequences of human needs and activities overload the assimilative capacity of the city's ecosystem, suitable waste management strategies become crucially important. These strategies must account for the limitations on an urban system's ability to assimilate its own wastes. A reduction in the present levels of waste generation and an increase in energy and materials recovery represent two of the most important future requirements for environmentally sound waste management practices (Marchettini et al. 2007).

Since the early 1980s, the emergy synthesis method has been widely used to analyze systems as diverse as ecosystems, industrial processes, and the economies of countries or regions. However, few studies have focused on the emergy of a city's wastes; such studies have included municipal solid waste (MSW; Luchi and Ulgiati 2000; Brown and Buranakarn 2003; Niccolucci et al. 2003; H. Yang et al. 2003) and municipal wastewater (H. Björklund et al. 2001). In many areas, wastes are incinerated to relieve pressure on landfills, and this approach to waste management has many consequences related to emergy flows. This is particularly true for the gaseous emissions produced by waste incineration. However, we found no published papers on emergy analysis of gaseous emissions, possibly because no transformity values have been published for air pollution. The study described in this chapter attempted to calculate (1) the transformity of the fly ash and slag that result from the incineration of MSW, (2) the emergy flows that characterize gaseous emissions,

K. Lei et al., *Ecological Emergy Accounting for a Limited System: General Principles and a Case Study of Macao*, Springer Environmental Science and Engineering,
DOI 10.1007/978-3-642-45170-6_6,

Table 6.1 Summary of the waste treatment methods that have been used in Macao

Time period	MSW		Sewage	
	Landfill	Incineration	No treatment	Biological treatment
Before 1992	+	−	+	−
1992 to 1996	−	+	+	−
After 1997	−	+	−	+

and (3) the efficiency of the waste treatment processes. To illustrate this process, we have used Macao as a case study of the methodology.

Before 1992, Macao's MSW was disposed of as landfill. Macao occupies only a small land area, thus the proper handling of landfill operations has always faced difficulties due to the spatial constraints. To conserve the city's limited land area for more useful purposes, Macao's government adopted a policy of incineration of MSW with energy recovery, and in 1992 the Macao incineration plant began operation (Wong 1997). The byproducts of incineration are gaseous emissions, fly ash, slag, and thermal energy. The thermal energy can be transformed into electricity and recycled to help run plant operations. Ferrous metals are retrieved and recycled. Some of the MSW is not suitable for incineration due to its low calorific value, and these wastes are therefore disposed of in landfills (ECM 2000). The emissions from the incinerator are filtered to reduce their content of dust and hazardous materials by 95 % to reach the required emission standard (W. L. Yang et al. 2001).

Before 1997, municipal wastewater was discharged straight into the sea without any treatment. Since then, biological treatment has been used. The sludge generated by this treatment is transferred to a special incinerator for burning. Currently, Macao has three wastewater treatment plants (on the Macao Peninsula, and on the islands of Taipa and Coloane), with a daily maximum treatment capacity of 234 000 m^3. The plants are expected to meet the city's needs for the next 30 years based on the city's projected future population and economic growth (ECM 2000).

Due to the development of the gambling and tourism industry, there has been a large increase in the number of tourists, which (together with a flourishing infrastructure construction industry and private investment) is expected to increase waste generation, thereby placing increased pressure on the treatment capacity of the incineration plant, the wastewater treatment plants, and landfill areas. In order to ensure the sustainable socioeconomic development of Macao, various waste handling techniques have been considered and adopted over time (Table 6.1).

Note: Because of the large number of parameters defined in this book, we have provided a summary of all parameters and their definitions in Appendix C.

6.2 Emergy Accounting for Macao's Wastes

The emergy of the city's wastes (W) represents an important category of emergy. In the present study, the wastes we included in our analysis included MSW, sewage,

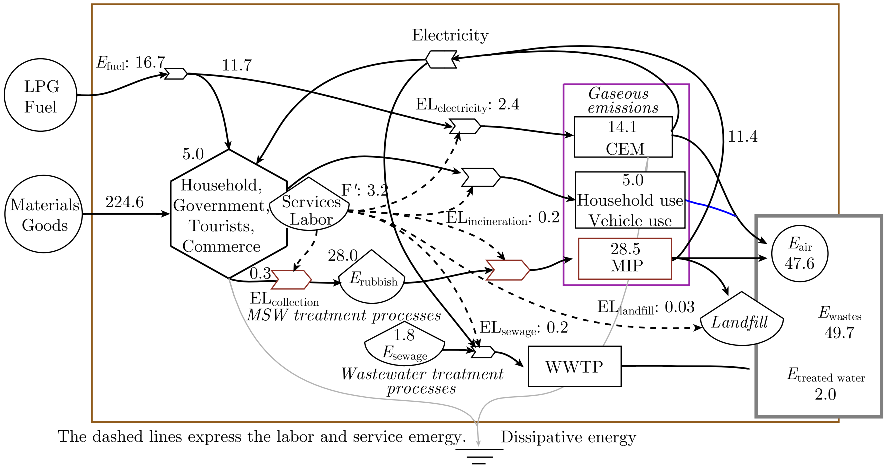

Fig. 6.1 A concise diagram of the emergy flows through Macao's municipal waste treatment system as it has existed since 1997 (all values $\times 10^{20}$ sej). E, emergy (of fuel, waste collection, *MSW*, sewage, air, wastes, treated water); *EL*, emergy of equipment plus labor (of collection, electricity, incineration, sewage, landfill); F' = waste treatment inputs; *LPG*, liquefied petroleum gas; *MIP*, Macao Incineration Plant; *WWTP*, wastewater treatment plant (Lei and Wang 2008)

and gaseous emissions that result partly from the combustion of fossil fuels and partly from incineration of MSW. The emergy to process wastes (E_{w}) takes the form of labor and services, as well as depreciation of the treatment plants and the related equipment (Fig. 6.1). The emergy in the gaseous emissions represents the "memory" of the available energy that was required to produce these emissions. In the present study, we treated gaseous emissions as originating from three sources:

1. The burning of fuels to generate electricity by the Companhia de Electricidade de Macau, a public utility company with the sole concession to transmit, distribute, and sell high-, medium-, and low-voltage electricity in Macao.
2. The burning of fuels by motor vehicles, restaurants, and households. In the present study, we omitted the emergy of services involved in these components of the system, such as the human labor involved in the transportation of these fuels from one location to another, because there was no reliable source of data we could use to evaluate this input.
3. Incineration of MSW by the Macao Incineration Plant, which releases carbon dioxide, carbon monoxide, sulfur dioxide, methane, hydrochloric acid, hydrogen sulfide, and many other gases. We did not include particulate matter in this component of the system's emergy because we found no reliable data on this component of wastes.

Since the heat value can be measured for each of these three processes, and the emergy added by human labor and the use of machines can be evaluated by calculating the emergy per unit of money (i.e., an $E_{\text{m}}/\$$ ratio), the emergy of wastes can be evaluated by tracking the treatment processes used to deal with wastes and can be expressed using the following equations (Lei and Wang 2008):

$$E_{\text{solid waste}} = E_{\text{rubbish}} + \text{EL}_{\text{collection}} + \text{EL}_{\text{incineration}} + \text{EL}_{\text{landfill}} \tag{6.1}$$

$$E_{\text{air}} = E_{\text{fuel}} + \text{EL}_{\text{electricity}} + E_{\text{rubbish}} + \text{EL}_{\text{collection}} + \text{EL}_{\text{incineration}} \tag{6.2}$$

$$E_{\text{treated water}} = E_{\text{sewage}} + \text{EL}_{\text{sewage}} \tag{6.3}$$

$$E_{\text{wastes}} = E_{\text{air}} + E_{\text{treated water}} + \text{EL}_{\text{landfill}} \tag{6.4}$$

where E represents the emergy of a material and EL represents the emergy of the associated equipment plus labor, with the subscripts representing the specific category of emergy. Thus, E_{air} represents the emergy of the gaseous emissions, E_{fuel} represents the emergy of fuel, $\text{EL}_{\text{electricity}}$ represents the labor and services embodied in electricity production, $\text{EL}_{\text{collection}}$ represents the labor and services embodied in waste collection, $\text{EL}_{\text{incineration}}$ represents the labor and services embodied in rubbish incineration, E_{wastes} represents the emergy of discharged wastes, $\text{EL}_{\text{landfill}}$ represents the emergy cost of landfill management, and $E_{\text{treated water}}$ represents the emergy embodied in the sewage treatment process. E_{sewage} represents the emergy of the sewage before treatment, and $\text{EL}_{\text{sewage}}$ represents the labor and services embodied in sewage treatment.

A large investment of labor and technology is required for the treatment of wastes (F'). The emergy feedback ratio (f_r) of wastes (E_{w}/W) can be used to represent the emergy investment in the treatment of each category of waste:

$$f_r = E_{\text{w}}/W = \text{EL}_i/E_i \tag{6.5}$$

where f_r compares the discharged emergy (E_i) with the treatment emergy (EL_i) for waste i. To sustain a system in a steady-state condition, the system must allocate some energy to the treatment of its wastes so as to maintain its metabolism and stability (Lei and Wang 2008).

6.3 Waste Emergy and Transformity in Macao

6.3.1 Waste Emergy Synthesis for Macao

Emergy accounting should account for all of the emergy flows in the transfers of materials and energy into and out of the system under study. To evaluate Macao's waste emergy, the emergy inputs in the forms of labor, fuel, water, electricity, and capital (machines and treatment plants) must be accounted for, in addition to the emergy of all wastes that represent inputs and outputs in the treatment processes. In this analysis, we adopted a value of 9.26×10^{24} sej as the planetary baseline for annual emergy input (Campbell et al. 2005). It was difficult to obtain detailed material and energy consumption data for Macao because the companies involved in waste management believed that this data was a commercial secret, or had not yet obtained detailed data on their own operations. Instead, with the help of the Infrastructure Development Office of Macao's government, we obtained money flow data for the processes we were interested in analyzing and used this as a proxy for the flows of materials and energy. Since the waste management companies receive their contracts as a result of open bidding, we assumed that the prices they receive for their services are economically and technologically rational prices. In addition, the monetary value of suitable treatment technologies should embody the information emergy (i.e., the accumulation of knowledge), which is reflected in these prices and in the technologies purchased to deal with waste treatment. Therefore, we used the monetary values provided by the companies to estimate the emergy used in the city's waste treatment processes. We used data from or about the following waste treatment companies (ECM 2005):

1. Macau Residue System Company, Ltd.: This company is responsible for the daily MSW collection, and uses 400 employees to provide this service. Their operating costs (including labor) totaled \$12.8 million in 2004. (We have presented all monetary values in U.S. dollars based on a conversion rate of 8.023 MOP per US\$ in 2004.) Their waste collection equipment included 80 vehicles and 4000 rubbish bins.
2. Wastewater treatment plants: Macao's three wastewater treatment plants have a daily maximum treatment capacity of 234 000 m^3, and employ 60 people. In 2004, the average volume of wastewater treated daily by the three plants amounted to 151 039 m^3. Their operating cost totaled \$6.4 million in 2004.
3. The Macao Incineration Plant: This plant is responsible for incinerating the city's MSW, and it had 60 employees in 2004. The daily maximum treatment capacity was 860 t, and its operating cost totaled \$3.89 million in 2004. The emergy flows for waste incineration are summarized in Figs. 6.1 and 6.2.
4. Landfill: These operations are controlled by Macao's Infrastructure Development Office. The management cost of the landfill work in 2004 was estimated to be \$1.1 million.

We calculated the waste emergy values for Macao in 2004 using Eqs. 6.1 to 6.5, and the results are summarized in Table 6.2. In 2004, the emergy of the total wastes was 49.71×10^{20} sej (Fig. 6.1), including MSW (27.99×10^{20} sej), gaseous emissions (47.60×10^{20} sej), and sewage (2.02×10^{20} sej). Note that some of these values may not match the values in Fig. 6.1 due to rounding errors. Using this data, we obtained the f_r values for the various components of the waste treatment processes (Table 6.3). Based on these results, the emergy of the wastes appears to be high, amounting to about 20.3 % of the total emergy used (U) by Macao. The f_r of sewage (0.137) was the highest of the values for the three waste categories, the f_r of all wastes combined was 0.065, and the f_r of wastes to total emergy used (U) was only 0.013. These ratios mean that only a tiny feedback emergy was required to treat the wastes.

We compared Macao's solid waste treatment process with those of two other cities (Table 6.4): Modena (Italy) for MSW and Surahammar (Sweden) for sewage. Modena is a small Italian city (Marchettini et al. 2007), with a population of 180 638

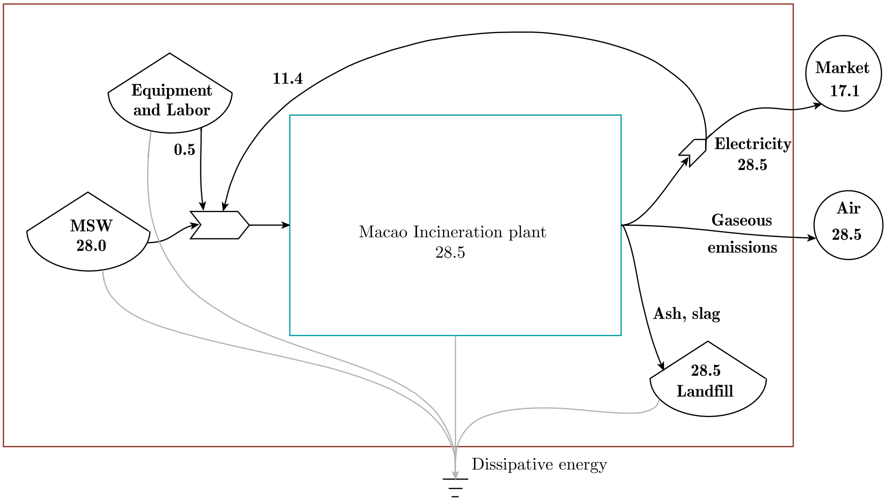

Fig. 6.2 The emergy involved in the incineration of Macao's MSW in 2004 (all values are $\times 10^{20}$ sej) (Lei and Wang 2008)

and an area of 182 km^2. In 1999, its incinerator plant generated 2.66×10^4 MW · h of electricity and 9.61×10^{14} J of heat from 1.08×10^{11} g of MSW. Its emergy investment in MSW collection in 1999 totaled 1.42×10^7 sej g^{-1}, which was roughly 12 % of the corresponding value for Macao (1.19×10^8 sej g^{-1}). The investment in waste collection in Modena was lower than in Macao because the Macau Residue System Company's collection process is more complex and its duties included the transfer and treatment of ash; in contrast, Modena has a simple collection process and is not responsible for the ash treatment cost (Marchettini et al. 2007). The emergy invested in incineration in Macao and Modena was nearly identical (7.85×10^7 versus 7.83×10^7 sej g^{-1}, respectively), and the landfill emergy investments were also similar (9.96×10^6 versus 9.82×10^6 sej g^{-1}, respectively).

Surahammar is a small Swedish town with a population of about 9500 and an area of 344 km^2. In 1995, the total inflow of wastewater to its treatment plant was 2 100 000 m^3 and the annual inflow of organic substances, nitrogen (N), and phosphorus (P) were 151, 46, and 7.5 t, respectively (H. Björklund et al. 2001). In terms of sewage treatment, the wastewater treatment costs for Surahammar and Macao were similar, with emergies of 4.17×10^5 sej g^{-1} and 4.63×10^5 sej g^{-1}, respectively, with corresponding treatment service emergy values of 0.009×10^{20} sej and 0.255×10^{20} sej, respectively (Table 6.4).

Macao's waste emergy values in 1990, 1993, 1995, 1999, 2003, and 2004 are shown in Fig. 6.3. In 1990, all of Macao's MSW was taken to the landfill, so the emergy of gaseous emissions was small. However, from 1993 onwards, the largest proportion of waste emergy was accounted for by the gaseous emissions produced by incineration of the MSW (Lei and Wang 2008).

Huang and Chen (2005) noted that waste emergy can be expressed as the entropy of a system's metabolism, and that this entropy will increase as a city develops.

Table 6.2 Summary of waste-related emergy components for Macao in 2004. Raw data were provided by DSEC (2005)

Item	Expression	Scale (units)	Value	Transformity (sej unit^{-1})	Emergy ($\times 10^{20}$ sej)	Emergy investment (sej g^{-1})
Fuel	$1+2$	Mass (g)	7.47×10^{11}	–	19.10	2.56×10^{9}
1. E_{fuel}	Fuel	Energy (J)	3.10×10^{16}	5.40×10^{4}	16.70	2.24×10^{9}
2. $\text{EL}_{\text{electricity}}$	Electricity, labor, etc.	Money ($)	1.01×10^{8}	2.38×10^{12}	2.40	3.21×10^{8}
Solid waste	$3+4+5+6$	Mass (g)	2.56×10^{11}	–	28.52	1.11×10^{10}
3. E_{MSW}[a]	MSW	Energy (J)	1.56×10^{15}	1.80×10^{6}	27.99	1.09×10^{10}
4. $\text{EL}_{\text{collection}}$	Collection labor and equipment	Money ($)	1.28×10^{7}	2.38×10^{12}	0.30	1.19×10^{8}
5. $\text{EL}_{\text{incineration}}$	$5.1+5.2$	Money ($)	8.46×10^{6}	2.38×10^{12}	0.20	7.85×10^{7}
5.1	Incineration service	Money ($)	3.89×10^{6}	2.38×10^{12}	0.09	3.61×10^{7}
5.2[b]	Equipment depreciation	Money ($)	4.57×10^{6}	2.38×10^{12}	0.11	4.24×10^{7}
6. $\text{EL}_{\text{landfill}}$	Landfill service	Money ($)	1.07×10^{6}	2.38×10^{12}	0.03	9.96×10^{6}
Gaseous emissions	$1+2+3+4+5$				47.59	
Sewage	$7+8$	Mass (g)	5.51×10^{13}	–	2.08	3.79×10^{6}
7. E_{sewage}	Sewage	Energy (J)	2.71×10^{14}	6.66×10^{5}	1.80	3.27×10^{6}
8. $\text{EL}_{\text{sewage}}$	Sewage service	Money ($)	1.20×10^{7}	2.38×10^{12}	0.28	5.18×10^{5}
8.1[c]	Drainage service	Money ($)	1.29×10^{6}	2.38×10^{12}	0.03	5.55×10^{4}
8.2	Sewage treatment service	Money ($)	6.40×10^{6}	2.38×10^{12}	0.15	2.76×10^{5}
8.3[b]	Plant setup and depreciation	Money ($)	4.32×10^{6}	2.38×10^{12}	0.10	1.86×10^{5}
Wastes	$1+2+3+4+5+6+7+8$		–	–	49.70	
Total feedback of wastes	$2+4+5+6+8$		–	–	3.21	

[a] The transformity of MSW was obtained from Lan et al. (2002)

[b] The depreciation periods for the Macao Incineration Plant and the three wastewater treatment plants were assumed to be 15 years, at an annual depreciation rate of 6.7 %

[c] The cost of installing sewers for the collection of sewage was not included in our calculations due to a lack of data for Macao

Table 6.3 Summary of waste-related indices for Macao in 2004. (f_r = feedback ratio; numbers refer to the parameters listed in Table 6.2)

Item	Expression	Value of index
W to U ratio	Waste emergy/Emergy used	0.203
f_r of MSW	$(4+5+6)$/MSW	0.019
f_r of sewage	8/Sewage	0.156
f_r of gaseous emissions	$(2+4+5)$/Gaseous emissions	0.061
f_r of wastes	$(2+4+5+6+8)$/Wastes	0.065
Ratio of f_r of waste treatment to U	Feedback ratio/Emergy used	0.013

Howard Odum (1994), quoting Prigogine, noted that "systems that are far from equilibrium (i.e., dissipative structures) can persist only as long as the system receives a continuous flow of energy or matter from outside the system". In the context of this chapter, waste emergy represents a positive entropy component, and the energy it embodies could be released after reducing its entropy level by means of suitable treatment through inflows of negative entropy from sources outside the system. The feedback emergy used by Macao for the treatment of wastes may represent a small proportion of the city's total emergy use, but this investment can reduce pollution, as well as the damage done to the surrounding systems that receive this pollution. Waste treatment also helps to sustain the city's steady-state condition. Since the feedback ratio for the wastes is small (Table 6.3), the feedback emergy used to treat the wastes is valuable, and provides welfare and health benefits for residents. Figure 6.4 shows that the f_r value for sewage increased rapidly after 1995 and became the largest f_r value after sewage treatment began in 1998; before this year, when sewage was not treated, its f_r value was zero. The f_r value for MSW was smaller than those for gaseous emissions throughout the study period and lower than those for sewage after 1998 because of its high emergy. The f_r of gaseous emissions decreased from 0.26 in 1990 to 0.06 by 2004; this change occurred because in 1990, this parameter resulted entirely from burning of fuels but not MSW, and the lower numerator thus led to a higher f_r value.

6.3.2 Transformities of Wastes in Macao

Because transformity represents the emergy of one type required to create a unit of energy of another type, it is a kind of efficiency measure that relates all inputs to a given output. The lower the transformity is, the more efficient the conversion is. It follows from the second law of thermodynamics that there is some minimum transformity consistent with maximum power generation with the smallest loss of energy dissipation. Currently, there is no known way to calculate this. However, we can use the lowest transformity value found in systems that have been operating for a long time as an approximation. To evaluate real systems, observed transformity values

Table 6.4 Comparison of the waste treatment efficiency for Macao (MSW and sewage) in 2004 with the corresponding values for MSW in Modena (Italy) in 1999 and for sewage in Surahammar (Sweden) in 1995

Waste category		Category	Emergy ($\times 10^{20}$ sej)	Emergy investment (sej g^{-1})
MSW	Macao (2004)	Total = 2.56×10^{11} g	28.525	1.11×10^{10}
		MSW embodied	27.994	1.09×10^{10}
		Collection labor and equipment	0.305	1.19×10^{8}
		Incineration service	0.201	7.85×10^{7}
		Landfill service	0.026	9.96×10^{6}
	Modena[a] (1999)	Total = 1.08×10^{11} g	11.910	1.10×10^{10}
		MSW embodied	11.799	1.09×10^{10}
		Collection labor and equipment	0.015	1.42×10^{7}
		Incineration service	0.085	7.83×10^{7}
		Landfill service	0.011	9.82×10^{6}
Sewage	Macao (2004)	Total = 5.51×10^{13} g	2.025	3.79×10^{6}
		Sewage embodied	1.802	3.27×10^{6}
		Drainage service	0.031	0.56×10^{5}
		Service and depreciation	0.255	4.63×10^{5}
	Surahammar[b] (1995)	Total = 2.1×10^{12} g	0.609	2.90×10^{7}
		Sewage embodied	0.600	2.86×10^{7}
		Treatment service[c]	0.009	4.17×10^{5}

[a] Data from Marchettini et al. (2007)

[b] Data from H. Björklund et al. (2001)

[c] The treatment service was derived by adding items 21 to 26 in Table 3 of H. Björklund et al. (2001)

for similar systems can be used or values can be determined based on theoretical calculations for the system. This is an important way to appraise a system before it is actually constructed and operating (H. T. Odum et al. 2000). Some scholars have successfully evaluated the transformity of waste materials using this approach (H. Björklund et al. 2001; Brown and Buranakarn 2003; Bastianoni et al. 2005). Because of their success, we used the same approach in the present study.

At the Macao Incineration Plant, the heat recovered from the incineration of MSW was used to generate 1.042×10^8 kW · h of electricity, of which 40 % ($11.4 \times 10^{20}/28.8 \times 10^{20}$; Fig. 6.2) was used by the plant itself. On this basis, we can calculate the solar transformity of the electricity produced by incineration:

$$\begin{aligned} T_r &= E_\mathrm{m}/E = \left(2.85 \times 10^{21}\right)/\left(1.042 \times 10^8\ \mathrm{kW \cdot h}\right) \\ &= 2.85 \times 10^{21}/\left(1.042 \times 10^8 \times 1000 \times 3600\right) = 7.60 \times 10^6\ \left(\mathrm{sej\,J^{-1}}\right) \end{aligned}$$

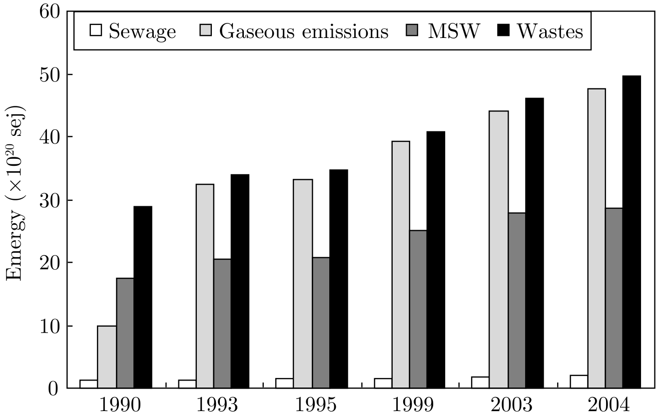

Fig. 6.3 Changes in the components of waste emergy in Macao from 1990 to 2004 (Lei and Wang 2008)

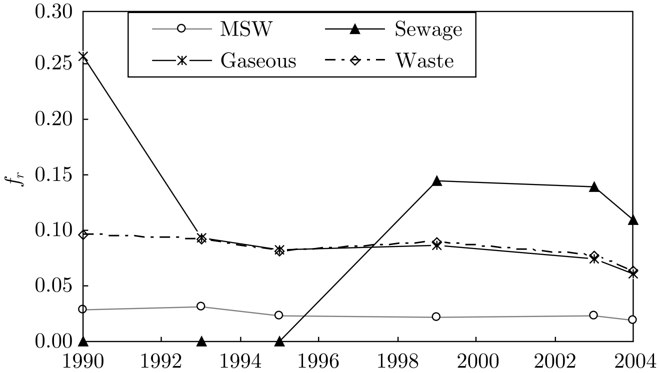

Fig. 6.4 Changes in the emergy feedback ratios (f_r) for Macao's wastes (Lei and Wang 2008)

where E represents the energy of the electricity generated by the process. This quantity is 47.5 times the amount obtained from burning petroleum (1.6×10^5 sej J^{-1}). The fly ash generated by this process totaled 5586 t, and the slag totaled 47 453 t, thus their transformities are

$$\text{Fly ash:} \quad T_r = E_\text{m}/E = 2.85 \times 10^{21}/\left(5586 \times 10^6\right) = 5.10 \times 10^{11} \text{ sej g}^{-1}$$

$$\text{Slag:} \quad T_r = E_\text{m}/E = 2.85 \times 10^{21}/\left(47\,453 \times 10^6\right) = 6.01 \times 10^{10} \text{ sej g}^{-1}$$

The discharged sewage had an emergy of 2.09×10^{20} sej after treatment, so its transformity can be expressed as

$$T_r = E_\text{m}/E = 2.08 \times 10^{20}/\left(5.51 \times 10^{13}\right) = 3.77 \times 10^6 \text{ sej g}^{-1}$$

6.4 Conclusions

If we consider wastes to be byproducts of all activities that result from the food, raw materials, and goods that we use, wastes will contain all the emergy used for the generation of these resources (H. Björklund et al. 2001). Hence, the emergy of wastes must carry all the emergy used by a system and should be very high. The amount of emergy in the wastes can also be seen as a reflection of our social and economic lifestyles. In our calculations, the transformity of the generation of electricity was 47.5 times the value for burning petroleum (Lei and Wang 2008).

The emergy in Macao's wastes totaled 49.7×10^{20} sej (Fig. 6.1, Table 6.2), which amounts to nearly 20.3 % of the emergy used by Macao in 2004. From this perspective, the wastes should not be seen solely as a hazardous byproduct, but rather as a tremendous potential energy resource for the city. Our emergy analysis indicated that the potential of the electricity generated from incineration of the wastes is high. Therefore, suitable technology should be developed and used to recover more of this available energy. However, our emergy analysis also indicates that burning MSW is not the most efficient way to generate electricity (e.g., compared with burning petroleum).

Our analysis also indicated that Macao's investment of resources and technology for the treatment of wastes is, nevertheless, small in relation to the emergy of the wastes, with an f_r value of 0.019 for MSW, 0.061 for gaseous emissions, and 0.156 for sewage in 2004. This relationship between treated wastes and feedback is consistent with waste recycling in natural ecosystems, where recycling proceeds with a small emergy cost, but over a long period of time and with low concentrations of wastes. This is typical, for example, of the purification of polluted water by natural systems, which is slower than human wastewater treatment (Lei and Wang 2008).

By employing the emergy synthesis method, we determined that the transformity was 3.79×10^6 sej g^{-1} for discharged sewage, 5.10×10^{11} sej g^{-1} for fly ash, and 6.01×10^{10} sej g^{-1} for slag. These values represent the first calculated transformities for such materials in the research literature. The waste treatment process decreased the environmental impact of the wastes, but also increased the related transformity. According to H. T. Odum (1996), high transformity values indicate a high potential environmental impact. From the above analysis, Odum's conclusion appears suitable for production and transfer processes but not for waste treatment processes.

Waste management requires considerable energy and other resources, but the use of local renewable resources, such as solar or wind power, is practically non-existent in Macao. There is thus an imbalance between Macao's need for external inputs and the capacity of the local environment to provide these inputs, and as a result, considerable imports of emergy are required to support the processing of Macao's wastes. This requirement for externally provided emergy could be greatly reduced by changing the lifestyle of residents to better control the input side of the system (i.e., their consumption of resources) in order to be able to better control the output side (i.e., the wastes generated by this consumption).

The emergy of gaseous emissions can be assessed by tracking the flows of these materials and the associated energy. Because good statistics were not available for these emissions, we used annual monetary flows as a proxy. Although this approach is not precise, it allows quantification of something that would otherwise be difficult or impossible to quantify. The principles discussed in this chapter provide a useful tool for solving new problems that may arise from these flows. For example, analysis of the transformity values can be used to assess the efficiency of current and proposed waste treatment processes.

As tourism develops and private enterprises become established in Macao, encouraging the sectors that provide related goods and services to implement environmental management will be an important part of any waste management solution. The reduction of waste at the source and the reutilization of wastes are potential methods to reduce overall waste production and thereby improve protection of the city's environment. Since increasing numbers of tourists are arriving in Macao each year, the amount of waste they generate will certainly increase, and the resulting increase in the future impact of these wastes on the city cannot be ignored. Because we used monetary values as proxies for the actual emergy values in the three categories of waste, there is clearly a need for better data on these emergy components so that more realistic values can be calculated. In particular, more data on gaseous emissions will be required in the future.

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Chapter 7
Per Capita Resource Consumption and Resource Carrying Capacity: A Comparison of the Sustainability of Macao and 17 Countries

7.1 Introduction

In 1987, the Brundtland Report defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987). This concept means that a nation's social, economic, and natural capital should be preserved for future generations. Contributors to the report believed that sustainable development requires harmonious development of the economy, of society, of natural resources, and of the environment (i.e., four kinds of capital). Economists have defined two levels of sustainability:

1. *Weak sustainability* preserves the total capital, but not necessarily each of the four kinds of capital; that is, the different types of capital are considered to be potentially substitutable for one another. Neoclassical economists tend to maintain that man-made capital can, in principle, replace all types of natural capital and that every technology can be improved upon or replaced as a result of innovation.
2. *Strong sustainability* requires that each type of capital be preserved independently; that is, the different types of capital can complement each other, but cannot substitute for one another. This premise of strong sustainability suggests that those who develop socioeconomic policy have a responsibility to the greater ecological world, and that sustainable development must therefore take a different approach to valuing natural resources and ecological functions.

A resource is any physical or virtual entity of limited availability that must be consumed to obtain a benefit. By definition, the Earth cannot tolerate continued economic and population growth and the consumerism they foster if these processes are unsustainable. Because energy, economic, and environmental constraints operate at all scales to limit future growth, failing to account for these constraints may lead to abrupt and highly disruptive changes instead of a "planned descent" (Brown et al. 2009). Thus, long-term sustainability is defined by the environment's long-term carrying capacity; from an economic perspective, carrying capacity is equivalent to a budget, and it is not possible to spend more than one's budget for more

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than a short period of time. The concept of carrying capacity for human use of the biosphere is important, since it defines the limits to the biosphere's ability to sustain life, absorb and recycle wastes, and provide resource inputs. There has therefore been renewed interest in understanding the relationship between human-dominated systems and their environmental support systems.

Rojstaczer et al. (2001) calculated that the proportion of the biosphere's total net terrestrial primary production carrying capacity that was being appropriated for human consumption ranged from 10 to 55 % of terrestrial photosynthetic production. Folke et al. (1997) used estimates of "appropriated ecosystem areas" by cities in the Baltic area as a metric for defining the region's carrying capacity for resource consumption and waste assimilation. Wackernagel and Rees (1996) evaluated the land required to provide resources for urban areas and coined the term "ecological footprint" to describe this impact. Brown and Ulgiati (2001) proposed emergy analysis techniques that could be used to evaluate the environment's carrying capacity for economic development. In this approach, "emergy" represents the "embodied energy" that is contained in flows of energy, materials, or money.

The main energy source of our world comes from the sun. Solar emergy can therefore be used to place a value on natural resources that the economy does not evaluate correctly (e.g., rain, raw materials from nature, water from rivers, biodiversity) and also on resources provided by the human economy, which mainly comprise fossil fuels and their derivatives (the goods and services provided by industrial economies). Emergy analysis therefore explicitly includes many factors that neoclassical economics treats as externalities. Emergy analysis uses a common unit for all flows, namely the equivalent "solar emergy joule" (sej). Emergy analysis includes geophysical characteristics to value the amount of energy connected to the production and use of natural resources (Siche et al. 2008). The aim of the methodology is to obtain a thermodynamic measure of the energy used by the production and consumption of a resource (H. T. Odum 1996).

The new interpretation of (strong) sustainability is that it implicitly incorporates carrying capacity by suggesting that the long-term greater good of humanity is best maximized by minimizing environmental impacts (ideally, by keeping their magnitude below the environment's carrying capacity) and by maximizing useful work. Here, we have built on this assumption by using the per capita emergy consumption of 17 nations to evaluate their sustainability based on the principle of sustainable use of natural resources and equitable distribution of those resources. In this chapter, we base equitability on the assumption that all humans have a right to a similar level of emergy consumption; we have used the global average to define the baseline for equitability (Lei and Zhou 2012).

Note: Because of the large number of parameters defined in this book, we have provided a summary of all parameters and their definitions in Appendix C.

7.2 Methods

7.2.1 The Principle of Environmental Sustainability

To operationalize the concept of strong sustainability, Gudmundsson and Höjer (1996), basing their work on the work of Daly (1991), defined four operational principles:

1. The main principle is to limit the human scale (throughput) to a level that, even if it is not optimal, is at least within the environment's carrying capacity and is therefore sustainable.
2. Technological progress should increase efficiency rather than throughput.
3. Renewable resources should be exploited on the basis of a profit-maximizing sustained yield to avoid depleting a resource.
4. Non-renewable resources should be exploited, but at a rate equal to the creation of renewable substitutes.

In the extensive discussion and use of the concept since then, there has generally been a recognition of three aspects of sustainable development (Harris 2003):

1. An *economically sustainable* system must be able to produce goods and services on a continuing basis, to maintain manageable levels of government and external debt, and to avoid extreme sectoral imbalances that can damage agricultural or industrial production.
2. A *socially sustainable* system must achieve distributional equitability, adequate provision of social services (including health and education), gender equitability, and political accountability and participation.
3. An *environmentally sustainable* system must also include the maintenance of biodiversity, atmospheric stability, and other ecosystem functions that are not ordinarily classified as economic resources.

The concept of sustainable development is therefore inherently intertwined with the concept of carrying capacity. When the consumption of natural resources exceeds nature's ability to replenish these resources, the carrying capacity is exceeded, the environment becomes increasingly degraded, and the system is not sustainable. The long-term consequence of continuing environmental degradation will be the Earth's inability to sustain human life; in economic terms, unsustainable spending results in bankruptcy.

Emergy consumption can be used to determine how much energy is needed at each point in a system (Brown et al. 2009). The per capita emergy consumption value is a suitable indicator of resource utilization and an indicator of whether consumption is balanced with the per capita carrying capacity; in addition, it serves as an indicator of the equitability of emergy consumption by allowing a comparison of how much emergy is available to each person to use. The interface between the resources supplied by the environment and the resources consumed by the ecological economy can be compared among countries using per capita indices of resource use intensity, energy-based trade balances, and the sustainability of production (Brown

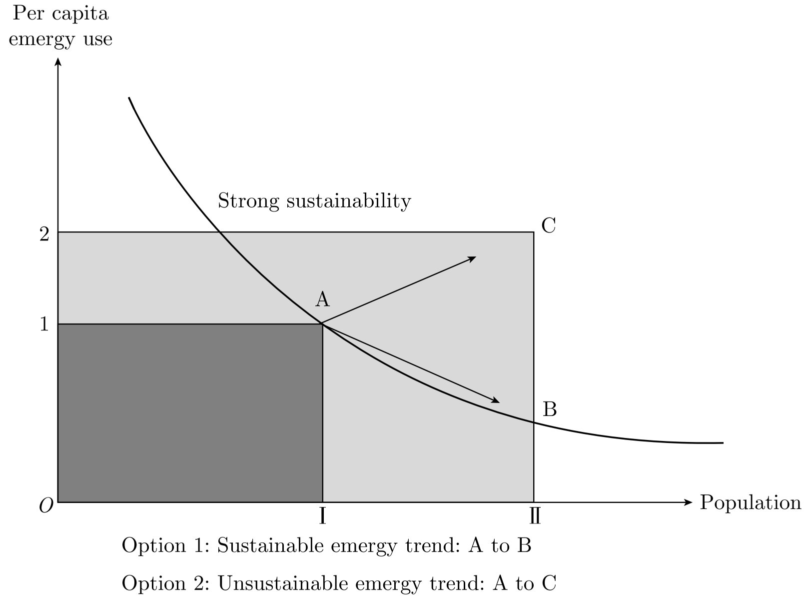

Fig. 7.1 The relationship between population and per capita emergy use as a function of socioeconomic development. The strong sustainability line represents the condition in which the consumption of all resources is sustainable (i.e., one form of capital cannot substitute for another form) (Lei and Zhou 2012)

2003). The advantage of this approach is that it can simultaneously provide insights into both sustainability and equitability issues.

Energy is required for all processes in an ecosystem, and resource consumption can be described using an emergy diagram that shows the relationship between population and per capita emergy use (Fig. 7.1). In the context of the present chapter, the renewable resource carrying capacity defines the basis for strong sustainability, and the available renewable resources should be consumed equitably by all citizens of the world (following the equitability principle of sustainable development). Since the available resources cannot increase, an increasing population will decrease the amount of emergy available for use by each person. As development progresses from point A to point B in Fig. 7.1, per capita emergy use must follow the sustainability curve AB, and the area under AB represents the range of sustainable combinations of population and per capita emergy use under the constraint of strong sustainability. The area A-I-O-1 represents the sustainable resource consumption (i.e., the range of sustainable combinations of population and per capita emergy use) for the whole world at development stage A. If the world's population increases, then less emergy is available for each person's use (distance B-II is smaller than distance A-I), and per capita emergy use must decrease to maintain sustainability.

In reality, however, development often follows a path from A to C (Fig. 7.1): as the population increases from I to II, resource consumption (represented by per capita emergy use) increases from 1 to 2, and because the new rate of consump-

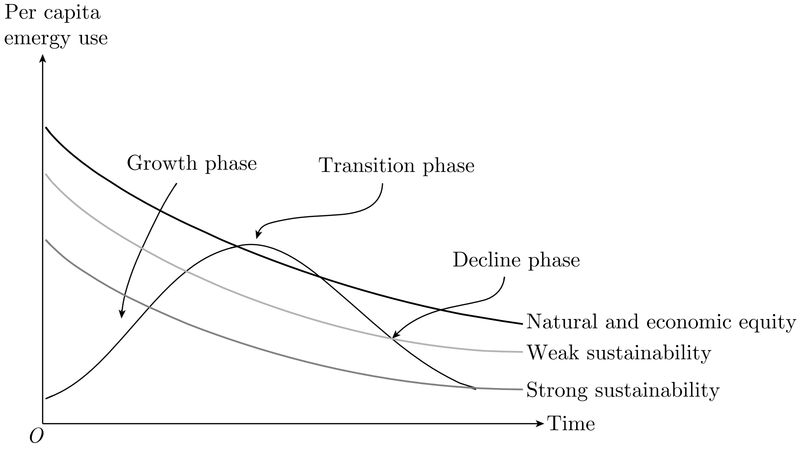

Fig. 7.2 The development stages of an economy in relation to its resource consumption levels and resource carrying capacity (Lei and Zhou 2012)

tion is above the sustainability line, this creates a deficit in sustainable resource use represented by the area above the strong sustainability line from 1 to 2 and from I to II. This deficit must be filled by the consumption of non-renewable resources. Since this will decrease the remaining store of non-renewable resources, future generations will be required to use less resources to achieve sustainability, and this resource consumption strategy is therefore unsustainable.

7.2.2 Resource Consumption and Carrying Capacity

The biosphere is driven by fluxes of renewable energies in the form of sunlight, tidal momentum, and deep-Earth heat. Human society draws energy directly from the environment by withdrawing the energy from short-term storage (typically considered to be from 10- to 1000-year turnover times), such as wood, soil, and groundwater, and from long-term storage, such as fossil fuels and minerals (Brown and Ulgiati 1999). Ultimately, the global carrying capacity for humanity is a kind of budget that is determined by the planet's annual emergy income from both renewable sources (such as sunlight, rain, wind, waves, and tide) and slowly renewable sources (i.e. dispersed non-renewable sources such as fisheries, forestry, soils, and water extraction), which are referred to as "free" emergy (Brown and Ulgiati 1999). In this book, "dispersed" refers to resources that are spread over large areas and that therefore have a low density compared with concentrated resources such as coal or oil deposits. By comparing a country's available support emergy with its emergy consumption, we can determine whether the country's socioeconomic activity is sustainable.

Any definition of sustainability must include a time factor. What is sustainable in a short time period may not be sustainable in the long run. For example, Fig. 7.2

illustrates the growth and decline of an economy. Practices and processes that are characteristic of the growth phase may be sustainable initially, but become unsustainable during the transition phase, when the per capita emergy use exceeds the value in the two lowest sustainability lines. This leads to a decline phase because the economy increasingly requires the consumption of a diminishing store of non-renewable emergy. On the other hand, practices that are sustainable during the decline phase because they do not rely on the consumption of non-renewable emergy are probably not competitive with the practices of faster-growing economies under the dog-eat-dog competition that is characteristic of an economy in its rapid growth phase (Brown and Ulgiati 1997).

Sweeney et al. (2007) summarized the socioeconomic development of 134 nations in a standardized database that compiled data on Earth's material, energy, and money flows, aggregated at a national scale for the year 2000. The result is the National Environmental Accounting Database (NEAD), which provides this data using standardized conversion factors (NEAD 2012). We used the average per capita emergy consumption in 2008 as the benchmark for per capita emergy consumption, because 2008 is the most recent year for which NEAD data has been completely analyzed; however, because the results of this analysis were not published when we were writing this chapter, the data was provided by Dr. S. Sweeney (University of Florida, Gainesville, personal communication, 2012). Previous research estimated that the total global input of renewable emergy was 9.26×10^{24} sej year^{-1} (Brown and Ulgiati 2004; Campbell et al. 2005), so we have used the same value here for consistency. The total per capita free emergy in 2008 was calculated by adding the renewable resource emergy ($R = 6.94 \times 10^{15}$ sej) and the dispersed non-renewable emergy ($N_0 = 0.60 \times 10^{15}$ sej), for a total of 7.54×10^{15} sej. This represents the strong sustainability curve in Fig. 7.2. Since we consume non-renewable emergy to maintain our high quality of life, the average per capita natural emergy (renewable plus non-renewable resources $= R + N$) produces a higher curve that represents weak sustainability at a total emergy value of 25.20×10^{15} sej in 2008.

Because most nations use both their internal resources and goods, minerals, and fuels imported from other countries, as well as the results of human labor from other countries, they are import-driven economies, and the total of these values represents imported "economic emergy" ($F_{(\mathrm{i})} + G_{(\mathrm{i})} + P_2 I_3$), where $F_{(\mathrm{i})}$ represents the sum of imports of fuels, metals, and minerals; $G_{(\mathrm{i})}$ represents imports of goods and electricity; and $P_2 I_3$ represents the emergy of services imported from other places. This represents the uppermost line in Fig. 7.2. Similarly, for an economy driven by resource exports, the nation will export large quantities of non-renewable resources; for example, Saudi Arabia exports oil and oil products and Australia exports iron minerals. The total export of these goods and human labor is also "economic emergy", but it is calculated differently: ($F_{(\mathrm{e})} + G_{(\mathrm{e})} + P_1 E_3$), where $F_{(\mathrm{e})}$ represents the sum of exports of fuels, metals, and minerals, $G_{(\mathrm{e})}$ represents exports of goods and electricity, and $P_1 E_3$ represents the emergy of exported services. This also represents the uppermost curve in Fig. 7.2. The sum of a country's natural and economic emergy equals its total emergy consumption. For some countries, this will equal total emergy use, but for resource-exporting countries, the value of total emergy consumption will be greater than the total emergy use.

The global average per capita emergy consumption represents the benchmark for equitable natural and economic emergy consumption. In 2008, this equaled 49.35×10^{15} sej per capita. If a nation's per capita emergy consumption is greater than this value, its consumption is not equitable (i.e., it uses more than its fair share of the overall emergy), and all emergy consumption above this level must be met from one of three sources: goods and services obtained by trade with other nations, emergy taken from the past (e.g., fossil fuels), and emergy borrowed from the future in the form of unsustainable resource use (e.g., by overexploitation of forests and fisheries). However, a nation that is rich in emergy resources may combine sustainable consumption with inequitable consumption if it consumes more emergy than the global average while still meeting the conditions for strong sustainability within that nation (Lei and Zhou 2012).

7.3 Results and Discussion

In this chapter, we have focused our analysis on humanity's place in the biosphere and the consequences of continued population growth accompanied by increased consumption of natural resources. Using data from a variety of sources, the NEAD team of the University of Florida analyzed the socioeconomic development of 102 nations and compiled the results in a standardized database at a national scale for the year 2008. The database represents the most comprehensive list of countries and their emergy flows that is currently available, so we have used it in our analysis. The database contains data for nations with a total population of 5.88×10^9, which amounted to 86.1 % of the world's population of 6.83×10^9 in 2008 (Department of Economic and Social Affairs 2009). To simplify our comparison, we used the average values of the emergy parameters for all 102 nations to approximate the global average, and this served as our benchmark value. Table 7.1 defines the key emergy parameters that we compiled in this study, and Table 7.2 presents the values for the 17 countries that we chose to compare in this study.

To capture a range of environmental, resource, and economic conditions, we chose the G7 countries (the United States, Japan, Germany, the United Kingdom, France, Italy, and Canada), the BRICS countries (Brazil, Russia, India, China, and South Africa), and several additional countries whose economy is driven by resource exports (labor for Mexico, Thailand, and Indonesia; natural resources for Australia and Saudi Arabia). We then compared the emergy parameters for these 17 countries using the methods described in the following sections.

In the rest of Sect. 7.3, we will focus on the data in Table 7.2, and will present graphs of this data as Figs. 7.3 to 7.9 to facilitate comparisons between nations.

7.3.1 Emergy Consumption by the 17 Nations

Renewable resources are those that can be easily replenished or reproduced. Some, like sunlight, air, and wind, are continuously available and their quantity is not af-

Table 7.1 Definitions of the emergy parameters used in the data in Table 7.2

Parameter	Variable name	Description
R	Renewable emergy flows	The largest terrestrial renewable flow + tides
N	Total non-renewable emergy flows	The sum of extraction of indigenous non-renewable resources
N_0	Dispersed non-renewable flows	The sum of forestry, fisheries, soil, and water resource extraction
N_1	Concentrated non-renewable flows	The sum of fuel, metal, and mineral production minus N_2
N_2	The portion of N_1 exported without use	The sum of raw fuel, metal, and mineral exports
$F_{(i)}$	Imports of fuels, metals, and minerals	The sum of fuels, metals, and minerals that are imported ($ value)
$G_{(i)}$	Imports of goods and electricity	The sum of other imported goods and electricity
I	Dollars paid for imports	Services included in imports ($ value)
P_2I_3	Emergy of services in imports	Services in imports ($) × world emergy per dollar ratio
$F_{(e)}$	Exports of fuels, metals, and minerals	The sum of the fuels, metals, and minerals that are exported ($ value)
$G_{(e)}$	Exports of goods and electricity	The sum of other exported goods and electricity
P_1E_3	Exports of services	Services in exports ($) × world emergy per dollar ratio
E	Dollars received for exports	Services received in exchange for exports ($ value)
P_2	World emergy money ratio (EMR)	Total global emergy use/gross world product
P_1	National emergy money ratio (EMR)	National emergy use/gross domestic product

Note: The factor definitions were obtained from Sweeney et al. (2007). For R, only the largest flow is included to avoid double-counting

fected by human consumption. Other renewable resources can be depleted by human use, but can also be replenished, thus maintaining a balance. Some of these, like agricultural crops, take a short time for renewal; others, like water, take a longer time, and others, like forests, take even longer. All of these resources are considered to be “free” because they can renew themselves at no cost without human intervention if the resources are managed sustainably. Large countries tend to have a richer store of renewable resources. Brazil had the highest total use of renewable emergy, followed by China, Canada, and Russia (Table 7.2, Fig. 7.3).

Non-renewable resources form over very long (geological) periods. Minerals and fossil fuels are included in this category. Since their rate of formation is extremely slow, they cannot be replenished on a human time scale once they are depleted. Some of these substances, such as metals, can be reused by recycling them, but others, such as coal and petroleum, cannot be recycled. Although non-renewable resources take a long time to form, they have a high energy quality and a corre-

Table 7.2 Emergy consumption data for 17 nations and combined value for all 102 nations in the University of Florida database[a]

Nations	Renewable emergy ($\times 10^{24}$ sej)	Non-renewable emergy ($\times 10^{24}$ sej)	Free emergy ($\times 10^{24}$ sej)	Natural emergy ($\times 10^{24}$ sej)	Imported emergy ($\times 10^{24}$ sej)	Exported emergy ($\times 10^{24}$ sej)
Calculation	R	$N_0 + N_1 + N_2$	$R + N_0$	$R + N$	$F_{(i)} + G_{(i)} + P_2 I_3$	$F_{(e)} + G_{(e)} + P_1 E_3$
All 102 nations	37.27	110.98	40.80	148.25	125.27	142.05
United States	2.28	19.49	2.40	21.77	12.56	6.47
China	3.35	17.91	3.53	21.26	9.79	5.89
Russia	2.60	9.54	2.75	12.14	1.78	6.92
Canada	3.07	3.27	3.09	6.34	2.34	3.72
Brazil	3.53	4.52	4.12	8.05	1.21	3.05
Mexico	0.41	2.30	0.47	2.71	2.83	1.73
Australia	2.36	5.05	2.39	7.41	1.05	3.59
Japan	0.20	1.80	0.21	1.99	5.72	2.63
United Kingdom	2.38	1.75	2.40	4.14	3.49	2.33
India	1.51	4.95	2.02	6.46	2.33	1.44
Indonesia	1.78	1.76	1.88	3.54	1.10	1.73
Germany	0.05	0.80	0.07	0.86	7.03	3.92
Italy	0.07	0.46	0.08	0.53	3.78	1.70
France	0.62	0.18	0.63	0.79	4.15	1.86
South Africa	0.16	1.77	0.20	1.93	0.56	1.49
Thailand	0.19	1.85	0.22	2.04	1.20	2.61
Saudi Arabia	0.08	4.17	0.12	4.25	0.68	4.34

Table 7.2 (*Continued*)

Nations	Economic emergy[b] ($\times 10^{24}$ sej)	EMR ($\times 10^{12}$ sej \$$^{-1}$)	Population ($\times 10^{8}$)	Total emergy use ($\times 10^{24}$ sej)	Total emergy consumption ($\times 10^{24}$ sej)
Calculation	The higher of the two values for imported and exported	Total emergy use/GDP	–	$R + N_0 + N_1 +$ Imported emergy	Natural emergy + Economic emergy
All 102 nations	142.05	4.48	58.83	260.17	290.30
United States	12.56	2.38	3.04	34.14	34.33
China	9.79	6.82	13.17	30.82	31.05
Russia	6.92	7.20	1.41	12.00	19.06
Canada	3.72	5.23	0.33	7.83	10.06
Brazil	3.05	4.52	1.96	7.40	11.10
Mexico	2.83	4.64	1.10	5.05	5.54
Australia	3.59	5.68	0.21	5.91	11.00
Japan	5.72	1.57	1.27	7.68	7.72
United Kingdom	3.49	2.75	0.62	7.33	7.62
India	2.33	6.88	11.41	8.35	8.79
Indonesia	1.73	8.08	2.38	4.13	5.27
Germany	7.03	2.15	0.82	7.81	7.88
Italy	3.78	1.87	0.58	4.30	4.31
France	4.15	1.72	0.63	4.91	4.95
South Africa	1.49	6.35	0.49	1.76	3.42
Thailand	2.61	11.52	0.66	3.14	4.65
Saudi Arabia	0.68	7.17	0.25	3.41	4.93

Notes: Countries are arranged in order of decreasing total emergy consumption

[a] Data provided by Dr. S. Sweeney (University of Florida, Gainesville, personal communication, 2011)

[b] Whether imported or exported emergy is higher determines the main direction of an economy and can therefore be used to represent the economy's emergy. See Sect. 7.2 for details

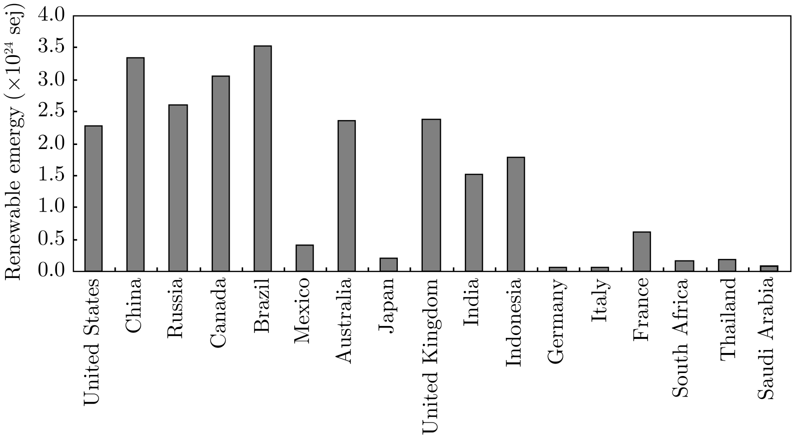

Fig. 7.3 Renewable emergy values for the 17 nations

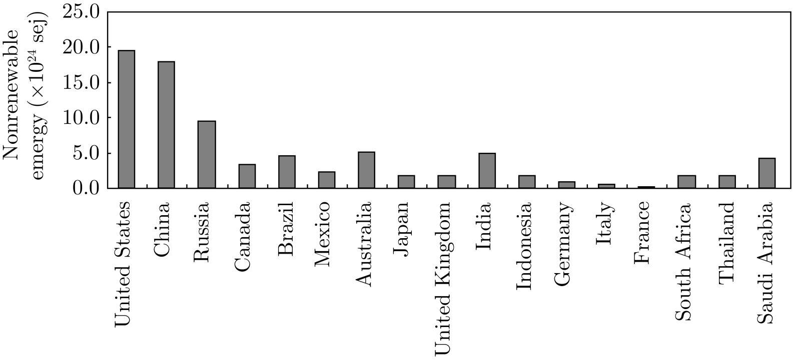

Fig. 7.4 Non-renewable emergy values for the 17 nations

spondingly high transformity (H. T. Odum 1996). The United States had the highest consumption of non-renewable emergy, followed by China, Russia, Australia, and India (Table 7.2, Fig. 7.4). Saudi Arabia consumed a surprisingly high amount of non-renewable resources (slightly less than that of India), driven primarily by consumption to exploit the fossil fuels that are the country's primary exports. However, Saudi Arabia is rich in oil and related products, and exported most of these resources (Lei and Zhou 2012).

The United States had the highest total use of economic emergy, followed by China, Germany, Russia, and Japan (Table 7.2, Fig. 7.5). Germany's high rank (driven primarily by imports) is somewhat surprising, but could perhaps be explained by the amount of manufacturing that it performs for the world market.

Thailand had the highest total emergy money ratio (EMR), followed by Indonesia, Russia, Saudi Arabia, India, China, and South Africa (Table 7.2, Fig. 7.6). Japan

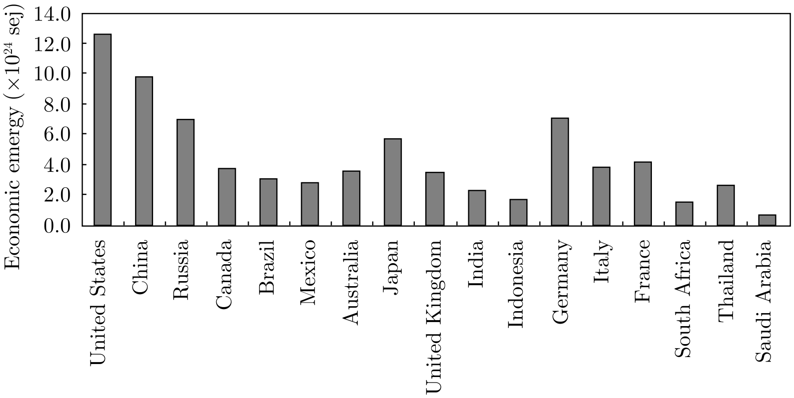

Fig. 7.5 Economic emergy values for the 17 nations

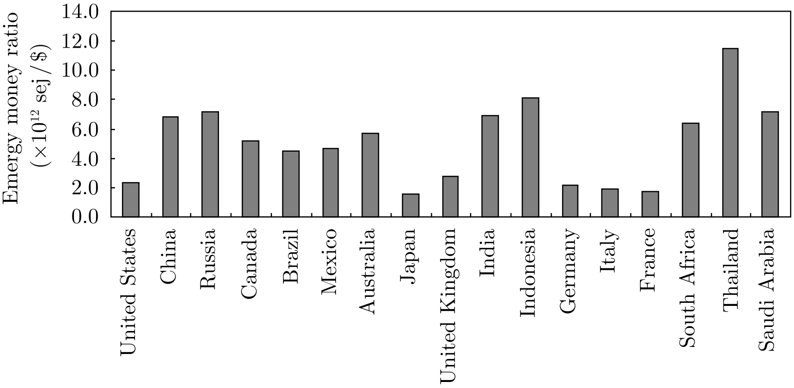

Fig. 7.6 Emergy money ratio values for the 17 nations

ranked last because its economy is driven primarily by imported resources consumed to produce exported products.

When expressed in terms of EMR, the most industrialized nations have the lowest ratios, suggesting that less emergy is consumed per unit of GDP in developed economies than in developing economies. On the other hand the countries with the highest ratios had the smallest GDPs, and higher EMR values indicate greater vulnerability of an economy to resource imperialism by developed economies, which all have lower EMR. These were often countries that supply raw resources to world markets instead of developing their own domestic industrial infrastructure (Brown et al. 2009). However, as Brown et al. (2003) noted, the currencies of developed economies have greater buying power in developing economies, thus capital investment flows continuously from developed economies to developing ones to pay for imports of resources by the developing nations (Lei and Zhou 2012).

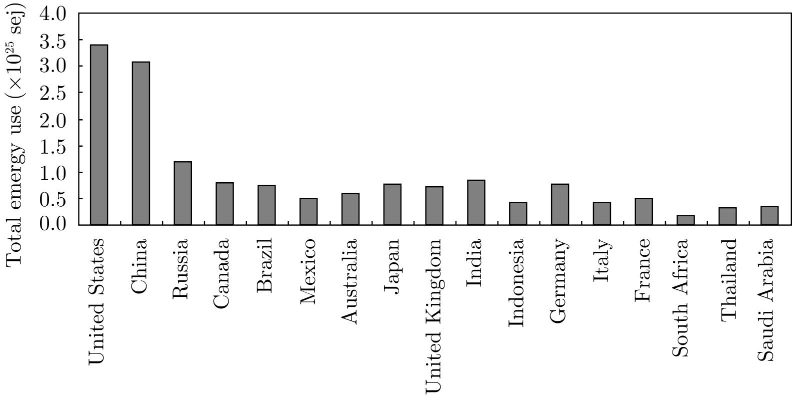

Fig. 7.7 Total emergy use values for the 17 nations

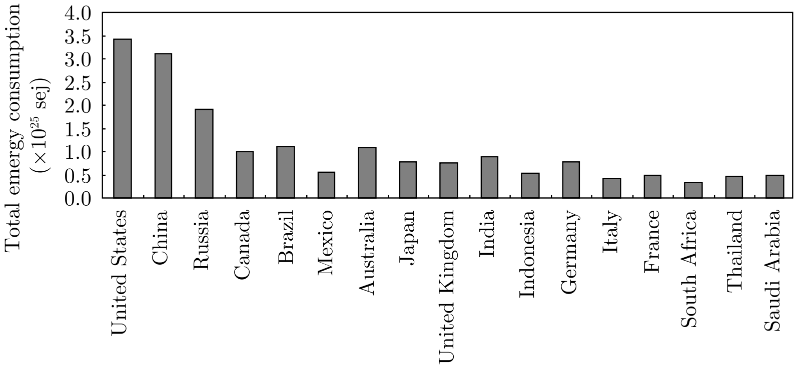

Fig. 7.8 Total emergy consumption values for the 17 nations

The United States had the highest total emergy use, followed by China, Russia, and India (Table 7.2, Fig. 7.7). The fact that Russia ranked third was due to its rich natural resources.

For the total emergy consumption (natural + economic), the United States ranked first, followed by China, Russia, Brazil, Australia, and Canada (Table 7.2, Fig. 7.8). The fact that Russia ranked third was surprising, but this was undoubtedly driven primarily by its huge area and rich natural resources.

The ratio of economic emergy to natural emergy is a measure of economic efficiency, but also indicates the pressure on a nation's resources. If the ratio is greater than 1, this means that local sources of emergy are insufficient to sustain the economy's activity. That is, since economic emergy measures the sum of F, G, and imports or exports (whichever of the two is greater), it is a measure of the emergy in imports that can be "purchased" by sales of emergy. If a nation imports raw resources and exports finished products, then the efficiency ratio will be higher be-

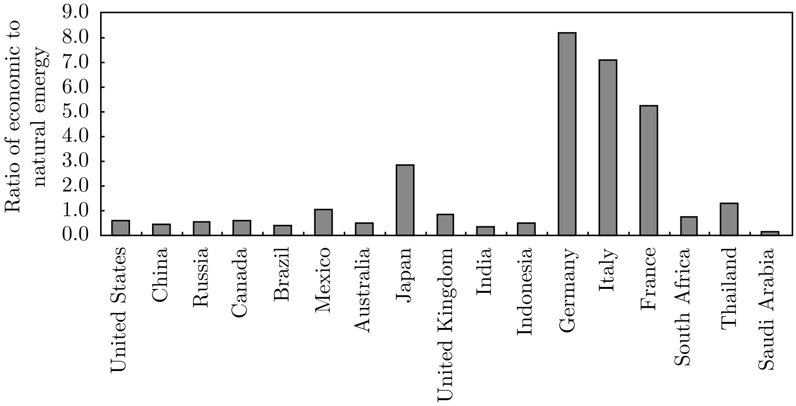

Fig. 7.9 Emergy efficiency values, calculated as the ratio of economic emergy to natural emergy

cause, dollar for dollar, the emergy in finished products is lower than that in raw resources (Lei and Zhou 2012).

The developed industrial countries (Germany, Italy, France, Japan, Thailand, and Mexico) had a ratio of economic emergy to natural emergy greater than 1 (Table 7.2, Fig. 7.9). Those with little or no resource base import large quantities of emergy while exporting far less emergy, and thus place high pressure on their resources. Germany placed the greatest pressure on its resources. The export-driven countries (Saudi Arabia, India, Brazil, China, Australia, Indonesia, Russia, the United States, Canada, South Africa, and the United Kingdom) have an efficiency ratio less than 1. The average ratio of the 102 nations was 0.96 (Lei and Zhou 2012).

7.3.2 Per Capita Emergy Consumption for the 17 Nations

The values of the per capita emergy consumption parameters can indicate the sustainability of a nation when these values are compared with the corresponding resource carrying capacity. Table 7.3 presents the data for the 17 nations, and Fig. 7.10 presents the values visually to facilitate comparisons with the average value, represented by the horizontal line.

One measure of a nation's natural richness is the per capita free emergy that is available from renewable resources and dispersed non-renewable sources such as wood (H. T. Odum 1996). Although the renewable resources can be replenished easily, or remain continuously available (e.g., sunlight, air, wind), they have a low energy quality and a lower emergy transformity (H. T. Odum 1996). Figure 7.10 shows the per capita free emergy of the 17 countries. Large flows of renewable emergy dominated the countries with high per capita free emergy, with the greatest value for Australia, followed by Canada. Both countries have large areas but sparsely populated interiors, and gain nearly 40 % of their total per capita emergy

Table 7.3 Per capita emergy consumption by the 17 nations that were compared in the present study. Data were provided by Dr. S. Sweeney (University of Florida, Gainesville, personal communication, 2011)

Nations	Emergy category (per capita sej)					
	Free ($\times 10^{15}$ sej)	Natural ($\times 10^{16}$ sej)	Economic ($\times 10^{16}$ sej)	Total use ($\times 10^{16}$ sej)	Total consumption ($\times 10^{16}$ sej)	Total use/total consumption
All 102 nations	6.94	2.52	2.41	4.42	4.93	0.90
United States	7.90	7.15	4.13	11.22	11.28	0.99
China	2.68	1.61	0.74	2.34	2.36	0.99
Russia	19.52	8.63	4.92	8.53	13.55	0.63
Canada	93.12	19.08	11.21	23.59	30.29	0.87
Brazil	20.99	4.10	1.55	3.77	5.65	0.67
Mexico	4.32	2.46	2.57	4.59	5.03	0.91
Australia	113.97	35.27	17.08	28.12	52.36	0.54
Japan	1.62	1.57	6.49	6.04	6.06	1.00
United Kingdom	38.71	6.68	5.63	11.83	12.32	0.96
India	1.77	0.57	0.20	0.73	0.77	0.95
Indonesia	7.92	1.49	0.73	1.74	2.22	0.78
Germany	0.82	1.04	8.53	9.48	9.57	0.99
Italy	1.30	0.91	6.49	7.39	7.40	1.00
France	10.01	1.27	6.63	7.84	7.90	0.99
South Africa	4.04	3.96	3.05	3.60	7.01	0.51
Thailand	3.38	3.08	3.94	4.74	7.02	0.68
Saudi Arabia	4.72	17.06	2.73	13.67	19.79	0.69

Notes: Countries are arranged in order of decreasing total emergy consumption

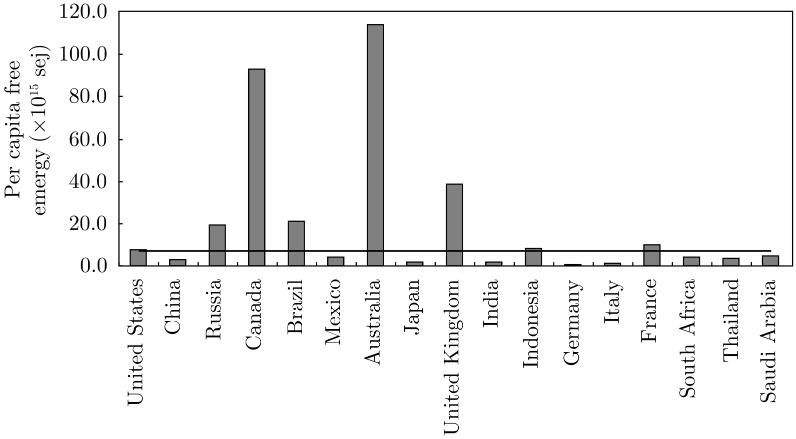

Fig. 7.10 Per capita free emergy values for the 17 nations. *The horizontal line* represents the mean value for the 102 nations in the NEAD database (Lei and Zhou 2012)

use from renewable sources. Eight countries had a per capita free emergy greater than the global average level, which means that they consume a disproportionate share of the world's renewable emergy sources. Italy, Japan, India, and China had very low per capita free emergy resources.

The renewable environmental energies such as wind, geothermal, and tidal energy only occur at intensities sufficient to provide net energy in limited areas of the planet, thus their total contribution will not replace a large proportion of current global energy needs. These dispersed renewable resources therefore cannot be efficiently utilized based on current technology, and countries with abundant renewable resources such as Australia and Canada, despite their high per capita free resource carrying capacity, waste or underutilize most of these resources because of the difficulty of economically exploiting them.

Figure 7.11 shows the per capita natural emergy for the 17 countries. The countries with the highest per capita natural emergy are countries that have a large area, relatively large stores of non-renewable flows, and relatively small population densities. This is why Australia has the highest per capita natural emergy, followed by Canada and Saudi Arabia; the latter's high value is driven primarily by the country's rich fossil fuel resources. Nine countries have a per capita natural emergy above the global average, which means that they consume a disproportionally high proportion of global natural resources, thereby weakening overall sustainability. India, Italy, Germany, France, Indonesia, Japan, and China consumed much less natural resources per capita than the other countries.

Figure 7.12 shows the per capita economic emergy values for the 17 countries. The countries with the highest per capita economic emergy are industrialized countries with relatively small population densities (i.e., Australia, followed by Canada). Thirteen of the countries had a per capita economic emergy greater than the global average, which means that their economy was too dense and exerted too much pres-

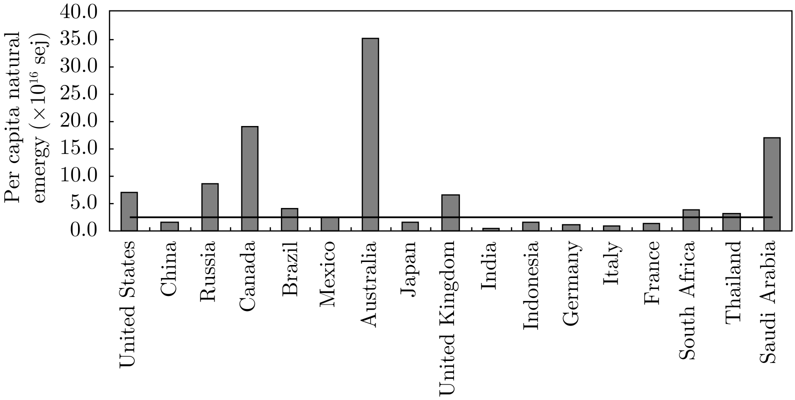

Fig. 7.11 Per capita natural emergy values for the 17 nations. *The horizontal line* represents the mean value for the 102 nations in the NEAD database (Lei and Zhou 2012)

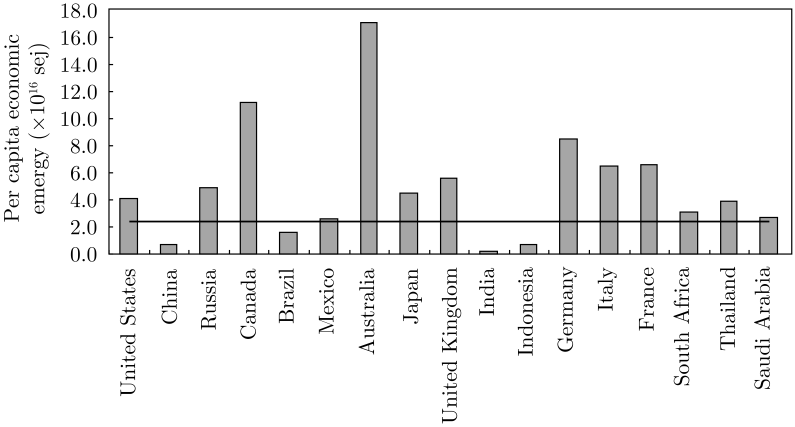

Fig. 7.12 Per capita economic emergy values for the 17 nations. *The horizontal line* represents the mean value for the 102 nations in the NEAD database (Lei and Zhou 2012)

sure on the global environment. India, Indonesia, and China consumed much less economic emergy per capita than the other countries.

Figure 7.13 shows the total per capita emergy use for the 17 countries. The countries with the highest total per capita emergy use are countries with a large area, relatively large flows of non-renewable emergy, and relatively small population densities. Twelve countries had a total per capita emergy use greater than the global average, with Australia highest, followed by Canada, Saudi Arabia, and the United States. This means that they consume too much emergy compared with citizens of other countries. India, Indonesia, and China had lower total per capita emergy use than the other countries.

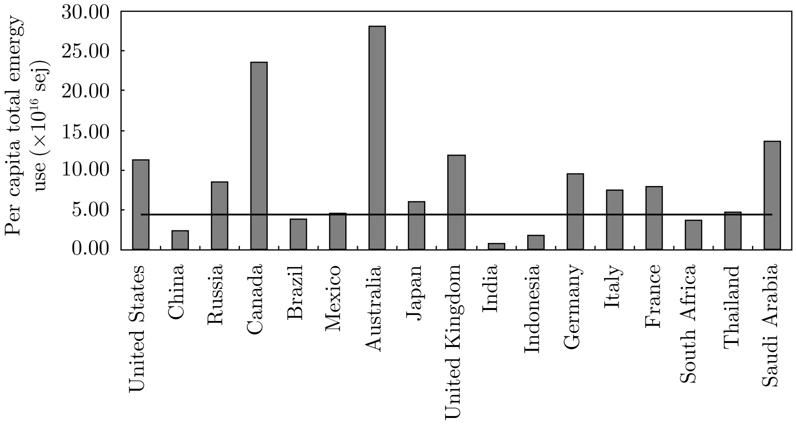

Fig. 7.13 Per capita total emergy use values for the 17 nations. *The horizontal line* represents the mean value for the 102 nations in the NEAD database (Lei and Zhou 2012)

It is increasingly being suggested that humanity should shift the global economy's driving energies from fossil fuels to more renewable forms of energy such as solar, wind, tidal, or biomass energy. Unfortunately, each of these renewable resources is less concentrated than fossil fuels and therefore has lower energy quality. To utilize these resources to power the complex tasks required by modern information and industrial economies will require that these energies be upgraded to a quality commensurate with the economy's requirements (i.e., technology must be improved sufficiently that these sources can replace non-renewable sources in the quantities that are currently consumed). Many analyses (e.g., Brown et al. 2009) of the emergy available from renewable resources suggest that we cannot shift to renewable resources and still provide enough energy to meet current demand, much less the projected future demand created by increasing populations and consumer-driven demand for improved quality of life. Biomass energy is a particular problem because it requires large areas of arable land and huge quantities of water, and thereby increases competition for these resources between food and energy crops.

7.3.3 National Emergy Consumption and Sustainability Conditions

The per capita total emergy consumption measures human consumption in terms of the solar energy needed to create the natural resources and sustain the global economy. Figure 7.14 concisely summarizes the sustainability of per capita emergy consumption for the 17 nations compared with the mean strong and weak sustainability lines and the natural and economic equitability line based on the global average emergy values. The strong sustainability line represents the average per capita free emergy of the 102 nations in the NEAD database in 2008, whereas the weak

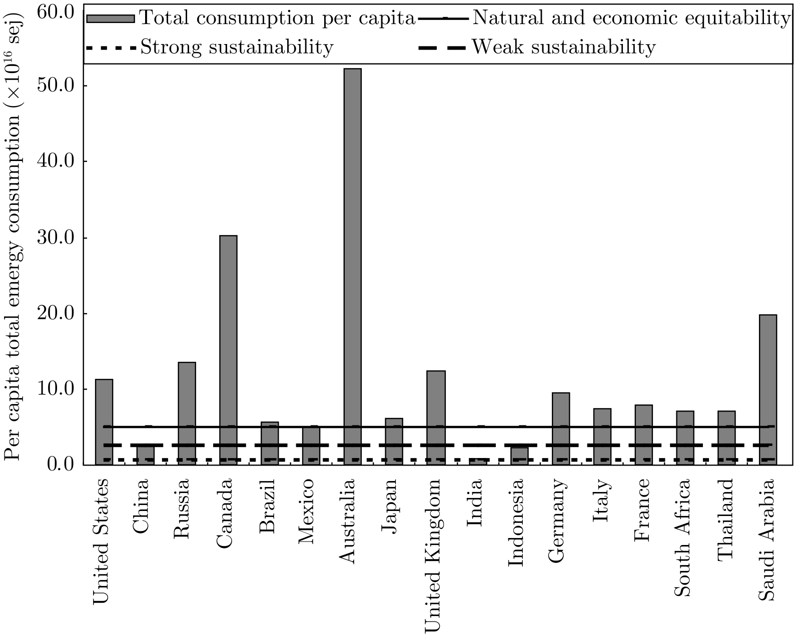

Fig. 7.14 National per capita total emergy consumption and the resulting level of sustainability. The natural and economic equitability line is provided so that the actual consumption can be compared with the equitable level of consumption (Lei and Zhou 2012)

sustainability line represents the average per capita natural emergy in 2008, and the natural and economic equitability line represents the average per capita total emergy consumption of the world in 2008. We found that all 17 countries had consumption greater than the strong sustainability line, which means that their style of emergy consumption is unsustainable in the long term. India, Indonesia, and China had consumption values below the weak sustainability line, which means that these countries consume less natural emergy than the global average. The United States, Russia, Canada, Brazil, Mexico, Australia, Japan, the United Kingdom, Germany, Italy, France, South Africa, Thailand, and Saudi Arabia also consumed more than the natural and economic equitability line. Australia consumed the most emergy per capita, followed by Canada, Saudi Arabia, and Russia. We found that the Asian countries used less emergy per capita than Australia and the North American and European countries. Although China used the third-lowest total per capita emergy, this is because the nation's high population decreased the average per capita emergy consumption. The absolute level of consumption by China remains high because of its tremendous population (Lei and Zhou 2012).

In 2008, the global per capita emergy consumption was 49.35×10^{15} sej, which was 1.96 times the global per capita natural ($R + N$) carrying capacity (25.20×10^{15} sej). This indicates that humans are not living within the planet's natural resource carrying capacity.

One important solution will be to reduce total emergy use in developed economies. Reducing emergy consumption per capita means reducing total emergy use, and this will require a change in consumption habits to avoid waste, combined with the development of more efficient technologies. Without such measures, emergy constraints will increasingly slow GDP growth. The competitive stance of economies that do not change their structure fast enough to avoid this problem will decline in comparison with their competitors unless all developed economies agree to decrease their total resource consumption equally. This was one of the intended consequences of the Kyoto Protocol, but unless all the major developed economies implement the measures specified by this international treaty, they will see their competitive advantage and their economy decline.

Our comparison of the per capita emergy consumption in the 17 countries reveals which nations are on sustainable resource utilization trajectories and which ones will exacerbate the current global resource squeeze. Only three of the 17 countries consume less per capita emergy than the global average per capita natural carrying capacity.

7.4 Comparison of the Per Capita Emergy Between 2000 and 2008

The International Energy Agency (IEA) regularly publishes a report on world consumption for most types of primary energy resources. According to IEA (2011), the total world energy supply was 102 569 TW · h (i.e., 1 TW · h = 10^{12} W · h) in 1990, 117 687 TW · h in 2000, and 143 851 TW · h in 2008. World oil prices have increased greatly in the past 10 years, but oil consumption has nonetheless continued to grow to meet rising demand.

In 2008, total worldwide energy consumption was 474×10^{18} J. From 1990 to 2008, IEA data (IEA 2011) suggests that the average use of energy per person increased by 10 % while the world population increased by 27 %; as a result, the world's energy use grew by 39 % from 1990 to 2008.

NEAD provides an automated system that stores the data required for the kind of analysis performed in this chapter, processes the data using standardized conversions, and computes standard tables that contain line items, summary flows, and various indices. The NEAD data is therefore immensely helpful for creating emergy accounts of individual nations, as well as for providing fast, efficient, and standardized sets of accounts for comparative purposes (Sweeney et al. 2007). In this section, we used NEAD data for all nations from 2000 (Sweeney et al. 2007) and 2008 (provided by Dr. S. Sweeney, University of Florida, Gainesville, personal communication, 2011). The compiled data is summarized in Table 7.4, which lists the per capita emergy consumption categories and the corresponding ratio of the 2008 value to the 2000 value. From 2000 to 2008, rapid population and economic growth led to increased resource consumption, and the per capita free emergy value in 2008 decreased to 0.91 times the 2000 value. In contrast, the per capita natural emergy

Table 7.4 Comparison of the per capita emergy categories between 2000 and 2008

Item	Emergy category (per capita sej)				
	Free	Natural	Economic	Total use	Total consumption
All 102 nations in 2008	6.94×10^{15}	2.52×10^{16}	2.41×10^{16}	4.42×10^{16}	4.93×10^{16}
All 134 nations in 2000	7.66×10^{15}	1.85×10^{16}	1.69×10^{16}	2.79×10^{16}	3.54×10^{16}
Ratio of 2008 to 2000 values	0.91	1.36	1.43	1.58	1.39

Notes: Data for all 134 nations in 2000 are from Sweeney et al. (2007); data for all 102 nations in 2008 were provided by Dr. S. Sweeney, University of Florida, Gainesville, personal communication (2011)

consumption increased to 1.36 times the 2000 value, the per capita economic emergy increased to 1.43 times the 2000 value, the per capita total emergy use increased to 1.58 times the 2000 value, and per capita total emergy consumption increased to 1.39 times the 2000 value.

Energy consumption is loosely correlated with GDP and climate (i.e., nations with cold climates consume more energy to generate heat). The United States consumes 25 % of the world's energy, with a 22 % share of global GDP and a 4.6 % share of the world's population (Department of Economic and Social Affairs 2011). The most significant growth of energy consumption is currently taking place in China, where consumption has been growing at 5.5 % per year over the last 25 years. The 2011 International Energy Outlook released by the U.S. Energy Information Administration presents updated projections for world energy markets through 2035 (USEIA 2011). According to the report, worldwide energy consumption is expected to grow by 53 % between 2008 and 2035 in the "reference" case under the heading "Global Trends and Forecasting", with much of the increase driven by strong economic growth in developing countries, and especially in China and India. China and India are expected to lead the growth in world demand for energy in the future. They continue to lead world economic growth and growth in energy demand. In 2008, China and India combined accounted for 21 % of total world energy consumption.

7.5 Summary of the Per Capita Emergy Analysis for Macao

To understand Macao's per capita energy consumption, we compared the data from our 2007 research (Lei et al. 2011) with data for 102 representative nations from the NEAD group (S. Sweeney, University of Florida, personal communication). Table 7.5 summarizes the results.

Macao's renewable (natural) resource carrying capacity is poor by global standards, with natural resources amounting to only 0.03 times the world level. However, Macao's economic emergy consumption and total per capita emergy use were higher

Table 7.5 Comparison of the mean per capita emergy values for 102 representative countries from around the world and for Macao

Categories	Emergy (per capita sej)				
	Free	Natural	Economic	Total use	Total consumption
All 102 nations in 2008	6.94×10^{15}	2.52×10^{16}	2.41×10^{16}	4.42×10^{16}	4.93×10^{16}
Macao	6.55×10^{13}	7.50×10^{14}	5.32×10^{16}	5.39×10^{16}	5.39×10^{16}
Macao/world value	0.01	0.03	2.21	1.22	1.09

Notes: Data for all 102 nations in 2008 were provided by Dr. S. Sweeney, University of Florida, Gainesville; values for Macao in 2007 were from Lei et al. (2011)

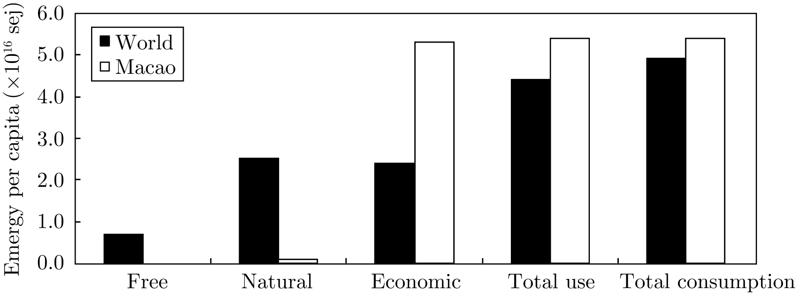

Fig. 7.15 Comparison of per capita emergy consumption by Macao in 2007 (Lei et al. 2011) and by 102 representative countries from around the world in 2008 (Dr. S. Sweeney, University of Florida, Gainesville, personal communication)

than the global average level (Fig. 7.15). These results show that Macao experiences higher energy consumption than the world level, and that it therefore violates the equitability principle (i.e., by consuming more per capita than is available to citizens of other countries).

7.6 Conclusions

Our results and those of previous studies confirm that environmental sustainability can be measured and that these measurements can provide important insights into problems at national and regional levels. Emergy analysis is a powerful tool for quantifying a nation's utilization of resources. By comparing the global resource carrying capacity with the resource consumption by a diverse group of 17 nations, we provided a clear image of each nation's sustainability status. Our results provide insights that will guide local, national, and global efforts to close the sustainability gap. The emergy sustainability analysis we have described is an effective strategic planning tool that can lead nations to a more secure, equitable, and sustainable future.

Our analysis provides additional strong evidence that the world's store of non-renewable resources is being used unsustainably, since most countries consume non-renewable fossil fuels at a rate far greater than the world's ability to replenish these resources. Declining supplies means that the energy available for use by society will decline with increasing speed as the global population increases and as citizens of developing nations begin to demand a quality of life comparable to that in developed nations. In other words, it will take more energy to generate power, and more emissions of pollutants and greater environmental destruction will result from production of the same amount of useful energy. Although shifting towards greater use of renewable forms of energy is desirable, each of the renewable sources is far less concentrated than fossil fuels and therefore has lower energy quality; this means that it is not possible to meet current demand by shifting to these energy sources without large improvements in the underlying technologies (Brown et al. 2009).

Our data confirms the many previous suggestions that humanity exerts too much pressure on the Earth. Humanity's average per capita free emergy carrying capacity is 6.94×10^{15} sej. However, we consume 49.35×10^{15} sej per capita of natural emergy. This means that the average emergy consumption is 7.12 times the available renewable emergy. This imbalance indicates that humanity's consumption exceeds what nature can provide on a continuous basis, and indicates that we are following a dramatically unsustainable road. We found that all countries except India exceeded the sustainable level of emergy consumption at the strong sustainability level. India, China, and Indonesia consumed less than the level at the weak sustainability line, which means that the three countries use less emergy than the average global per capita natural emergy consumption.

Developing strategies to reduce resource consumption will be an important approach. Emergy consumption can be reduced by increasing the efficiency of resource use (e.g., energy-saving light bulbs, high-efficiency wood stoves, solar-heated warm water) and by reducing consumption (e.g., working less, spending less). The proportion of total resource use derived from renewable sources can be calculated based on the total input from renewable sources divided by a country's area. The area cannot be increased, since it represents the total available input, thus to increase the proportion of renewable sources and thereby increase a nation's sustainability requires either confiscating land currently allocated to other uses and using it to generate more renewable emergy or reducing the use of non-renewable emergy.

Howard Odum and Odum (2001) have outlined principles and policies to guide the transition from our current growth ethic, which assumes that we can grow our way out of any problem, to an ethic that is sustainable in the long run. They suggest that the only real solution will be a contraction of national economies, a decline in overall energy consumption and production, and reducing populations at the same rate as the decrease in available annual emergy—in short, to consume less emergy than is available. It will soon become necessary to accept a decreasing development style to increase the probability of long-term human survival.

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Chapter 8
Conclusions and Outlook

8.1 Conclusions

8.1.1 Emergy Synthesis and Ecological Energy Accounting

Emergy synthesis offers an obvious advantage compared with traditional ecological or economics methods: it accounts for both human socioeconomic flows and natural flows of materials, energy, information, and money within a single consistent framework. That is, it converts flows with different units (e.g., mass, energy, money) into a single consistent set of units (solar em joules, sej). As a result, it permits a more holistic analysis of the complex systems that develop where human socioeconomic systems such as cities interact with the natural systems that sustain them.

Howard Odum is widely considered the father of emergy analysis, but many subsequent researchers have used and expanded on his insights. Perhaps the most important insight from his work is that an overall system or any part of the system can be evaluated by examining the balance between the flows into and out of the system being studied (i.e., the net emergy). Such analyses can be conducted at scales ranging from industrial sectors or cities (e.g., the gambling industry and Macao in the present book) to countries, continents, and the whole world (Chap. 7 in this book). For a declining system, outflows exceed inflows; for an expanding system, inflows exceed outflows. A fully sustainable system balances inflows with outflows in the long term, despite short-term fluctuations, so that there is no net change. Our analysis of Macao showed a rapidly expanding system that is sustained almost entirely by inflows, most of which come from the tourism sector.

As is often the case in studies of complex systems, no one indicator can completely explain the details of the flows within the system and between the system and its environment. Emergy synthesis is no exception, and analyses of systems as complex as a city are inevitably based on the definition of a range of parameters and indicators that evaluate different aspects of a system's overall sustainability. Our analysis revealed that indicators such as the emergy sustainability index (ESI) and the net emergy ratio (NER) provided good overall indications of sustainability,

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and that a lower NER represented a more sustainable system because it represents a lower impact on the external environment that sustains a city's life-support systems.

Macao is unusual in that its socioeconomic system is dominated by tourism, with a large and increasing number of tourists every year. Tourists import resources (e.g., money) from outside the system when they visit a city, consume local resources, and export local resources when they leave. Because tourism differs from the subjects of many previous emergy studies, it was necessary to develop a new emergy accounting method that accounted for the city's unique characteristics. In addition to accounting for the flows of tourism-related materials and energy, it was also necessary to account for the large inputs of money into Macao's system. Since Macao's resources are shared by local residents and tourists, we developed a method to account for consumption of resources by the tourists: specifically, we estimated their emergy as a proportion of the total emergy used by their host (Macao).

An additional index, the emergy exchange ratio (EER), can be used to express the relative benefits for two partners in an exchange of emergy. For Macao's tourism sector, this ratio equals the monetary income provided by tourism activities divided by the emergy consumed by the tourists. This balance can also be evaluated in terms of the net emergy surplus of the tourism industry, which equals the difference between the emergy imported into the system through tourist spending and the emergy consumed by the tourists.

During our study period, a tremendous positive net emergy flowed into Macao because tourists consumed only a small part of the emergy they contributed to the system. This huge net emergy has sustained Macao's socioeconomic development. Our analysis revealed that most of the tourism-related emergy indicators increased during the past 20 years of Macao's rapid development. However, the industrial simplification that occurred during this period heightened the importance of tourism for Macao's future survival and growth. Even if the city's rapid development can be made more sustainable, there is a risk created by such excessive dependence on a single economic sector. Diversifying the city's economy may both make its growth more sustainable and help the city to withstand economic shocks such as a recession that would dramatically decrease tourism.

8.1.2 Ecological Energy Accounting for Macao's Socioeconomic and Ecological Systems

Macao is a tourist city with a dense population, but is short on natural resources. Almost all of the city's life-support systems depend on imports of resources from outside the system. During the past 20 years, Macao's rapid socioeconomic development has depended heavily on the tourism industry (including gambling, hotel accommodations, restaurant dining, and shows). In this chapter, we employed ecological emergy accounting to characterize the urban evolution and development that occurred in Macao from 1983 to 2004. Macao's tourism industry has existed almost from the establishment of the city, with the legalization of gambling in Macao occurring in 1850. Since then, tourism has grown to become the biggest industry in Macao, contributing more than half of the city's revenues since 1995. We tracked and analyzed the emergy flows related to tourism to measure this sector's contribution to Macao.

We investigated the evolution of Macao's hybrid natural and socioeconomic system from 1983 to 2004 by means of ecological energy accounting. Time-series analyses proved to be particularly useful in understanding the dynamics of Macao's ecology and economy. The approach described in this book can be applied to all countries, and if the available data is of sufficient quality, can provide equally profound insights. Our results highlight the importance of updating national analyses yearly, since indicators vary greatly among years, and it is necessary to examine long-term trends to fully understand a country's evolution. An agreed-upon, standardized, and homogeneous emergy analysis procedure is necessary to allow a reliable evaluation of region's performance over time, as well as to facilitate comparisons among regions. Our comparison of Macao, Italy, and Sweden showed that emergy accounting significantly improves our understanding of the performance of such regional economies over time.

Cities rely more strongly on ecosystems beyond the city limits than is the case for more self-contained natural ecosystems. As cities draw more and more resources from distant areas, they also accumulate large amounts of materials, including wastes discharged into the surrounding systems. From the point of view of systems ecology, cities are self-regulating systems and may be seen as super-organisms, created for the benefit of human beings and for sustaining their livelihood. Prigogine pointed out that systems that are far from equilibrium (i.e., dissipative structures) can exist only as long as the system is sustained by a continual flow of energy or matter (i.e., negative entropy) through the system. For a micro-ecosystem such as that of a small city, oscillations in emergy can always be found; this variability reflects the instability and fragility of the system.

Our research demonstrated that by relying on an attractive gambling industry and an imbalance between imports and exports, Macao has absorbed large amounts of emergy through negative entropy inflows to support not only its survival, but also its booming development. Statistical analysis revealed that the emergy-based indicators in the present study could be divided into three categories (namely, positively and negatively correlated indicators, and non-correlated indicators) according to their correlation with development trends.

8.1.3 Emergy Synthesis and Simulation for Macao

Almost all of Macao's life-support systems depend on imports of external resources. We used emergy accounting to investigate and characterize the evolution and development of Macao from 1983 to 2003 as a result of land reclamation from the sea (to provide room to build) accompanied by large-scale imports of sand, rocks, and other construction materials from China to let residents take advantage of the new land. By simulating the emergy trends using the STELLA software, we were able to predict the consequences of Macao's development in the coming 20 years.

Howard Odum defined sustainability as preserving a system's ability to meet both human and environmental needs. Thus, sustainability is a process of adapting to the oscillations that occur in natural capital, recognizing that such unstable states are "possibly the most general patterns in nature". For a limited ecosystem such as that of a small city, emergy fluctuations are more frequent and potentially more severe than they would be in larger systems with greater buffering capacity. Because systems exhibit variation at various temporal and spatial scales, the emergy flows, emergy storage, and various related parameters and indicators also fluctuate. During our simulation period, the emergy used by Macao is predicted to increase with increasing urban development and population growth, and the area occupied by Macao will expand as the city continues to recover more land from the sea and accumulate emergy storage.

It would be helpful to obtain more and better data to permit more exact results from modeling such as that described in this chapter. Using the limited data that is currently available, it is difficult to accurately predict the future. However, despite the inherent inaccuracy of our approach, our results reveal areas of concern that should be investigated in more detail, and therefore provide a good starting point for future studies with improved methods and more accurate data. In particular, the ability of our analysis to reveal problem areas will let the city's government allocate resources to obtaining better statistics in those areas. Even though Macao is a tourism-driven city, our analysis suggested that the resources provided to tourists amounted to only about 15 % of total emergy use. However, our analysis in this chapter did not separate the emergy that tourists consumed from the emergy consumed by Macao's residents; therefore, the increase in the per capita emergy consumption produced an inflated estimate. We addressed this issue with the system dynamics software to some extent in Chap. 1, but do so in more detail in Chaps. 4 and 5.

8.1.4 Emergy Analysis for Tourism Systems: Principles and a Case Study for Macao

As we noted earlier in this chapter, a sustainable combined ecological and socioeconomic system must balance its flows and quantities of emergy; that is, a net surplus of emergy must flow into the system to account for the fact that socioeconomic systems are rarely self-sustaining. Although emergy accounting provides a better method for measuring the sustainability of an economic system than simplistic quantifications of monetary flows, it is difficult to evaluate specific systems such as tourism due to a lack of sufficient data and the lack of a powerful accounting method for flows of materials and energy. To permit this analysis, it is important to understand the advantages and drawbacks of the various emergy accounting approaches so that the correct technique can be used to assess the sustainability of tourism at local to national levels. In this chapter, we compared the four main emergy accounting approaches that are available for studying emergy flows through tourism, distinguished the consumption of emergy by tourists from the equivalent emergy their expenditures could purchase, and demonstrated the insights permitted by these approaches using a case study of tourism in Macao from 1983 to 2007.

Our analysis confirmed that visitors to Macao were strongly attracted by gambling, and spent a large proportion of their money on gambling and related activities. Gambling has been legal in Macao since the 1850s, when the Portuguese government legalized the activity in their colony. However, the gambling industry has also been a source of instability in Macao's economy, since the nature of the gambling business does not appear to be susceptible to technological advancement or productivity growth. The gambling business also depends strongly on the prosperity of other Asian economies, especially those of China and Hong Kong, since the majority of the tourists come from this region.

Sustainable tourism development depends on the wise use of resources and an understanding of the flows of energy embodied in these resources (i.e., the emergy flows). Due to a lack of data on services and imports from other regions, we used the world $E_m/\$$ ratio for all imported services. This approach undervalued the imports of labor and services, since (for example) China's $E_m/\$$ value is higher than the global average, and using a higher value in our accounting would have decreased Macao's net emergy since China is the main source of tourists for Macao. Finding ways to adopt more realistic $E_m/\$$ values for Macao and for the regions that exchange emergy with the city remains a challenge for future research.

8.1.5 Ecological Energy Accounting for the Gambling Sector: A Case Study in Macao

In parallel with an expanding gambling sector, tourism became the most important driving force in Macao's economy. Economic growth in Macao has now benefited from the gambling boom and associated tourism for more than two decades. Although traditional economic theory has been used by previous researchers to deal with the economics of the gambling sector, the materials and energy that provide the foundation for this sector have not been previously analyzed. This is an important omission from the literature, since the gambling sector provides gamblers with food, tickets, services (such as housing), water, electricity, equipment, labor, and other services that consume large quantities of materials and energy. In this chapter, we introduced emergy accounting to analyze the state of Macao's gambling sector in 2004. Macao's casinos provide a dense flow of services that favor gambling tourists, since the $E_m/\$$ ratio (1.42×10^{12} sej $\$^{-1}$) for the gambling sector was much lower than that for Macao as a whole (2.38×10^{12} sej $\$^{-1}$). The emergy of services therefore played an important role in Macao's gambling sector, and the transformity of an employee in this sector (11.2×10^{16} sej person^{-1}) was much higher than that of a typical person in Macao (5.27×10^{16} sej person^{-1}).

Because gambling activities include special recreation values that are attractive to gamblers, the conventional calculation method undervalues the relative emergy involved. Here, we developed a new equation to account for this problem by using the transformity per person (employee) to provide a more reasonable value for the emergy of the services consumed by gambling activities. Our results also revealed the differences between gambling and other economic activities. In the gambling sector, the proportion of imported service emergy (0.901) was much higher than that for Macao as a whole (0.097), but the NER was much lower (0.018) than that for Macao as a whole (0.259) because government taxation of this sector is too high. The majority of the earned emergy is imposed as taxes, and these taxes become an inflow for the government.

In the gambling sector, emergy exchange processes are simpler than in a broader system such as Macao. The concentrated emergy and currency flows in this narrow realm usually create a lower $E_{\mathrm{m}}/\$$ ratio than that of a city or region. That was the case in the present study, in which this ratio was 1.42×10^{12} sej \$$^{-1}$ for gambling in Macao, versus 2.38×10^{12} sej \$$^{-1}$ for Macao as a whole in 2004.

8.1.6 Emergy Synthesis for Waste Treatment in Macao

Socioeconomic growth differs from the growth that occurs in purely natural ecosystems, which tend to tightly recycle wastes and use them as resources that sustain the ecosystem. Losses are inevitable from even a natural system due to the laws of thermodynamics, but these losses are far smaller than those from any system that has been significantly modified by human activities. Because the production processes that underlie current modes of socioeconomic development are highly wasteful compared with the processes that govern the development of natural systems, waste management becomes a crucial issue for human systems such as cities.

The debate over waste management practices has become increasingly important as human activities have begun to overload the biosphere's assimilative capacity. An effective waste management policy should therefore be based on the principles of sustainable development, with wastes regarded as a potential resource rather than solely as something to eliminate, and with wastes produced at levels no higher than what the human and natural systems can absorb. This approach requires an integrated waste management plan that makes full use of all available technologies. During the past 20 years, Macao's discharged wastes have steadily increased. In this chapter, we employed emergy accounting to investigate Macao's waste treatment in six years (1990, 1993, 1995, 1999, 2003, and 2004). Since 1992, Macao's municipal solid waste (MSW) has mostly been incinerated to reduce its volume; this was necessary because of the lack of space in which to dispose of wastes by other methods (e.g., using landfills). A large investment of natural resources and technology is required to treat wastes, and this investment could be reduced if more of the wastes could be captured for reuse.

Analysis of waste generation and flows is complicated by a lack of adequate statistics and the difficulty of tracking materials and energy through the many transformations they undergo between the original raw materials and the final products. Nonetheless, in this chapter we used emergy analysis to mitigate some of these difficulties and develop a method that improves on previous methods of accounting for these flows. Specifically, we analyzed the waste collection and treatment processes for solid wastes, sewage, and gaseous emissions so that we could obtain their emergy.

Our analysis also demonstrated how the investment of resources and technology for the treatment of wastes could be assessed using a parameter that we named the emergy feedback ratio (f_r), which represents the emergy consumed to treat that waste divided by the emergy embodied in each category of waste. We found that the treatment input was a small proportion of the emergy embodied in the wastes, with an f_r of 0.14 for sewage, 0.02 for solid wastes, and 0.06 for gaseous emissions.

Our analysis confirmed that the waste treatment process decreased the environmental impact of the wastes, but increased the related transformity; that is, much energy was lost through waste treatment. Howard Odum's original formulation treats a high transformity as a high potential impact on Macao's environment and on its overall socioeconomic system. However, our analysis suggests that this was not necessarily the case. Macao's urban development will continue to increase the quantity of emergy flowing into the city, and the waste emergy will rise as a result. Our approach therefore provided new insights that will be useful in solving Macao's wastes problems and those of other cities.

8.1.7 Per Capita Resource Consumption and Resource Carrying Capacity: A Comparison of the Sustainability of Macao and 17 Countries

Sustainability involves aspects of society, the economy, and the environment. Environmental sustainability is increasingly being recognized as crucial to support global energy and resource consumption and to absorb the pollution generated by human activities. A comparison of the carrying capacity of natural resources with the consumption of these resources (i.e., the pressure being placed on those resources) at regional or global scales can provide insights into the relative progress towards sustainability in each region. To assess sustainability around the world using the techniques developed in previous chapters of this book, we selected 17 broadly representative countries from the 102 nations in the National Environmental Accounting Database (2008 data). Our analysis revealed that most of the countries consumed too many resources, thereby decreasing overall global sustainability of the natural resources that sustain human society. The sustainability analysis we have described is an effective strategic planning tool that can lead nations to a more secure, equitable, and sustainable future. Our results confirm previous predictions that to ensure long-term sustainability, it will be necessary to control population increases, reduce emergy consumption, and promote emergy efficiency.

Our analysis provides additional strong evidence that the world's store of non-renewable resources is being used unsustainably, since most countries consume non-renewable resources such as fossil fuels at a rate far greater than the world's ability to replenish these resources; that is, humanity exerts too much pressure on the Earth in most countries. We estimated that humanity's average per capita free emergy carrying capacity is 6.94×10^{15} sej, but we consume 49.35×10^{15} sej per capita of natural emergy. This means that the average emergy consumption is 7.12 times the available renewable emergy. This imbalance indicates that humanity's consumption greatly exceeds what nature can provide on a continuous basis, and indicates that we are following a dramatically unsustainable road. We found that all countries exceeded the sustainable level of emergy consumption at the strong sustainability level (in which each type of natural capital must be preserved independently; that is, the different types of capital can complement each other, but they cannot substitute for one another). India, China and Indonesia consumed less than the level at the weak sustainability line (in which the total natural capital is preserved, but not necessarily all kinds of capital; that is, the different types of capital are considered to be potential substitutes); this means that the three countries use less emergy than the average global per capita natural emergy consumption, but are not yet following a truly sustainable path.

The current growth ethic adopted by modern industrial civilization assumes that we can grow our way out of any problem, but our results and those of previous researchers suggest that this is not sustainable in the long run. The only real solution will be a contraction of national economies, a decline in overall energy consumption and production, and a reduction of populations at the same rate as the decrease in available annual emergy—in short, to consume less emergy than is available. It will soon become necessary to accept a decreasing rate of development to increase the probability of long-term human survival.

8.2 Outlook

Although the techniques of emergy accounting have advanced remarkably in recent decades, as illustrated by our discussion in this book, many important questions have not yet been answered, and there is much room for methodological improvements in future research.

8.2.1 Better Statistics and More Exact Transformity Values

The accuracy of the outputs of any analysis depends strongly on the quality of the input data. As we have noted at several points in this book, the quality of the statistics that are available to support emergy analysis is barely adequate. That is, the available statistics can provide a crude overall assessment of a system or its components, but much work remains to be done to find ways to obtain more data, and more accurate data. Despite this limitation, our results show the value of emergy synthesis techniques, and this value will only increase as more and better data becomes available.

Because of the importance of transformity for converting flows with disparate units (e.g., mass, energy, and money) into a single consistent framework, more accurate transformity values are also required. Most of the analysis in the research presented in this book used transformity values provided by previous researchers, usually for regions outside China that possess very different social, environmental, and technological characteristics from those in China. In addition, as technology becomes more advanced, transformity values will inevitably change. Thus, it is necessary to find ways to efficiently obtain more accurate transformity values for a given study area.

Other factors, such as the $E_\mathrm{m}/\$$ ratios that we used for studying tourism emergy, require separate calculation for each region that is a source of flows and better knowledge of the proportion of the total flows that originates in each region. This is an example of a case in which both better statistics and better transformities (or other conversion factors) will improve the ability of emergy synthesis to accurately describe a system, thereby providing better guidance for managers.

8.2.2 The Importance of Wastes and Their Treatment

The laws of thermodynamics tell us that although energy is conserved, much of the useful energy is lost through transformation into other forms, such as heat. For any complex system, whether a natural ecosystem or a hybrid natural–socioeconomic system, additional losses occur in the form of waste generation and the need to treat these wastes. Wastes are an inevitable byproduct of material transfer and transformation processes, and it is increasingly realized that we must find more effective ways to reduce the generation of these wastes, reuse some of the wastes as inputs for new processes, and decrease the treatment cost (in both economic and energy terms) of wastes that can neither be avoided nor reused. Our analysis in this book shows the usefulness of emergy analysis for evaluating these issues, but as we note in Sect. 8.2.1, much more work is necessary to obtain better statistics on waste generation and treatment and better transformities so that flows of wastes can be analyzed more accurately. Better theoretical treatment of these issues is also necessary.

8.2.3 Integrating Catabolic Processes with Emergy Accounting

The emergy accounting framework that we established was based on research on assimilation (anabolic) processes, but it is not yet clear whether it is equally suitable for catabolic processes such as waste treatment. Additional case studies and analyses, and possibly improved methods, will be required. There are hints from our study of Macao's waste treatment that catabolic processes may behave differently from other forms of emergy data. For example, sewage treatment processes transform contaminated water into pure water. The sewage contains many materials that add considerable emergy value to the polluted water. By providing an input of energy and by performing suitable treatment processes, the sewage becomes pure water, but it is not clear how similar this is to the situation for natural water. For example, is its emergy transformity higher than that of natural pure water with similar chemical and physical characteristics? Based on our review of emergy theory, the treated pure water should have a higher transformity than natural pure water, even if the two types of water are indistinguishable. Deciding how to handle such problems will be a challenge that must be solved in future emergy accounting frameworks.

Appendix A

Supplementary Tables That Summarize the Inflow and Outflow Emergy Values for Macao in 2004[1]

Table A.1 Emergy evaluation for Macao's food imports in 2004

Item	Raw mass (g)	Heat value (cal g^{-1})	Energy (J)	Transformity (sej J^{-1})	Emergy (sej $year^{-1}$)	Reference for transformity
Meat	2.20E+10	5.80E+03	5.35E+14	3.17E+06	1.70E+21	Yan and Odum (2001)
Live animals	1.78E+10	5.80E+03	4.32E+14	1.71E+06	7.39E+20	H. T. Odum (1996)
Fish, aquatic animals	2.26E+10	1.00E+03	9.47E+13	1.71E+06	1.62E+20	Lan et al. (1998)
Animal fats and oils	8.62E+09	5.50E+03	1.99E+14	1.71E+06	3.40E+20	Lan et al. (1998)
Meat offal, fats, etc.	1.34E+08	2.00E+03	1.12E+12	1.71E+06	1.91E+18	Lan et al. (1998)
Preparations of meal	1.01E+10	2.00E+03	8.44E+13	1.71E+06	1.44E+20	Lan et al. (1998)
Dairy; eggs; honey	1.57E+10	1.70E+03	1.11E+14	2.00E+06	2.23E+20	Yan and Odum (2001)
Live trees; cut flowers	3.30E+09	4.50E+03	6.21E+13	4.40E+04	2.73E+18	H. T. Odum and Odum (1983)
Edible vegetables	3.31E+10	1.02E+03	1.41E+14	2.70E+04	3.81E+18	Lan et al. (1998)
Wheat gluten	8.24E+06	2.00E+03	6.90E+10	6.90E+05	4.76E+16	H. T. Odum (1987)
Potatoes	1.20E+09	1.02E+03	5.13E+12	2.70E+03	1.39E+16	Lan et al. (1998)
Edible roots	1.55E+09	1.02E+03	6.60E+12	2.70E+04	1.78E+17	Lan et al. (1998)
Starchy roots; tubers	3.12E+09	8.00E+02	1.04E+13	2.70E+04	2.82E+17	Lan et al. (1998)
Edible fruits and nuts	2.16E+10	5.00E+02	4.53E+13	5.30E+04	2.40E+18	Ulgiati et al. (1994)
Coffee, tea	1.60E+09	3.90E+03	2.61E+13	2.00E+05	5.22E+18	Ulgiati et al. (1994)
Cereals	2.27E+08	3.70E+03	3.51E+12	1.48E+05	5.18E+17	Yan and Odum (2001)
Corn	3.23E+07	3.95E+03	5.34E+11	5.81E+04	3.10E+16	H. T. Odum (1996)
Rice	2.51E+10	3.70E+03	3.88E+14	3.59E+04	1.39E+19	Yan and Odum (2001)
Milled products	9.97E+09	4.50E+03	1.88E+14	6.80E+04	1.28E+19	H. T. Odum (1987)
Seeds, spores	2.54E+06	5.00E+03	5.32E+10	6.80E+04	3.62E+15	H. T. Odum (1987)
Other meslin flour	8.49E+08	4.50E+03	1.60E+13	1.48E+05	2.37E+18	Lan et al. (1998)
Starches; inulin	3.54E+08	4.50E+03	6.67E+12	8.49E+04	5.67E+17	Yan and Odum (2001)
Medicinal plants, straw	3.44E+09	5.00E+03	7.21E+13	8.60E+04	6.20E+18	Yan and Odum (2001)

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[1] *Note*: The references in Appendix A correspond to Chap. 2.

K. Lei et al., *Ecological Emergy Accounting for a Limited System: General Principles and a Case Study of Macao*, Springer Environmental Science and Engineering,
DOI 10.1007/978-3-642-45170-6,

Table A.1 (*Continued*)

Item	Raw mass (g)	Heat value (cal g^{-1})	Energy (J)	Transformity (sej J^{-1})	Emergy (sej year^{-1})	Reference for transformity
Oil seeds or fruits	2.14E+05	5.00E+03	4.48E+09	1.30E+06	5.82E+15	H. T. Odum (1996)
Beans	1.35E+09	1.85E+03	1.05E+13	6.90E+05	7.24E+18	H. T. Odum (1987)
Resins, vegetable saps	3.74E+06	5.00E+03	7.82E+10	1.60E+05	1.25E+16	Lan et al. (1998)
Vegetable materials	3.10E+09	3.50E+03	4.54E+13	4.40E+04	2.00E+18	H. T. Odum and Odum (1983)
Sugars	7.78E+09	4.50E+03	1.47E+14	8.50E+04	1.25E+19	Lan and Odum (1994)
Cocoa	9.05E+08	5.50E+03	2.08E+13	8.60E+05	1.79E+19	Lan and Odum (1994)
Kinds of preparations	8.55E+09	5.00E+03	1.79E+14	1.71E+06	3.06E+20	Lan et al. (1998)
Soya sauce	1.66E+09	1.00E+03	6.94E+12	8.00E+03	5.55E+16	Lan et al. (1998)
Plant preparations	1.17E+10	2.10E+03	1.03E+14	1.71E+06	1.75E+20	Lan et al. (1998)
Beverages	9.25E+10	1.30E+03	5.04E+14	6.00E+04	3.02E+19	H. T. Odum (1987)
Prepared animal fodder	2.88E+09	1.70E+03	2.05E+13	8.00E+04	1.64E+18	H. T. Odum (1987)
Tobacco substitutes	3.48E+09	3.90E+03	5.68E+13	8.49E+04	4.82E+18	Yan and Odum (2001)
Total	3.36E+11		3.52E+15		3.92E+21	

Table A.2 Emergy evaluation for Macao's mineral imports in 2004

Item	Raw mass (g)	Money (US$)	Transformity (sej g^{-1})	Emergy (sej $year^{-1}$)	Reference for transformity
Sulfur; stone; plastering materials	2.85E+11	4.42E+06	1.00E+09	2.85E+20	H. T. Odum (1996)
Natural sands	3.63E+11	8.99E+05	1.00E+09	3.63E+20	H. T. Odum (2000)
Salt	2.01E+09	1.72E+05	1.00E+09	2.01E+18	H. T. Odum (1996)
Clays	2.88E+08	2.61E+04	1.00E+09	2.88E+17	H. T. Odum (2000)
Chalk	2.19E+08	1.45E+04	1.00E+09	2.19E+17	H. T. Odum (2000)
Marble	1.21E+10	6.36E+04	1.00E+09	1.21E+19	H. T. Odum (2000)
Ores, slag, and ash	5.07E+10	1.69E+05	2.07E+09	1.05E+20	H. T. Odum (2000)
Cement clinker	2.37E+11	6.42E+06	2.07E+09	4.90E+20	Brown and Buranakarn (2003)
Total	9.50E+11	1.22E+07		1.26E+21	

Table A.3 Emergy evaluation for Macao's imports of raw and processed materials in 2004

Item	Raw mass (g)	Money (US$)	Heat value (cal g^{-1})	Energy (J)	Transformity (sej unit^{-1})	Emergy (sej year^{-1})	Reference for transformity
Dyes, paints; putty; inks ($)	4.29E+09	7.36E+06			1.66E+12	1.22E+19	Abel (2000)
Perfumery, cosmetic preparations ($)	8.03E+09	5.55E+07			1.66E+12	9.21E+19	Abel (2000)
Soap; candles ($)	1.37E+10	1.68E+07			1.66E+12	2.79E+19	Abel (2000)
Protein; modified starches ($)	2.93E+09	3.86E+06			1.66E+12	6.40E+18	Abel (2000)
Explosive preparations ($)	7.94E+07	3.62E+05			1.66E+12	6.01E+17	Abel (2000)
Photographic goods ($)	1.31E+09	6.84E+06			1.66E+12	1.14E+19	Abel (2000)
Miscellaneous chemical products ($)	6.62E+09	1.27E+07			1.66E+12	2.10E+19	Abel (2000)
Plastics and articles thereof ($)	2.85E+10	4.41E+07			4.94E+12	2.18E+20	Zhao (2002)
Rubber and articles thereof ($)	4.16E+09	1.20E+07			1.66E+12	1.99E+19	Abel (2000)
Leather, fur, etc. ($)	7.98E+08	4.45E+06			1.66E+12	7.39E+18	Abel (2000)
Raw hides and leather ($)	3.18E+08	1.19E+07			1.66E+12	1.98E+19	Abel (2000)
Articles of leather; handbags ($)	6.71E+07	1.23E+06			1.66E+12	2.04E+18	Abel (2000)
Wood and articles of wood	2.97E+10		4.50E+03	5.60E+14	3.20E+04	1.79E+19	H. T. Odum (1996)
Fuelwood in logs or faggots	3.20E+09		3.50E+03	4.68E+13	3.20E+04	1.50E+18	H. T. Odum (1996)
Wood in the rough	1.38E+09		3.00E+03	1.73E+13	3.20E+04	5.53E+17	H. T. Odum (1996)
Cork and articles of cork	2.22E+07		4.50E+03	4.18E+11	4.40E+04	1.84E+16	Lan et al. (2002)
Manufactured straw goods	1.06E+08		3.50E+03	1.55E+12	4.40E+04	6.81E+16	Lan et al. (2002)
Pulp of wood or fibrous materials	7.96E+05		4.50E+03	1.50E+10	4.40E+04	6.60E+14	Lan et al. (2002)
Paper and paperboard	3.36E+10		4.50E+03	3.99E+07	4.40E+04	1.76E+12	Lan et al. (2002)
Books, newspapers, pictures ($)	1.94E+09	5.91E+06			1.66E+12	9.81E+18	Abel (2000)
Silk	8.28E+07		5.50E+03	1.91E+12	3.80E+06	7.24E+18	H. T. Odum and Odum (1983)

Table A.3 (*Continued*)

Item	Raw mass (g)	Money (US$)	Heat value (cal g^{-1})	Energy (J)	Transformity (sej unit^{-1})	Emergy (sej year^{-1})	Reference for transformity
Wool, animal hair	8.06E+09		5.50E+03	1.86E+14	4.40E+06	8.17E+20	H. T. Odum (1996)
Cotton (g)	2.73E+10				2.31E+10	6.30E+20	Brandt-Williams (2001)
Vegetable textile fibers	8.03E+08		3.00E+03	1.01E+13	3.80E+06	3.83E+19	Lan et al. (2002)
Man-made filaments	1.21E+10		4.50E+03	2.29E+14	3.80E+06	8.69E+20	Lan et al. (2002)
Man-made staple fibers	5.87E+09		4.50E+03	1.11E+14	3.80E+06	4.20E+20	Lan et al. (2002)
Wadding, felt, ropes, articles thereof	1.37E+09		4.50E+03	2.58E+13	3.80E+06	9.81E+19	Lan et al. (2002)
Carpets, textile floor coverings	6.51E+08		4.50E+03	1.23E+13	3.80E+06	4.66E+19	Lan et al. (2002)
Woven fabrics; embroidery	3.39E+09		4.50E+03	6.38E+13	3.80E+06	2.43E+20	Lan et al. (2002)
Textile articles for industrial use	1.74E+09		4.50E+03	3.28E+13	3.80E+06	1.24E+20	Lan et al. (2002)
Knitted fabrics	3.77E+10		4.50E+03	7.10E+14	3.80E+06	2.70E+21	Lan et al. (2002)
Clothing accessories, crocheted	6.14E+10		4.50E+03	1.16E+15	3.80E+06	4.39E+21	Lan et al. (2002)
Clothing accessories, not crocheted	4.60E+10	4.31E+08			1.66E+12	7.15E+20	Abel (2000)
Other manufactured textile articles	5.83E+08		4.50E+03	1.10E+13	3.80E+06	4.17E+19	Lan et al. (2002)
Footwear	2.37E+10	7.71E+07			1.66E+12	1.28E+20	Abel (2000)
Headgear and parts thereof (g)	5.95E+08				4.30E+09	2.56E+18	Lan et al. (2002)
Articles made of feathers, flowers (g)	6.13E+07				4.30E+09	2.64E+17	Lan et al. (2002)
Plaster, asbestos, mica (g)	1.69E+11				1.98E+09	3.34E+20	Lan et al. (2002)
Total	5.41E+11					1.21E+22	

Table A.4 Emergy evaluation for Macao's imports of goods in 2004

Item and units	Mass (g)	Money (US$)	Transformity (sej per unit)	Emergy (sej year^{-1})	Reference for transformity
Chemicals ($)	2.47E+10	4.28E+07	1.66E+12	7.1E+19	Abel (2000)
Fertilizers (g)	3.26E+08		2.8E+09	9.14E+17	Lan et al. (2002)
Ceramic products (g)	9.69E+10		1.98E+09	1.92E+20	H. T. Odum and Odum (1983)
Glass and glassware (g)	1.40E+10		8.4E+08	1.17E+19	Lan et al. (2002)
Iron and steel (g)	1.70E+11		1.40E+09	2.38E+20	H. T. Odum and Odum (1983)
Copper and articles thereof (g)	2.00E+09		6.8E+10	1.36E+20	Yan and Odum (2001)
Aluminum and articles thereof (g)	5.58E+09		1.6E+10	8.93E+19	H. T. Odum (1996)
Nickel and articles thereof (g)	3.62E+06		1.00E+09	3.62E+15	Ulgiati et al. (1994)
Other metals (g)	2.71E+09		1.25E+10	3.39E+19	H. T. Odum (1996)
Machinery, electrical equipment ($)	8.24E+10	9.78E+08	1.66E+12	1.62E+21	Abel (2000)
Other manufactured articles ($)	2.36E+09	7.79E+07	1.66E+12	1.29E+20	Abel (2000)
Works of art, antiques ($)	1.79E+09	2.36E+07	1.66E+12	3.92E+19	Abel (2000)
Pearls, precious metals, jewellery; coins ($)	1.38E+07	6.60E+05	1.66E+12	1.1E+18	Abel (2000)
Umbrellas, seat-sticks, whips (g)	6.42E+07		4.30E+09	2.76E+17	Abel (2000)
Total	4.03E+11	1.25E+09		2.57E+21	

Table A.5 Emergy evaluation for Macao's food exports in 2004

Item	Raw mass (g)	Heat value (cal g^{-1})	Energy (J)	Transformity (sej J^{-1})	Emergy (sej $year^{-1}$)	Reference for transformity
Live animals	1.13E+08	5.80E+03	1.92E+12	1.71E+06	3.29E+18	H. T. Odum (1996)
Meat and meat offal	1.47E+08	5.80E+03	3.56E+12	3.17E+06	1.13E+19	Yan and Odum (2001)
Fish, aquatic invertebrates	6.89E+08	1.00E+03	2.88E+12	1.71E+06	4.93E+18	Lan et al. (1998)
Dairy produce; eggs; honey	8.41E+07	1.70E+03	5.98E+11	2.00E+06	1.20E+18	Yan and Odum (2001)
Edible vegetables	1.33E+07	1.02E+03	5.69E+10	2.70E+04	1.54E+15	Lan et al. (1998)
Dried leguminous vegetables	1.13E+07	3.40E+03	1.61E+11	6.90E+05	1.11E+17	Lan et al. (1998)
Edible fruits and nuts	1.95E+07	5.00E+02	4.09E+10	5.30E+04	2.17E+15	Lan et al. (1998)
Coffee, tea	3.90E+08	3.90E+03	6.37E+12	2.00E+05	1.27E+18	Ulgiati et al. (1992)
Wheat or meslin flour	1.53E+07	4.50E+03	2.89E+11	6.80E+04	1.96E+16	Ulgiati et al. (1992)
Cereals	2.40E+05	3.70E+03	3.72E+09	1.48E+05	5.50E+14	H. T. Odum (1987)
Rice	5.40E+07	3.70E+03	8.37E+11	3.59E+04	3.00E+16	Yan and Odum (2001)
Medicinal plants, straw	1.61E+08	5.00E+03	3.37E+12	8.60E+04	2.89E+17	H. T. Odum (1987)
Vegetable plaiting materials	4.00E+05	3.50E+03	5.86E+09	4.40E+04	2.58E+14	H. T. Odum and Odum (1983)
Animal or vegetable fats and oils	1.84E+08	5.50E+03	4.25E+12	1.71E+06	7.26E+18	Lan et al. (1998)
Sugars and confectionery	1.14E+08	4.50E+03	2.14E+12	8.50E+04	1.82E+17	Lan and Odum (1994)
Cocoa	3.47E+07	5.50E+03	7.98E+11	8.60E+05	6.86E+17	Lan and Odum (1994)
Preparations of cereals, or milk	3.58E+08	5.00E+03	7.49E+12	1.71E+06	1.28E+19	Lan et al. (1998)
Preparations of vegetables	1.69E+08	2.10E+03	1.49E+12	1.71E+06	2.55E+18	Lan et al. (1998)
Beans (shelled, not frozen)	1.98E+06	1.85E+03	1.54E+10	6.90E+05	1.06E+16	H. T. Odum (1987)
Miscellaneous preparations	1.47E+09	5.00E+03	3.08E+13	1.71E+06	5.26E+19	Lan et al. (1998)
Soya sauce	1.16E+07	1.00E+03	4.84E+10	1.71E+06	8.27E+16	Lan et al. (1998)
Beverages, spirits, and vinegar	1.73E+09	1.30E+03	9.40E+12	6.00E+04	5.64E+17	H. T. Odum (1987)
Prepared animal fodder	1.52E+08	1.70E+03	1.08E+12	8.00E+04	8.65E+16	H. T. Odum (1987)
Total	5.92E+09		7.76E+13		9.93E+19	

Table A.6 Emergy evaluation for export minerals for Macao in 2004

Item	Mass (g)	Money (US$)	Transformity (sej g^{-1})	Emergy (sej $year^{-1}$)	Reference for transformity
Sulfur; stone materials	6.97E+07	4.68E+04	1.00E+09	6.97E+16	H. T. Odum (1996)
Salt	1.10E+07	6.86E+02	1.00E+09	1.10E+16	H. T. Odum (1996)
Cement clinker	1.23E+10	6.64E+05	2.07E+09	2.55E+19	Brown and Buranakarn (2003)
Total	1.24E+10	7.11E+05		2.55E+19	

Table A.7 Emergy evaluation for Macao's exports of raw and processed materials in 2004

Item	Raw mass (g)	Money (US$)	Heat value (cal g^{-1})	Energy (J)	Transformity (sej unit^{-1})	Emergy (sej year^{-1})	Reference for transformity
Dyes, paints; putty; inks ($)	7.61E+08	2.57E+06			2.38E+12[a]	6.11E+18	
Perfumery, cosmetics ($)	1.90E+09	2.66E+06			2.38E+12[a]	6.32E+18	
Soap, candles ($)	2.35E+09	4.15E+06			2.38E+12[a]	9.86E+18	
Protein; modified starches ($)	1.71E+09	2.95E+06			2.38E+12[a]	7.01E+18	
Photographic goods ($)	5.50E+08	1.45E+06			2.38E+12[a]	3.46E+18	
Miscellaneous chemical products ($)	1.35E+09	5.71E+06			2.38E+12[a]	1.36E+19	
Plastics and articles thereof (g)	1.14E+10	1.13E+07			3.80E+08	4.35E+18	Cialani et al. (2005)
Rubber and articles thereof (g)	3.04E+08	2.31E+06			4.30E+09	1.31E+18	Cialani et al. (2005)
Raw hides and leather ($)	6.72E+08	3.20E+06			2.38E+12[a]	7.62E+18	
Articles of leather, handbags ($)	2.10E+08	2.04E+06			2.38E+12[a]	4.85E+18	
Fur, skins, artificial fur ($)	5.91E+07	5.02E+05			2.38E+12[a]	1.19E+18	
Wood and articles of wood	6.32E+09	1.38E+06	4.50E+03	1.19E+14	3.20E+04	3.81E+18	H. T. Odum (1996)
Fuelwood in logs or faggots	3.60E+08	1.88E+04	3.00E+03	4.52E+12	3.20E+04	1.45E+17	H. T. Odum (1996)
Cork and articles of cork	1.31E+07	4.96E+03	4.50E+03	2.46E+11	4.40E+04	1.08E+16	Lan et al. (2002)
Manufactured straw goods	5.42E+05	6.20E+02	3.50E+03	7.94E+09	4.40E+04	3.49E+14	Lan et al. (2002)
Pulp of wood	2.16E+10	6.44E+05	4.50E+03	4.07E+14	4.40E+04	1.79E+19	Lan et al. (2002)
Paper and paperboard	3.20E+09	5.84E+06	4.50E+03	6.03E+13	4.40E+04	2.65E+18	Lan et al. (2002)
Books, newspapers ($)	4.19E+08	5.07E+05			2.38E+12[a]	1.21E+18	
Silk	5.38E+07	6.41E+05	5.50E+03	1.24E+12	3.80E+06	4.71E+18	H. T. Odum and Odum (1983)
Wool, animal hair	7.46E+09	6.96E+07	5.50E+03	1.72E+14	4.40E+06	7.56E+20	H. T. Odum (1996)
Cotton (g)	1.63E+10	8.87E+07		1.63E+10	2.31E+10	3.77E+20	Brandt-Williams (2001)

Table A.7 (*Continued*)

Item	Raw mass (g)	Money (US$)	Heat value (cal g^{-1})	Energy (J)	Transformity (sej $unit^{-1}$)	Emergy (sej $year^{-1}$)	Reference for transformity
Vegetable textile fibers	2.93E+08	1.97E+06	3.00E+03	3.68E+12	3.80E+06	1.40E+19	Lan et al. (2002)
Man-made filaments	6.91E+09	3.31E+07	4.50E+03	1.30E+14	3.80E+06	4.95E+20	Lan et al. (2002)
Man-made staple fibers	1.73E+09	9.43E+06	4.50E+03	3.26E+13	3.80E+06	1.24E+20	Lan et al. (2002)
Wadding, felt, ropes	4.94E+08	3.50E+06	4.50E+03	9.30E+12	3.80E+06	3.53E+19	Lan et al. (2002)
Carpets, textile floor coverings	7.46E+06	6.53E+04	4.50E+03	1.41E+11	3.80E+06	5.34E+17	Lan et al. (2002)
Woven fabrics; embroidery	1.06E+09	1.16E+07	4.50E+03	2.00E+13	3.80E+06	7.61E+19	Lan et al. (2002)
Textile articles for industrial use	8.56E+08	1.85E+06	4.50E+03	1.61E+13	3.80E+06	6.13E+19	Lan et al. (2002)
Knitted or crocheted fabrics	2.13E+10	8.71E+07	4.50E+03	4.02E+14	3.80E+06	1.53E+21	Lan et al. (2002)
Clothing accessories (knitted)	7.90E+10	1.35E+09	4.50E+03	1.49E+15	3.80E+06	5.66E+21	Lan et al. (2002)
Clothing accessories ($)	6.01E+10	1.07E+09			2.38E+12[a]	2.55E+21	
Other textile articles; rags	1.67E+09	3.20E+05	4.50E+03	3.14E+13	3.80E+06	1.19E+20	Lan et al. (2002)
Footwear ($)	2.38E+10	1.04E+08			2.38E+12[a]	2.47E+20	
Headgear and parts thereof (g)	6.60E+08	7.51E+06		6.60E+08	4.30E+09	2.84E+18	Lan et al. (2002)
Articles made from feathers, flowers (g)	4.47E+07	3.68E+05		4.47E+07	4.30E+09	1.92E+17	Lan et al. (2002)
Plaster, asbestos, mica (g)	5.41E+08	1.06E+05		5.41E+08	1.98E+09	1.07E+18	Lan et al. (2002)
Total	2.76E+11	2.89E+09				1.21E+22	

[a] 2.38E+12 sej $\$^{-1}$ is our calculated result for Macao's $E_m/\$$ ratio

Table A.8 Emergy evaluation for Macao's exports of goods in 2004

Item	Raw mass (g)	Money (US$)	Transformity (sej per unit)	Emergy (sej year^{-1})	Reference for transformity
Chemicals	6.55E+08	9.28E+06	2.38E+12[a]	2.21E+19	
Umbrellas, seat-sticks, whips (g)	1.90E+04		4.30E+09	8.17E+13	H. T. Odum and Odum (1983)
Ceramic products (g)	1.41E+08		1.98E+09	2.79E+17	Lan et al. (2002)
Glass and glassware (g)	8.11E+09		8.40E+08	6.81E+18	Lan et al. (2002)
Pearls, precious metals, jewellery; coins ($)	1.65E+08	2.38E+07	2.38E+12[a]	5.65E+19	
Iron and steel (g)	5.28E+10		1.40E+09	7.39E+19	H. T. Odum and Odum (1983)
Copper and articles thereof (g)	6.43E+09		6.80E+10	4.37E+20	Yan and Odum (2001)
Aluminum and articles thereof (g)	2.42E+09		1.60E+10	3.87E+19	H. T. Odum (1996)
Nickel and articles thereof (g)	4.60E+05		1.00E+09	4.60E+14	H. T. Odum (1996)
Other base metals; cermets (g)	5.29E+08		1.25E+10	6.62E+18	H. T. Odum (1996)
Machinery, electrical equipment	1.26E+10	2.84E+08	2.38E+12[a]	6.74E+20	
Other manufactured articles ($)	1.48E+09	1.42E+07	2.38E+12[a]	3.38E+19	
Manufactured articles ($)	6.31E+08	7.36E+06	2.38E+12[a]	1.75E+19	
Works of art, antiques ($)	8.94E+06	1.00E+05	2.38E+12[a]	2.39E+17	
Total	8.60E+10	3.98E+08		1.37E+21	

[a] 2.38E+12 sej $\$^{-1}$ is our calculated result for Macao's $E_{\mathrm{m}}/\$$ ratio

Appendix B

Supplementary Tables That Summarize the Inflows and the Outflows of Emergy for Macao in 2007[2]

Table B.1 Emergy evaluation for foods imported by Macao in 2007

Item	Raw mass (g)	Heat content value[a] (cal g^{-1})	Energy (J)	Transformity (sej J^{-1})	Emergy (sej year^{-1})	Reference
Meat and meat offal	2.92E+10	5800	7.09E+14	792 000	5.62E+20	Campbell et al. (2005)
Fish, aquatic animals	1.86E+10	1000	7.79E+13	1 961 800	1.53E+20	Campbell et al. (2005)
Animal fats and oils	4.68E+09	5500	1.08E+14	792 000	8.53E+19	Campbell et al. (2005)
Dairy; eggs; honey	2.17E+10	1700	1.54E+14	792 000	1.22E+20	Campbell et al. (2005)
Live trees; cut flowers	4.47E+09	4500	8.42E+13	20 600	1.73E+18	Campbell et al. (2005)
Edible vegetables	4.12E+10	1020	1.76E+14	20 600	3.62E+18	Campbell et al. (2005)
Edible roots and potatoes	7.15E+09	1020	3.05E+13	27 000	8.24E+17	Lan et al. (1998)
Edible fruits and nuts	2.27E+10	500	4.76E+13	53 000	2.52E+18	Ulgiati et al. (1994)
Coffee, tea	2.63E+09	3900	4.29E+13	200 000	8.58E+18	Ulgiati et al. (1994)
Cereals and corn	3.04E+10	3700	4.71E+14	147 524	6.94E+19	Yan and Odum (2001)
Rice	3.02E+10	3700	4.68E+14	35 900	1.68E+19	Yan and Odum (2001)
Milling products	3.52E+10	4500	6.64E+14	68 000	4.51E+19	H. T. Odum (1987)
Medicinal plants, straw	4.68E+09	5000	9.79E+13	86 000	8.42E+18	Yan and Odum (2001)
Oil seeds or fruits	2.05E+10	5000	4.28E+14	1 300 000	5.57E+20	H. T. Odum (1996)
Beans	1.26E+09	1850	9.72E+12	690 000	6.71E+18	H. T. Odum (1987)
Sugars	1.14E+10	4500	2.14E+14	85 000	1.82E+19	Lan and Odum (1994)
Cocoa	1.76E+09	5500	4.04E+13	860 000	3.48E+19	Lan and Odum (1994)
Kinds of preparations	2.93E+10	5000	6.14E+14	1 710 000	1.05E+21	Lan et al. (1998)
Soya sauce	2.85E+09	1000	1.19E+13	8000	9.54E+16	Lan et al. (1998)
Plant preparations	1.64E+10	2100	1.45E+14	1 710 000	2.47E+20	Lan et al. (1998)
Beverages	1.10E+11	1300	5.98E+14	60 000	3.59E+19	H. T. Odum (1987)
Prepared animal fodder	2.28E+09	1700	1.62E+13	80 000	1.30E+18	H. T. Odum (1987)
Tobacco substitutes	3.65E+09	3900	5.96E+13	84 900	5.06E+18	Yan and Odum (2001)
Total	4.52E+08		5.27E+15		3.03E+21	

[a] The heat content values in this table were obtained from Luo et al. (1987)

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[2] *Note*: The references in Appendix B correspond to Chap. 4.

K. Lei et al., *Ecological Emergy Accounting for a Limited System: General Principles and a Case Study of Macao*, Springer Environmental Science and Engineering,
DOI 10.1007/978-3-642-45170-6,

Table B.2 Emergy evaluation for minerals imported by Macao in 2007

Item	Raw mass (g)	Money (US$)	Transformity (sej g^{-1})	Emergy (sej $year^{-1}$)	Reference for transformity
Salt	2.28E+09	2.27E+06	9.80E+08	2.24E+18	H. T. Odum (1996)
Stone; plastering materials	1.59E+12	7.66E+07	9.80E+08	1.56E+21	H. T. Odum (1996)
Clays	1.26E+09	2.56E+06	1.90E+09	2.39E+18	H. T. Odum (2000)
Natural sands	1.06E+12	1.88E+07	1.30E+09	1.38E+21	H. T. Odum (2000)
Cement clinker	7.70E+11	2.04E+08	2.07E+09	1.59E+21	Brown and Buranakarn (2003)
Ores, slag, and ash	3.06E+11	1.71E+07	2.07E+09	6.33E+20	H. T. Odum (2000)
Total	3.42E+12	3.04E+08		4.53E+21	

Table B.3 Emergy evaluation for raw and processed materials imported by Macao in 2007

Item	Raw mass (g)	Money (US$)	Heat content value (cal g^{-1})	Energy (J)	Transformity (sej $unit^{-1}$)	Emergy (sej)	Reference for transformity
Dyes, paints; putty; inks	8.73E+09	9.01E+06			1.13E+12	1.02E+19	Jiang et al. (2008)
Perfumery, cosmetic preparations	1.07E+10	9.77E+07			1.13E+12	1.10E+20	Jiang et al. (2008)
Soap; candles	1.98E+10	2.58E+07			1.13E+12	2.91E+19	Jiang et al. (2008)
Protein; modified starches	2.97E+9	3.82E+06			1.13E+12	4.32E+18	Jiang et al. (2008)
Explosive preparations	1.76E+08	6.68E+05			1.13E+12	7.55E+17	Jiang et al. (2008)
Photographic goods	1.07E+09	5.33E+06			1.13E+12	6.03E+18	Jiang et al. (2008)
Miscellaneous chemical products	3.12E+10	1.44E+07			1.13E+12	1.62E+19	Jiang et al. (2008)
Rubber and articles thereof	3.88E+10	6.76E+07			1.13E+12	7.64E+19	Jiang et al. (2008)
Leather, fur, etc.	2.26E+09	8.93E+06			1.13E+12	1.01E+19	Jiang et al. (2008)
Raw hides and leather	5.55E+08	5.23E+07			1.13E+12	5.90E+19	Jiang et al. (2008)
Articles of leather; handbags	7.28E+07	1.43E+06			1.13E+12	1.62E+18	Jiang et al. (2008)
Books, newspapers, pictures	2.88E+09	1.48E+07			1.13E+12	1.67E+19	Jiang et al. (2008)
Clothing accessories, not crocheted	4.65E+10	4.12E+08			1.13E+12	4.66E+20	Jiang et al. (2008)
Footwear	1.27E+10	6.16E+07			1.13E+12	6.96E+19	Jiang et al. (2008)
Plastics and articles thereof	3.64E+09	1.00E+07			1.13E+12	1.13E+19	Jiang et al. (2008)
Wood and articles of wood	4.86E+10		4500	9.16E+14	3.20E+04	2.93E+19	H. T. Odum (1996)
Fuelwood, in logs or faggots	3.23E+09		4500	6.09E+13	3.20E+04	1.95E+18	H. T. Odum (1996)
Wood in the rough	4.38E+08		4500	8.26E+12	3.20E+04	2.64E+17	H. T. Odum (1996)
Cork and articles of cork	1.77E+07		4500	3.33E+11	3.20E+04	1.06E+16	Lan et al. (2002)
Manufactured items of straw	3.33E+08		4500	6.28E+12	3.20E+04	2.01E+17	Lan et al. (2002)
Wool, animal hair	2.02E+09		5500	4.65E+13	4.40E+06	2.05E+20	H. T. Odum (1996)

Table B.3 (*Continued*)

Item	Raw mass (g)	Money (US$)	Heat content value (cal g^{-1})	Energy (J)	Transformity (sej $unit^{-1}$)	Emergy (sej)	Reference for transformity
Pulp of wood or fibrous material	5.22E+08		4500	9.84E+12	4.40E+04	4.33E+17	Lan et al. (2002)
Paper and paperboard	3.63E+10		4500	6.83E+14	4.40E+04	3.01E+19	Lan et al. (2002)
Silk	3.82E+07		5500	8.80E+11	3.80E+06	3.34E+18	H. T. Odum and Odum (1983)
Vegetable textile fibers	3.00E+08		4500	5.65E+12	3.80E+06	2.15E+19	Lan et al. (2002)
Man-made filaments	4.75E+09		4500	8.95E+13	3.80E+06	3.40E+20	Lan et al. (2002)
Man-made staple fibers	2.87E+09		4500	5.40E+13	3.80E+06	2.05E+20	Lan et al. (2002)
Wadding, felt, ropes, articles thereof	1.04E+09		4500	1.96E+13	3.80E+06	7.47E+19	Lan et al. (2002)
Carpets, textile floor coverings	1.81E+09		4500	3.41E+13	3.80E+06	1.29E+20	Lan et al. (2002)
Woven fabrics; embroidery	1.88E+09		4500	3.55E+13	3.80E+06	1.35E+20	Lan et al. (2002)
Textile articles for industrial use	8.37E+08		4500	1.58E+13	3.80E+06	5.99E+19	Lan et al. (2002)
Knitted or crocheted fabrics	2.55E+10		4500	4.80E+14	3.80E+06	1.82E+21	Lan et al. (2002)
Clothing accessories, crocheted	6.26E+10		4500	1.18E+15	3.80E+06	4.48E+21	Lan et al. (2002)
Other manufactured textile articles	1.33E+09		4500	2.51E+13	3.80E+06	9.55E+19	Lan et al. (2002)
Cotton	2.08E+10				2.31E+10	4.79E+20	Brandt-Williams (2001)
Headgear and parts thereof	1.84E+08				4.30E+09	7.93E+17	Lan et al. (2002)
Articles made of feathers, flowers	4.19E+08				4.30E+09	1.80E+18	Lan et al. (2002)
Plaster, asbestos, mica	3.15E+11				1.98E+09	6.25E+20	Lan et al. (2002)
Total	7.13E+11					9.63E+21	

Table B.4 Emergy evaluation for goods imported by Macao in 2007

Item	Mass (g)	Money (US$)	Transformity (sej unit^{-1})	Emergy (sej year^{-1})	Reference for transformity
Fertilizers	1.72E+08		2.80E+09	4.81E+17	Lan et al. (2002)
Ceramic products	9.29E+10		1.98E+09	1.84E+20	H. T. Odum and Odum (1983)
Glass and glassware	2.84E+10		8.40E+08	2.39E+19	Lan et al. (2002)
Iron and steel	6.64E+11		3.38E+09	2.25E+21	H. T. Odum and Odum (1983)
Copper and articles thereof	3.78E+09		6.80E+10	2.57E+20	Yan and Odum (2001)
Aluminum and articles thereof	1.16E+10		1.60E+10	1.86E+20	H. T. Odum (1996)
Nickel and articles thereof	1.54E+08		1.00E+09	1.54E+17	Ulgiati et al. (1994)
Other metals etc.	4.25E+09		1.25E+10	5.31E+19	H. T. Odum (1996)
Chemicals	7.72E+10	7.92E+07	1.13E+12	8.95E+19	Jiang et al. (2008)
Machinery, electrical equipment	6.12E+10	9.65E+08	1.13E+12	1.09E+21	Jiang et al. (2008)
Other manufactured articles	4.81E+10	3.07E+08	1.13E+12	3.46E+20	Jiang et al. (2008)
Works of art, antiques	1.62E+09	2.29E+07	1.13E+12	2.59E+19	Jiang et al. (2008)
Pearls, precious metals, jewelry; coins	2.82E+07	3.89E+06	1.13E+12	4.39E+18	Jiang et al. (2008)
Total	9.94E+11			4.51E+21	

Table B.5 Emergy evaluation for foods exported by Macao in 2007

Item	Raw mass (g)	Heat content value (cal g^{-1})	Energy (J)	Transformity (sej J^{-1})	Emergy (sej year^{-1})	Reference for transformity
Meat and meat offal	9.68E+07	5800	2.35E+12	792 000	1.86E+18	Campbell et al. (2005)
Fish, aquatic animals	5.89E+08	1000	2.47E+12	1 961 800	4.84E+18	Campbell et al. (2005)
Animal fats and oils	3.71E+07	5500	8.54E+11	792 000	6.77E+17	Campbell et al. (2005)
Dairy; eggs; honey	4.46E+07	1700	3.17E+11	792 000	2.51E+17	Campbell et al. (2005)
Edible vegetables	9.77E+06	1020	4.17E+10	20 600	8.60E+14	Campbell et al. (2005)
Edible fruits and nuts	3.34E+07	500	6.99E+10	53 000	3.71E+15	Ulgiati et al. (1994)
Coffee, tea	6.25E+08	3900	1.02E+13	200 000	2.04E+18	Ulgiati et al. (1994)
Cereals and corn	1.07E+07	3700	1.65E+11	147 524	2.43E+16	Yan and Odum (2001)
Rice	9.17E+06	3700	1.42E+11	35 900	5.10E+15	Yan and Odum (2001)
Milling products	5.83E+07	4500	1.10E+12	68 000	7.46E+16	H. T. Odum (1987)
Oil seeds or fruits	1.49E+08	5000	3.13E+12	1 300 000	4.06E+18	H. T. Odum (1996)
Sugars	1.06E+08	4500	1.99E+12	85 000	1.69E+17	Lan and Odum (1994)
Cocoa	4.74E+07	5500	1.09E+12	860 000	9.39E+17	Lan and Odum (1994)
Kinds of preparations	7.31E+08	5000	1.53E+13	1 710 000	2.62E+19	Lan et al. (1998)
Soya sauce	3.52E+07	1000	1.47E+11	8 000	1.18E+15	Lan et al. (1998)
Plant preparations	4.15E+08	2100	3.65E+12	1 710 000	6.24E+18	Lan et al. (1998)
Beverages	1.05E+09	1300	5.70E+12	60 000	3.42E+17	H. T. Odum (1987)
Prepared animal fodder	1.73E+09	1700	1.23E+13	80 000	9.88E+17	H. T. Odum (1987)
Tobacco substitutes	1.42E+09	3900	2.31E+13	84 900	1.96E+18	Yan and Odum (2001)
Total	7.20E+09		8.42E+13		5.07E+19	

Table B.6 Emergy evaluation for raw and processed materials exported by Macao in 2007

Item	Raw mass (g)	Money (US$)	Heat content value ($\mathrm{cal\,g^{-1}}$)	Energy (J)	Transformity ($\mathrm{sej\,unit^{-1}}$)	Emergy ($\mathrm{sej\,year^{-1}}$)	Reference for transformity
Dyes, paints; putty; inks	4.56E+08	9.05E+05			1.82E+12[a]	1.65E+18	
Perfumery, cosmetics	1.53E+09	2.66E+06			1.82E+12[a]	4.84E+18	
Soap etc., candles	2.22E+09	4.14E+06			1.82E+12[a]	7.55E+18	
Protein; modified starches	8.33E+08	2.95E+06			1.82E+12[a]	5.37E+18	
Photographic goods	6.19E+08	1.45E+06			1.82E+12[a]	2.65E+18	
Miscellaneous chemical products	7.17E+08	5.71E+06			1.82E+12[a]	1.04E+19	
Raw hides and leather	7.27E+08	3.20E+06			1.82E+12[a]	5.84E+18	
Articles of leather; handbags	1.21E+08	2.04E+06			1.82E+12[a]	3.71E+18	
Fur, skins, artificial fur	7.24E+07	5.02E+05			1.82E+12[a]	9.15E+17	
Books, newspapers, pictures	4.81E+08	5.07E+05			1.82E+12[a]	9.25E+17	
Clothing accessories	5.53E+10	1.07E+09			1.82E+12[a]	1.95E+21	
Footwear	1.04E+10	1.04E+08			1.82E+12[a]	1.90E+20	
Wood and articles of wood	2.41E+09		4500	4.53E+13	3.20E+04	1.45E+18	H. T. Odum (1996)
Fuelwood, in logs or faggots	1.50E+08		4500	2.83E+12	3.20E+04	9.04E+16	H. T. Odum (1996)
Manufactures of straw	9.05E+06		4500	1.71E+11	3.20E+04	5.46E+15	Lan et al. (2002)
Pulp of wood	2.62E+10		4500	4.93E+14	4.40E+04	2.17E+19	Lan et al. (2002)
Paper and paperboard	2.17E+09		4500	4.08E+13	4.40E+04	1.80E+18	Lan et al. (2002)
Silk	3.45E+07		5500	7.95E+11	3.80E+06	3.02E+18	H. T. Odum and Odum (1983)
Wool, animal hair	1.52E+09		5500	3.49E+13	4.40E+06	1.53E+20	H. T. Odum (1996)
Vegetable textile fibers	1.50E+08		3000	1.89E+12	3.80E+06	7.18E+18	Lan et al. (2002)
Man-made filaments	2.64E+09		4500	4.96E+13	3.80E+06	1.89E+20	Lan et al. (2002)

Table B.6 (*Continued*)

Item	Raw mass (g)	Money (US$)	Heat content value (cal g^{-1})	Energy (J)	Transformity (sej unit^{-1})	Emergy (sej year^{-1})	Reference for transformity
Man-made staple fibers	1.04E+09		4500	1.96E+13	3.80E+06	7.47E+19	Lan et al. (2002)
Wadding, felt, ropes	2.24E+08		4500	4.23E+12	3.80E+06	1.61E+19	Lan et al. (2002)
Carpets, textile floor coverings	3.77E+07		4500	7.09E+11	3.80E+06	2.70E+18	Lan et al. (2002)
Woven fabrics; embroidery	1.61E+10		4500	3.03E+14	3.80E+06	1.15E+21	Lan et al. (2002)
Textile articles for industrial use	1.54E+10		4500	2.91E+14	3.80E+06	1.11E+21	Lan et al. (2002)
Clothing accessories	7.90E+10		4500	1.49E+15	3.80E+06	5.66E+21	Lan et al. (2002)
Other textile articles; rags	1.41E+09		4500	2.66E+13	3.80E+06	1.01E+20	Lan et al. (2002)
Umbrellas, seat-sticks, whips	1.68E+08		1000	7.04E+11	4.30E+09	3.03E+21	Brown and Buranakarn (2003)
Cotton	1.08E+10				2.31E+10	3.77E+20	Brandt-Williams (2001)
Plastics and articles thereof	1.49E+10				3.80E+08	5.64E+18	Lan et al. (2002)
Rubber and articles thereof	2.67E+08				4.30E+09	1.15E+18	Brown and Buranakarn (2003)
Headgear and parts thereof	1.10E+08				4.30E+09	4.72E+17	Lan et al. (2002)
Articles made of feathers, flowers	2.23E+07				4.30E+09	9.57E+16	Lan et al. (2002)
Plaster, asbestos, mica	5.92E+08				1.98E+09	1.17E+18	Lan et al. (2002)
Total	2.49E+11					1.41E+22	

[a] 1.82E+12 sej $$^{-1}$ is our calculated emergy/US$ ratio for Macao

Table B.7 Emergy evaluation for goods exported by Macao in 2007

Item	Raw mass (g)	Money (US$)	Transformity (sej unit^{-1})	Emergy (sej year^{-1})	Reference for transformity
Ceramic products	2.11E+08		1.98E+09	4.18E+17	Lan et al. (2002)
Glass and glassware	9.14E+09		8.40E+08	7.68E+18	Lan et al. (2002)
Iron and steel	9.95E+10		3.38E+09	3.36E+20	H. T. Odum and Odum (1983)
Copper and articles thereof	1.15E+10		6.80E+10	7.83E+20	Yan and Odum (2001)
Aluminum and articles thereof	4.77E+09		1.60E+10	7.64E+19	H. T. Odum (1996)
Nickel and articles thereof	4.97E+06		1.00E+09	4.97E+15	H. T. Odum (1996)
Other base metals; cermets	8.46E+08		1.25E+10	1.06E+19	H. T. Odum (1996)
Chemical	6.55E+08	9.26E+06	1.82E+12	1.69E+19	H. T. Odum (1996)
Pearls, precious metals, jewelry; coins	4.79E+07	4.96E+07	1.82E+12	9.03E+19	H. T. Odum (1996)
Machinery, electrical equipment	4.53E+10	4.57E+08	1.82E+12[a]	8.34E+20	
Other manufactured articles	5.17E+08	1.82E+07	1.82E+12[a]	3.31E+19	
Manufactured articles	2.04E+09	3.98E+07	1.82E+12[a]	7.26E+19	
Works of art, antiques	3.76E+06	1.57E+05	1.82E+12[a]	2.87E+17	
Total	1.75E+11			2.26E+21	

[a] 1.82E+12 sej $\$^{-1}$ is our calculated emergy/US$ ratio for Macao

Appendix C
Definitions of the Parameters Used in This Book

A = area (Chap. 2)
B = exported emergy of production (Chaps. 1, 2)
C = a particular economic monetary input (Chap. 1)
C_t = monetary income provided by the tourism activities (Chap. 1)
d = the average duration of a tourist's stay (Chap. 1)
E_3 = the monetary income for exports of services (Chap. 2)
E_n = the available energy or mass (Chap. 4)
E_g = emergy of labor in the gambling industry (Chap. 5)
E_i = the available energy (free energy) content of the ith independent input flow (Chap. 1)
$EL_{subscript}$ = the emergy of labor and services for treating waste "subscript" (Chap. 6)
E_m = emergy (Chap. 1)
$E_m/\$$ = the emergy money ratio, equivalent to U/GDP (Chap. 1)
E_n = energy output (Chap. 1)
E_w = emergy of wastes (Chap. 6)
E_x = exergy (Chap. 1)
EER = emergy exchange ratio (Chap. 1)
EIR = emergy investment ratio = $F/(R+N)$ (Chap. 1)
EL = emergy of equipment and labor involved in waste treatment (Chap. 6)
ELE = electricity consumption (Chap. 2)
ELR = environmental loading ratio = $(U-R+F)/R$ (Chap. 1)
EMR = emergy money ratio = U/GDP (Chap. 1)
ESI = emergy sustainability index = EYR/ELR (Chap. 1)
ESR = emergy self-sufficiency ratio, the proportion of total U accounted for by R (Chap. 1)
EYR = emergy yield ratio = Y/F (Chap. 1)
f_r = feedback ratio = E_w/W (Chap. 6)
F = imported emergy (Chap. 1)
F' = waste treatment inputs (Chap. 6, Fig. 6.1)
$F_{(e)}$ = the sum of exports of fuels, metals, and minerals (Chap. 7)

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$F_{(i)}$ = the sum of imports of fuels, metals and minerals (Chap. 7)
G = purchased goods (Chap. 1)
$G_{(e)}$ = exports of goods and electricity (Chap. 7)
$G_{(i)}$ = imports of goods and electricity (Chap. 7)
GDP = gross domestic product (Chap. 1); note that this term is italicized as a variable
I_3 = dollars paid for imports of services (Chaps. 2, 7)
M = mass of a substance that flows through a system (Chap. 1)
M_t = emergy consumed by tourists (Chap. 1)
N = non-renewable resources (Chap. 1)
N_0 = dispersal into rural environment (Chap. 2), dispersed non-renewable flows (Chap. 7)
N_1 = concentrated use (Chap. 2)
N_2 = exports of non-renewable resources (Chap. 1)
N_e = number of employees in the city (Chap. 5)
N_g = number of employees in the gambling sector (Chap. 5)
NE = net emergy = $F + R - Y$ (Chap. 1)
NER = net emergy ratio = NE/U (Chap. 1)
P = the population of the host region (Chap. 1)
P_x = exergy power (Chap. 1)
P_1 = Macao's E_m/\$ ratio (Chap. 2)
$P_1 E_3$ = the emergy of exported services (Chap. 2)
P_2 = world E_m/\$ ratio (Chap. 2)
$P_2 I_3$ = the emergy of services in imports (Chaps. 2, 7)
$P_3 = E_m$/\$ of the gambling sector (Chap. 4)
r = the ratio of tourist spending to the spending of residents of the host region (Chap. 1)
R = renewable resources (Chap. 1)
R_t = proportion of the total emergy used (U) consumed by tourists (Chap. 1)
%Ren = proportion of the emergy used (U) accounted for by renewable resources (R)
S = purchased services (Chap. 1)
T = number of tourists (Chap. 1)
T_m = emergy imported into the system by tourists through their spending (Chap. 1)
T_{ri} = the solar transformity of the ith input flow (Chap. 1)
T_{rs} = solar transformity of direct solar radiation (Chap. 1)
U = total emergy used by a system (Chap. 1)
W = waste emergy (Chap. 2)
Y = emergy yield = $R + N + F$, exported from the system (Chap. 1)