Landscape and Urban Planning 118 (2013) 18–28

Contents lists available at ScienceDirect

Landscape and Urban Planning

journal homepage: www.elsevier.com/locate/landurbplan

Research paper

An emergy analysis for urban environmental sustainability assessment, the Island of Montreal, Canada

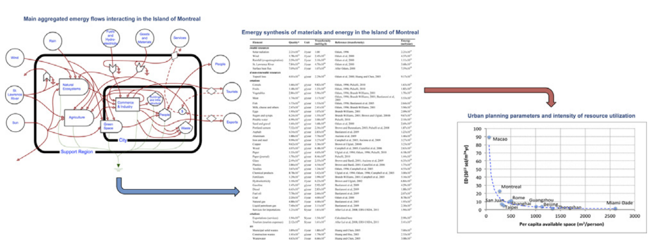
Ricardo Enrique Vega-Azamar[a,*], Mathias Glaus[a], Robert Hausler[a], Norma Angélica Oropeza-García[a], Rabindranarth Romero-López[b]

[a] Station expérimentale des procédés pilotes en environnement, École de Technologie Supérieure, Université du Québec, Canada
[b] Universidad Veracruzana Facultad de Ingeniería Civil, Lomas del Estadio s/n Zip Code 91000, Zona Universitaria, Xalapa, Veracuz, Mexico

HIGHLIGHTS

- The major emergy flows interacting in the Island of Montreal were identified and quantified.
- The most important emergy flows were the monetary ones and those corresponding to the building materials entering the island.
- When compared to other selected cities, available space per inhabitant was correlated to empower density.
- The findings may be used as a guide to propose a methodology for the determination of intensity of development from an environmental perspective.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 7 December 2011
Received in revised form 17 May 2013
Accepted 2 June 2013
Available online 9 July 2013

Keywords:
Urban environmental sustainability
Occupation intensity
Resource utilization
Emergy synthesis
Emergy-based indicators

ABSTRACT

Today, the sustainability of cities is a critical consideration in the development of modern societies. One important dimension of this concept is the influence of occupation intensity on resource consumption and its associated waste generation. Emergy analysis constitutes an appropriate methodology for evaluating the sustainability of cities, given that it integrates the different types of flows interacting in urban regions in a common basis of comparison, the solar emergy joule (seJ). In this study, emergy analysis was used to evaluate the environmental sustainability of the Island of Montreal, Canada, in 2005 and to compare its situation with that of other nine urban centers. Results indicate that the total emergy used in 2005 stood at 1.153×10^{23} seJ, with renewable resources representing 3.2%, and a waste-to-emergy ratio of 0.09. In comparing the cities, it was observed that the empower density, an emergy measure for the intensity of activities, fell markedly when each inhabitant had about 300 m^2 or more of available land. Results for the Island of Montreal point to the need to improve the city's environmental performance. Particularly, the high empower density indicates that projects involving the re-development of recovered areas provide a significant opportunity for attaining this objective.

1. Introduction

Since 2007, about 50% of the world's population has been living in a city, and current trends point to more than 60% by 2030 (UN-HABITAT, 2006). The constant increase in natural resource consumption to meet the needs of the urban population and the associated generation of waste is leading to a less and less sustainable ecological footprint. Given that cities generate the majority of carbon emissions (UN-HABITAT, 2011), their evolution is definitely

* Corresponding author at: 1100, rue Notre-Dame Ouest, H3C 1K3, Montréal, Québec, Canada. Tel.: +1 514 396 8499.
E-mail addresses: ricardo-enrique.vega-azamar.1@ens.etsmtl.ca, rievaz@yahoo.com.mx (R.E. Vega-Azamar), mathias.glaus@etsmtl.ca (M. Glaus), robert.hausler@etsmtl.ca (R. Hausler), norma-angelica.oropeza-garcia.1@ens.etsmtl.ca (N.A. Oropeza-García), rabromero@uv.mx (R. Romero-López).

0169-2046/$ – see front matter
http://dx.doi.org/10.1016/j.landurbplan.2013.06.001

an issue to be considered in the development of present day societies. One important aspect that must be considered is the influence of the urban form (i.e., the nature and intensity of occupation of the city's territory) on resource consumption and the associated waste generation and polluting emissions. Understanding this relationship is essential for future development and planning decisions and for the creation of urban regions with lower environmental impacts (Perkins, Hamnett, Pullen, Zito, & Trebilcock, 2009).

Several approaches have been used to evaluate sustainability of urban regions, with the concept of urban metabolism arguably ranking among the best known (Kennedy, Pincetl, & Bunje, 2011). Originally, this concept was introduced to the field of urban studies in the form of "city metabolism" by the social urban ecologist, Ernest W. Burgess (1925). He drew an analogy between the anabolic and catabolic processes in the human body and the organization and disorganization processes occurring in the city in response to changes, resulting in urban growth (Lin et al., 2012a, 2012b). During the 1990s, following the pioneering work of Wolman (1965) and other authors, analyses of urban metabolism flourished, focusing on the quantification of material and energy flows interacting in urban regions (Kennedy et al., 2011). The bulk of the work that has been done in this area has examined one or more cities through particular flows, such as water, or specific materials and nutrients (Forkes, 2007; Hermanowicz & Asano, 1999; Kennedy, Cuddihy, & Engel-Yan, 2007; Newman, 1999; Sahely, Dudding, & Kennedy, 2003). Recently, a novel approach to the holistic modeling of the metabolism of cities, applied particularly to the carbon cycle, pointed to the need to examine the urban structure and mutual interactions between the different urban sectors through a network environ analysis, which is a systems-oriented technique (Chen & Chen, 2012).

Further, material flow accounting (Decker, Elliott, Smith, Blake, & Rowland, 2000; Hendriks et al., 2000), ecological footprint (Folke, Jansson, Larsson, & Constanza, 1997; Muñiz & Galindo, 2005; Rees & Wackernagel, 1996), and energetic life cycle analysis (Perkins et al., 2009; Pullen, 2000; Steemers, 2003; Treolar, Love, & Holt, 2001) are methods that are widely used to account for inputs, outputs, throughputs and storages in urban regions. Emergy synthesis (Odum, 1996) and extended exergy accounting (Liu, Yang, Chen, Su, et al., 2011; Sciubba, Bastianoni, & Tiezzi, 2008) are part of the 'energy family' of approaches, and although the latter allows the integration of the resources used and the internalization of other factors, such as labor and remediation costs through exergetic equivalents (Sciubba et al., 2008; Sciubba & Ulgiati, 2005), the present study drew on emergy synthesis, as the analysis was conducted from a deep environmental sustainability perspective (Kennedy et al., 2011). Indeed, this methodology advances the environmental support that provides the resource flows sustaining the economy of the area under study, as well as the associated supporting ecosystem services (Sciubba & Ulgiati, 2005; Zhang, Singh, & Bakshi, 2010), rather than other aspects, such as thermodynamic and utilization efficiencies (Liu, Yang, Chen, & Zhang, 2011).

Emergy analysis provides a way to incorporate environmental and socioeconomic flows, such as currency and labor, through a common unit of measure, the solar emergy joule (seJ), taking into consideration the 'free' work that the environment carries out and the quality of the resources used, as emergy is "the total amount of available energy of one kind (usually solar) that is directly and indirectly required to make a given product or to support a given flow" (Odum, 1996). Emergy analysis is an appropriate methodology for evaluating and comparing the sustainability of cities, as it integrates the different types of flows interacting in urban ecosystems (Ascione, Bargigli, Campanella, & Ulgiati, 2011). This methodology has been successfully applied to studies of several urban areas, such as Taipei (Huang, 1998), Macao (Lei, Wang, & Ton, 2008), Rome (Ascione, Campanella, Cherubini, & Ulgiati, 2009), and Beijing (Zhang, Yang, Liu, & Yu, 2011).

In this context, the environmental sustainability of the Island of Montreal, located in the southeastern part of Canada (45°30′ N, 73°30′ W), was assessed. In 2005, the Island had more than 1.8 million inhabitants within its 499.1 km^2 area (City of Montreal, 2009), which represents a high population density (3700 persons/km^2). The Island of Montreal is an urban agglomeration formed by 16 municipalities (around 73% of the Island's territory is occupied by the municipality of Montreal), which is part of the industrial and commercial region of eastern North America. It is also one of the main centers of commercial exchanges between the United States and Europe (City of Montreal, 2005). The Island's economy is highly diversified, covering both a traditional consolidated industrial sector, and more recently, the growing services, technology and knowledge sectors, with important research centers, hospitals, universities and other educational institutions and museums (City of Montreal, 2011). The present work aims to evaluate the environmental performance of the Island of Montreal through an emergy analysis of its material, energy and economic input and output flows for 2005. Using published studies, it also compares the Island of Montreal with other selected cities, in a bid to explore the applicability of emergy-based indicators to urban planning parameters, such as density.

2. Methodology

2.1. Emergy analysis

The principles of energy transformation and quality were introduced by Odum in his concept of energy hierarchy: all energy transformations can be arranged in a hierarchy, from sunlight to electrical power, with many joules of the first required to obtain one joule of the latter (Brown & Ulgiati, 2004a). One of the key concepts in this hierarchy is that of the unit emergy value or emergy intensity, i.e., the amount of emergy needed to produce one unit of output. Transformity, the most widely used unit of emergy value (expressed in seJ/J), is defined as the amount of seJ required to produce 1 J of available energy at the output. It is a measure of the process efficiency: the lower the transformity, the more efficient the conversion (Brown & Ulgiati, 2004a). Other emergy units frequently used are specific emergy and emergy per unit of currency, expressed respectively in seJ/g and seJ/$. From the transformities of rain, wind, fossil fuels, minerals, etc., other natural and human-made products have been analyzed, and many more unit emergy values have been obtained (Ascione et al., 2009; Brandt-Williams, 2001; Odum, 2000).

An emergy evaluation begins with the preparation of the diagram of the system under analysis, including the main input and output flows of materials, energy, currency and labor. Fig. 1 shows the main flows interacting in Montreal. The St. Lawrence River, with its mean annual flow ranging from 7800 m^3/s near its source to 16,800 m^3/s at its mouth (Environment Canada, 2010), has played an historic role in the development of the region. The climate in the area varies widely: the yearly daily average is 6.2 °C, ranging from −10.2 °C to 20.9 °C, with an annual average rainfall of 763.8 mm and snowfall of 217.5 cm, and finally an annual average wind speed of 14.3 km/h (Environment Canada, 2011). In 2005, there were about 3500 ha of forest and 4100 ha of permanent farmland on the Island (City of Montreal, 2006; Hodder, Thiffault, & Saia, 2001). A major component of the energy flows entering Montreal was the 30,508 GWh of hydroelectricity consumed in 2005 (Hydro-Québec, 2009), while building materials, such as gravel and sand, came entirely from outside the Island (MNRW, 2011). It is estimated that more than 900 thousand tons of municipal solid waste (CMM, 2011) and 925 million cubic meters of wastewater (Purenne, 2007)