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APPLICATION OF EMERGY AS ENVIRONMENTAL PERFORMANCE INDICATOR FOR ASSISTING SUSTAINABLE CITIES PLANNING

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APPLICATION DE L'ÉMERGIE COMME INDICATEUR DE PERFORMANCE ENVIRONNEMENTALE DÉDIÉ À LA PLANIFICATION DE VILLES DURABLES

Ricardo Enrique VEGA AZAMAR

RÉSUMÉ

L'augmentation constante de la consommation de ressources et la production de déchets associées aux régions urbaines, dont la participation importante du secteur résidentiel, conduisent à une empreinte écologique de moins en moins tolérable. Ces problèmes sont directement ou indirectement liés à la planification. Un point important pour mieux informer les décisions en planification urbaine est l'influence de la forme urbaine, c'est-à-dire la nature et l'intensité de l'occupation de la ville, sur l'intensité de consommation des ressources.

L'objectif général du travail a été d'étudier la pertinence de la synthèse d'émergie, une méthode de comptabilité environnemental, pour aider les processus de planification urbaine, en appliquant les principes de l'approche systémique d'analyse à l'environnement urbain, en particulier du point de vue de l'empreinte énergétique à travers le temps (émergie) générée par la fonction primaire de logement (usage résidentiel). La plus haute priorité a été donnée à la compréhension de l'ensemble du comportement du système à partir de l'exploration des relations structurelles de ses principaux éléments: les sous-systèmes de logement, nourriture, transport, dépenses, ressources naturelles et déchets générés. Pour atteindre cet objectif, trois échelles géographiques ont été abordées, l'agglomération urbaine, l'unité résidentielle et l'arrondissement, à travers l'analyse des flux matériaux, d'énergie et économiques, pour explorer la performance basée sur l'émergie sous différentes densités, espaces de vie par habitant, et d'autres variables, comme le revenu par ménage et la taille du ménage.

Les résultats ont permis l'identification de la disponibilité d'espace et du produit intérieur brut par habitant comme les variables les plus importantes affectant l'intensité d'utilisation d'émergie au niveau de la ville. Au niveau de l'unité résidentielle, les résultats montrent que, même si un revenu par ménage plus élevé a augmenté l'utilisation d'émergie par personne, l'augmentation de la disponibilité d'espace par habitant n'a pas abouti à une diminution de la densité d'émergie après 50 m^2/personne. Enfin, au niveau de l'arrondissement, les résultats ont confirmé le revenu, la taille du ménage et de la distance au centre-ville comme les variables les plus importantes.

D'après les résultats, sur la base de la procédure méthodologique et de la gestion des données réalisée pour les trois échelles d'analyse, il est possible de développer un outil pour le calcul rapide de l'utilisation d'émergie dans des zones soumises à des plans de développement futur, ce qui associé à une plate-forme de systèmes d'information géographique, permet le diagnostic de la distribution spatiale du comportement des principaux indicateurs émergétiques. Cet outil de calcul rapide peut évoluer pour devenir un outil de simulation dynamique.

Mot clés : forme urbaine, utilisation de ressources, indicateurs émergétiques, planification.

APPLICATION OF EMERGY AS ENVIRONMENTAL PERFORMANCE INDICATOR FOR ASSISTING SUSTAINABLE CITIES PLANNING

Ricardo Enrique VEGA AZAMAR

ABSTRACT

Constant increase in resource consumption and the associated waste generation rate in urban regions are leading to a less and less bearable ecological footprint. These problems are directly or indirectly associated to deficient planning, particularly, high resource utilization by the residential sector. One key point to better inform planning decisions on urban development contexts is the influence of urban form, that is the nature and intensity of occupation of the city's territory, on resource consumption intensity.

The general objective of this work was to explore the appropriateness of emergy synthesis, an environmental accounting method, to assist urban planning decision-making efforts, applying the principles of the systems approach to the analysis of the urban environment, particularly from the perspective of the energy footprint through time (emergy) generated by the primary function of accommodating people (residential land use), that is, giving the highest priority to the understanding of the entire system behaviour from the exploration of the structural relationships of its main elements: the housing, food, transportation, spending, natural resources and generated wastes subsystems. To achieve this objective, three geographic scales were assessed, the urban agglomeration, the housing unit and the borough, through the analysis of material, energy and economic flows, to explore the performance of emergy-based indicators under different densities, per capita living spaces, and other variables, such as per household income and household size.

Results allowed the identification of availability of space and per capita Gross Domestic Product as important variables affecting emergy use intensity at the city level. At the housing unit level, results showed that, while a higher per household income increased per capita emergy use in all the analyzed cases, increasing the availability of space per resident did not result in a decrease of empower density after 50 m^2/person. Finally, at the borough level, the results confirmed income, household size and distance to downtown as the variables affecting more noticeably emergy use intensity.

From the findings, the methodological procedure and the data management conducted for the three scales of analysis reviewed in the work, it is possible to develop a tool for the rapid calculation of emergy use in areas subject to urban planning or future development plans, which associated to a geographic information systems platform, allows the spatial distribution diagnosis of emergy use intensity by means of emergy indicators maps. It is feasible to scale up the emergy calculator up to become a dynamic simulation tool.

Keywords: urban form, resource use intensity, emergy-based indicators, urban planning.

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ED	Empower density, emergy used per unit area for a given year (seJ/m^2·year)
ED_{Hab}	Empower density of the habitable space in a building, emergy used per unit of living area for a given year (seJ/m^2·year)
EH	Empower per household, emergy used by all the residents of a dwelling for a given year (seJ/household or dwelling·year)
ELR	Environmental loading ratio, ratio of non-renewable and imported emergy to renewable emergy (dimensionless)
EMR	Emergy-to-money ratio, *U*/Income or *U*/Gross Domestic Product, for a given year (seJ/$)
ESI	Emergy sustainability index, *EYR/ELR*, measure of long-term sustainability (dimensionless)
Exp	Emergy from exports (seJ/year)
EYR	Environmental yield ratio, *U/F*, yield of the emergy used (dimensionless)
F	Purchased (imported) emergy (seJ/year)
N	Local non-renewable emergy (seJ/year)
R	Renewable emergy (seJ/year)
SA_{cap}	Per capita support area or emergy-based ecological footprint for a given year (m^2/person·year)
seJ	Solar emergy joule (or solar emjoule), emergy equivalent to one joule of sunlight
U	Total emergy used in a given year (seJ/year)
U_{cap}	Per capita emergy used for a given year (seJ/person·year)
W	Emergy from wastes for a given year (seJ/year)
WH	Per household emergy from wastes for a given year (seJ/household or dwelling·year)

INTRODUCTION

More than half of the world's population lives in a city, and current trends point to a continuous increment for the next decades. Constant increase in resource consumption, decline in forest and agricultural lands, construction materials extraction in large amounts, solid waste generation, pollution of water courses, air contamination and large emissions of greenhouse gases associated to urban regions are leading to a less and less bearable ecological footprint. Many of these problems are directly or indirectly associated to deficient planning. High resource utilization is one of the distinctive features of modern day cities that must be addressed. A major contributor to this utilization rate is the residential sector: around one third of energy use in the world corresponds to housing activities, and in certain countries, such as Canada, household water utilization may account for up to 30% of total water use.

One key point to better inform planning decisions on urban development contexts is the influence of urban form, that is the nature and intensity of occupation of the city's territory, on resource consumption. By way of an example, one widely acknowledged issue is that densely populated cities use less energy from transport per person than low-density urban centers, even though there is still some controversy on the causes. For the residential sector, the urban form concept involves, besides housing density, spatial distribution of dwellings, housing typology, and other aspects related to the urban macro structure, such as streets, roads and highways configuration and distance to the city center. For its part, land-use planning is the primary policy intervention influencing the form of urban settlements used by urban planners to try to contribute to sustainable urban development. An important aspect to achieve this is the knowledge of the interrelationships between socio-economic drivers and environmental performance at the land use level.

Several approaches have been used to evaluate urban regions sustainability. One of the best-known concepts is that of urban metabolism, which focuses primarily on the material and energy flows interacting in urban regions through the consideration and evaluation of inputs,

outputs, throughputs and accumulations. An essential part of this kind of analyses is the flow quantification, traditionally made through material flow accounting, which is based on the concepts of mass and energy balance, ecological footprint-based methods, which estimate the productive land area required to support the resource consumption and waste assimilation requirements of a given population, and energy analysis, a tool derived from life-cycle assessment with the particularity of using energy as the only measure of environmental impact; all of that frequently at the city and at the building level.

In this context, the general objective of this work was to explore the appropriateness of an environmental accounting method belonging to the energy analysis approach, the emergy synthesis method, to assist urban planning decision-making efforts at the residential land use level.

Work approach: Emergy synthesis for physical urban planning

One distinctive feature of the emergy synthesis method is that it provides a way to incorporate environmental and socioeconomic flows, such as currency and labor, through a common unit of measure in terms of solar energy equivalents, the solar emergy joule (seJ). The method takes into consideration the 'free' work that the environment carries out and the quality of the resources used, as emergy is the total available solar energy equivalent directly and indirectly utilized to make a given product or to support a given flow or service (Odum, 1996), that is, the 'solar energy footprint through time', which gives this approach a deep environmental sustainability perspective.

At the city level, this method has been applied mostly to urban regions as a whole for sustainability assessment, whether for a given year of study or for a time period in which evolution of the environmental trends are observed and evaluated. With respect to the residential land use, few emergy evaluations have been conducted both at the scale of single buildings and at the scale of residential units, although they have been carried out from a building materials/energy performance perspective and in housing units so large that might

be considered small cities by their own. It is important to remark that, although all emergy evaluations in urban contexts may be related somewhat to urban planning domains, studies directly related to land use planning are scarce.

Working hypothesis

The work explores the potential relationship between certain urban parameters, such as density and space availability, with the intensity of resource utilization, measured by means of emergy-based indicators like per capita emergy consumption and empower density (in both cases, higher values indicating higher resource utilization levels).

Particularly, it was expected that occupation density would affect resource use intensity, at least at some interval of the density. Moreover, at the city level, it was expected that the higher the emergy used, the higher the Gross Domestic Product and, at the borough and residential unit levels, the higher the income level, the greater the resource consumption, both in total amounts and on a per capita basis.

This hypothesis was based on an analogy with the behavior observed in some social insects, such as ants, which change their energy consumption under crowded conditions or with variations in colony size (Cao and Dornhaus, 2008; Fonck and Jaffe, 1996).

Given all the above, this work aimed at the exploration of the applicability of the emergy method specifically to widely used parameters in urban planning processes, such as density, space availability, distance to the city center and other variables related to household consumption, such as income level and household size, not only at the city scale, but also at dwelling unit and borough scales. Thus, the following specific objectives were raised.

Particular objective 1

Compare the environmental performance, through an emergy analysis of material, energy and economic input and output flows, of several cities in a bid to contrast the variations of

emergy-based indicators in function of urban planning parameters, such as density and space availability, and of other traditional economic measures of well being, such as Gross Domestic Product.

Particular objective 2

Assess the environmental performance of typical present-day residential units through the analysis of their material, energetic and economic flows, using the emergy method, to explore the performance of emergy-based indicators under different housing densities, per capita living spaces, and other variables, such as per household income and household size.

Particular objective 3

Evaluate the environmental performance of the residential land use at the borough level, through the quantification and analysis of material, energetic and economic flows by means of the emergy synthesis method, to observe the response of emergy-based indicators to changes in urban planning parameters and in household consumption variables.

The thesis is composed of six chapters of which chapter one displays the literature review. Chapters two, three and four show the research articles that shape the core of the work. Chapter five presents theoretical and practical implications arising from the results and findings obtained during the development of the three articles. Finally, the last pages present some global concluding remarks of the work.

Chapter 1

Summarizes the review of the literature used as theoretical and practical basis for the development of the work, the most important points in this chapter include the influence of urban form on resource use intensity and the potential implications on urban planning decision efforts, an outline of the most widely used methods for the quantification of flows interacting in urban environments, and the methodological framework of emergy analysis and its application to urban studies.

Chapter 2

Shows the research results in the article entitled "An emergy analysis for urban environmental sustainability assessment, the Island of Montreal, Canada". The article was submitted to the Journal Landscape and Urban Planning and accepted for publication on June 2, 2013. The results allowed the identification of availability of space and per capita Gross Domestic Product as important variables affecting emergy use intensity. The results reported in this article were presented at the 2011 ACFAS Congress that took place May 9 to 13, 2011, in Sherbrooke, Quebec, Canada.

Chapter 3

Presents the research results in the article “Emergy Evaluation of the Environmental Support of Residential Units in the Island of Montreal, Canada” submitted to the Journal Habitat International. Results suggest that variables affecting markedly emergy utilization intensity are per household income and per capita habitable space and, while a higher income increased per capita emergy in all analyzed cases, increasing the availability of space per resident did not result in a decrease of empower density after 50 m^2/person. The results reported in this article were presented at the 2012 ACFAS Congress that took place May 7 to 11, 2012, in Montreal, Quebec, Canada.

Chapter 4

Provides the research results in the article “Emergy Analysis of the Residential Land Use in Seven Boroughs of the Island of Montreal, Canada” submitted to the Journal Ecological Indicators. Natural resources, food, water, acquired goods and services, electricity, fuels, municipal solid wastes and wastewater were the main flows considered in the analysis. The results suggest that income, household size and distance to downtown are the variables affecting more noticeably emergy use intensity and that further studies should consider emergy modeling at the scale of urban planning unities based on these variables.

Chapter 5

Presents theoretical and operational implications arising from the results and findings obtained during the development of the work, as well as the main considerations for future research avenues.

CHAPTER 1

LITERATURE REVIEW

1.1 Urban regions and their ecological footprint

Since 2007, about 50% of the world's population has been living in a city (see Figure 1.1), and current trends point to more than 60% by 2030 (UN-HABITAT, 2006) with more than 75% of this population living in settlements of 5 million residents or less; for a long time, it will be this type of urban regions which will continue to absorb the majority of the urban population in the world (LEAD International, 2008). 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.

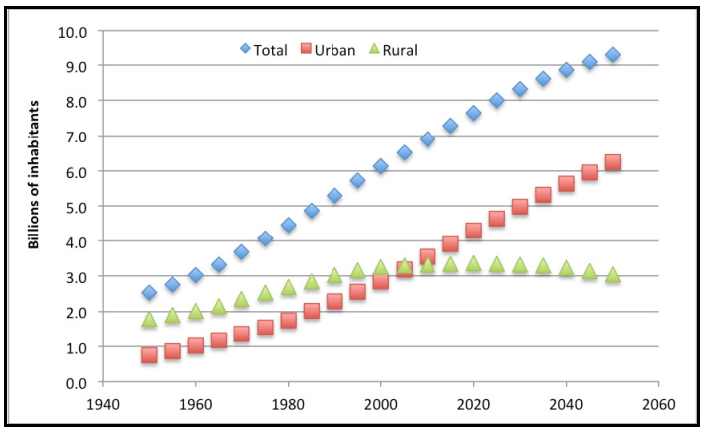

Figure 1.1 World urbanization trend
Adapted from UN (2012)

Among the main local level to global scale environmental problems related to urban growth are decline in agricultural and forest land, drying out of marshes, extraction of construction materials in large quantities, pollution of water courses by untreated wastewater, air pollution and large emissions of greenhouse gases from motor vehicles and industries (UNEP, 2002). Urban regions are among the main originators of local to global scale environmental problems, such as the generation of the majority of carbon emissions (UN-HABITAT, 2011).

Figure 1.2 depicts the relationship between urbanization (here, urbanization level indicates the proportion of urban to rural population) and carbon emissions generation (before the application of the natural log, CO_2 per capita was expressed in thousands of metric tons per year). Given that many of these problems are directly or indirectly associated to poor planning (UN-HABITAT, 2008), the proper development of cities is in the center of current concerns.

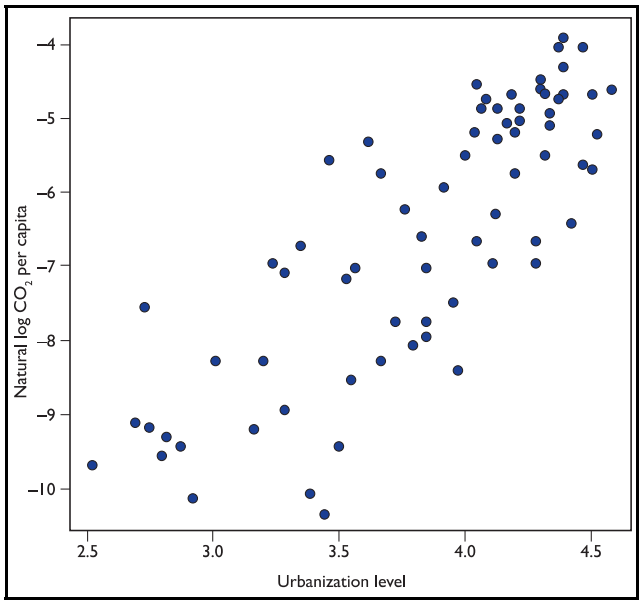

Figure 1.2 Per capita carbon dioxide generation and urbanization level
From UN-HABITAT (2011, p. 9)

1.2 Urban form, resource use intensity and urban planning

High resource utilization is a common feature of modern day cities that must be addressed. For instance, operation of buildings in urban areas requires a substantial fraction of the energy used in the world, reaching up to 50, 41 and 36% in the United Kingdom, the European Union and the United States, respectively, on a national basis (Steemers, 2003), and fractions corresponding to the transport and industry sectors should also be added.

A major contributor to this utilization rate is the domestic (residential) sector. Around 30% of the energy use in the world goes to housing (Pulselli et al., 2007). In countries like Canada,

household water utilization accounts for around 30% of all the water used (Statistics Canada, 2013), while water use corresponding to the municipal sector in the Province of Quebec reaches 42% (see Figure 1.3). Likewise, domestic consumption from households is a major source of carbon emissions in urban areas (Chen and Chen, 2012).

Also, several works have found food, mobility of people, housing and energy-using products, among the main domestic-related aspects affecting sustainability, accounting, aggregately, for almost 80% of the environmental impacts in industrialized nations (Tukker et al., 2010).

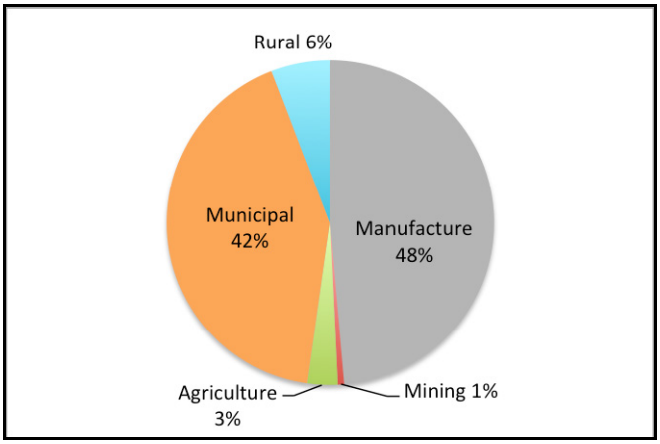

Figure 1.3 Water consumption by sector in the Province of Quebec
Adapted from Environment Canada (2012)

For its part, according to the Canadian Institute of Planners, the term planning comprises "the scientific, aesthetic, and orderly disposition of land, resources, facilities and services with a view to securing the physical, economic and social efficiency", concerning more and more urbanization aspects like the conversion of natural environments to built areas, the preservation of natural habitats in urban regions, and the development of infrastructure, among other critical issues (CIP, 2013).

Land-use planning is the primary policy intervention influencing the form of urban settlements (Bramley and Power, 2009) that continues to be among the most powerful instruments for design and control used by urban planners. One of the main objectives of

physical urban planning is to look for simultaneous territorial integrity for both the human and the natural subsystem (Campbell, 1996). An important aspect for this is the knowledge of the interrelationships between the socio-economic drivers and the environmental performance at the land use level (Pauleit and Duhme, 2000).

Usually, planning by-laws, building codes and zoning regulations restrict the development possibilities. In particular, zoning regulations set out the mix of residential, commercial and other uses in each delimited zone of a Master Plan (Engel-Yan et al., 2005).

The mix of uses is majorly defined through the land use designation, which specifies the particular set of uses for each planning zone according to the vocation intended, and through the intensity of activity, expressed ordinarily for each zone by means of the building density, which in turn shapes the built form (City of Montreal, 2004), see Figure 1.4.

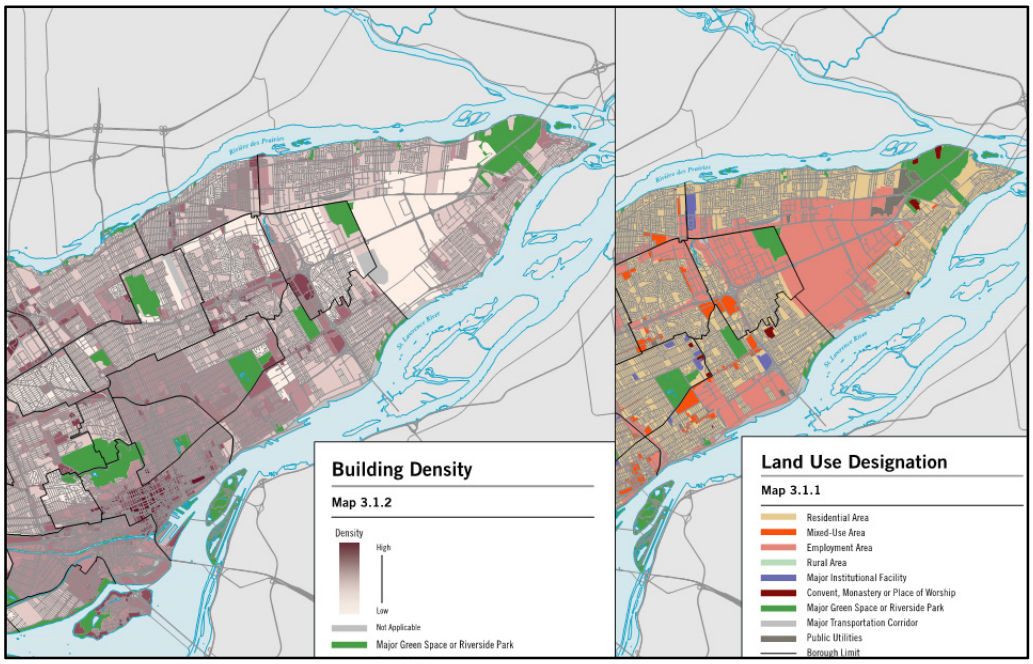

Figure 1.4 Physical urban planning: the Montreal's Master Plan land uses and densities
From City of Montreal (2004, p. 199 and 204)

One key point to better inform planning decisions on urban areas future development with less environmental burden is the influence of the nature and the intensity of occupation of the city's territory on resource consumption and the associated waste generation and polluting emissions (Perkins et al., 2009); for instance, is widely acknowledged that densely populated cities use less energy from transport per person than cities with low density (Figure 1.5), even though the debate continues on the causal mechanisms involved (Rickwood et al., 2008).

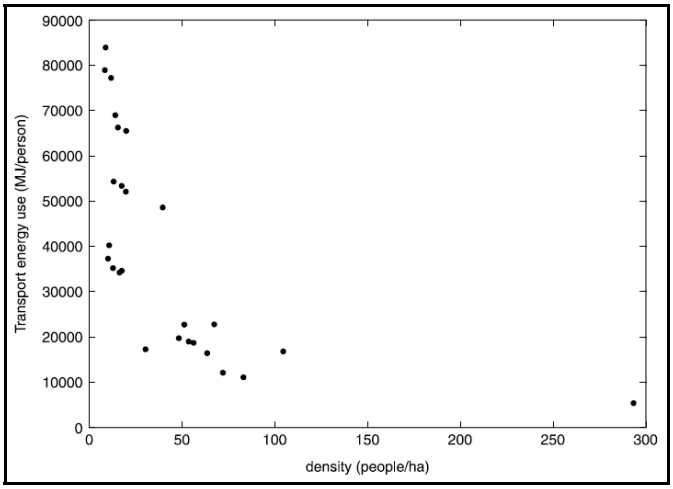

Figure 1.5 Population density and energy consumption from transport
From Newman and Kenworthy (1989, p. 31)

For the residential sector, the concept of urban form involves, besides the housing density, the spatial distribution of the dwellings, the housing typology (Bramley and Power, 2009; Perkins et al., 2009) and other aspects related to the urban macro structure, such as the streets, roads and highways configuration and the distance to central business districts (CMHC, 2000).

1.3 Methodological approaches for quantifying urban flows

Several approaches have been used to evaluate urban regions sustainability. One of the best-known concepts is that of urban metabolism. During the 90s, following the pioneering work of Wolman (1965), urban metabolism analyses grew vigorously, focusing on the

quantification of material and energy flows interacting in urban regions (Kennedy et al., 2011). The bulk of the work has examined one or more cities through particular flows, such as water, or specific materials and nutrients (Forkes, 2007; Hermanowicz and Asano, 1999; Kennedy et al., 2007; Newman, 1999; Sahely et al., 2003, etc.), usually through the consideration and evaluation of inputs (materials and energy), outputs (exports of products and wastes) throughputs and accumulations (building stock, infrastructure, material storage). Recently, the general view of urban metabolism analysis has begun to change to a holistic perspective that points to the need to examine the urban structure and mutual interactions between the different urban sectors (Chen and Chen, 2012).

In any case, an essential part of this kind of analyses is the quantification of the flows interacting in urban regions. In this section, the main methodological approaches that deal with flow quantification are reviewed.

1.3.1 Ecological footprint

Ecological footprint is an environmental accounting method for the estimation of resource consumption and waste assimilation requirements of a given population in reference to the productive land area required to support it (Figure 1.6): “an ecological footprint of a population is estimated by calculating how much land and water area is required on a continuous basis to produce all the goods consumed, and to assimilate all the wastes generated” (Wackernagel and Rees, 1996).

Here, some studies related to urban contexts are reviewed amongst the vast literature of the ecological footprint.

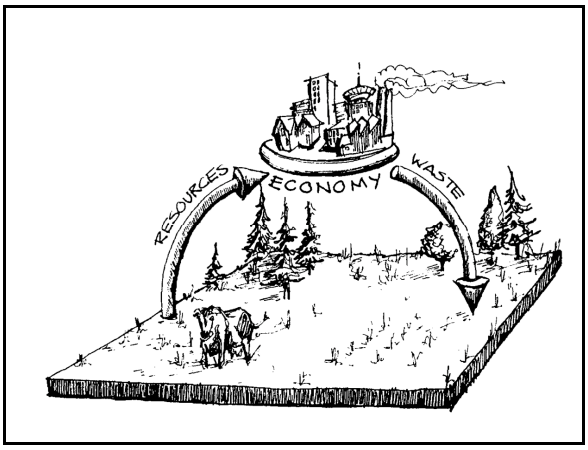

Figure 1.6 Ecological footprint conceptual framework
From Rees and Wackernagel (1996, p. 228)

Rees and Wackernagel (1996) applied the methodology to the city of Vancouver and to the Lower Fraser Basin area (with 18% of urban land use), where Vancouver is located. They found that the city's ecological footprint was about 200 times its actual geographic area and the basin's footprint was about 14 times its area, and noted that these figures were similar to others estimated for urban regions in the world, exercising an ecological deficit in exchange for their economic growth; however, they identify several advantages associated to urban regions, for example, high densities can help decrease per capita footprints of the residents and may facilitate access to services and infrastructure.

Folke et al. (1997) calculated the appropriated ecosystem area of the 29 largest cities in northern Europe (industrial region in the Baltic Sea drainage basin), and the marine and forest footprints for seafood consumption and CO_2 capture, respectively, of 744 large urban regions in the world representing 20% of the world's population. Footprints of the Baltic cities ranged from 565 to 1130 times the actual cities areas, while the 744 cities exhausted 25% of the fishing coastal areas for their seafood supply and surpassed by more than 10% the capacity of the world's forests to sequester carbon emissions.

Muñiz and Galindo (2005) analyzed Barcelona urban region municipalities to examine the ecological footprints originated by commuting in function of urban form, and other factors

such as household income. They found that footprints caused for travelling to work are more related to net population density and to distances to the city center and to major transport axis than to other variables such as income and job ratios, so that they conclude that urban form have a clear influence on ecological footprint of commuters transport.

1.3.2 Material flow accounting

Material flow accounting is based on the concepts of mass and energy balance (law of the conservation of mass): since raw materials are gathered from the environment, transformed and returned to nature as waste, total inputs must be equal to total outputs plus the accumulation in the system under analysis (Figure 1.7). Among the main objectives of material flow accounting are the procurement of information about the evolution of the metabolism of economies, and the estimation of resource use, productivity and efficiency indicators; however, some limitations are associated to this approach, among which is the addition of material flows of different qualities to generate aggregated indicators and the difficulty for connecting this weight-based indicators to environmental impact evaluations (Hinterberger et al., 2003).

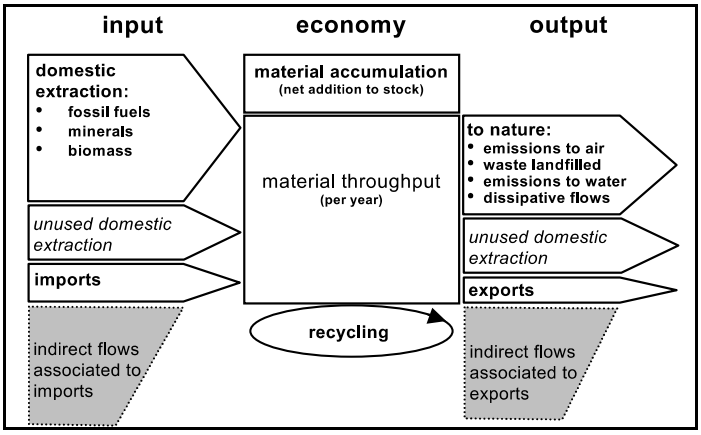

Figure 1.7 Material flow accounting conceptual framework
From EC (2001, p. 16)

For the urban context, in the reviewed literature there is a wide availability of studios using material flow accounting as a methodical basis for the quantification of flows, some of which are outlined below.

Decker et al. (2000) analyzed energy and material flows, centered on atmospheric pathways, for the world's 25 largest cities, examining fuels, food, water and air; they remarked that while cities do not depend directly on their surrounding environment to obtain fuels, food and other entries they do rely on the regional environment for water supply and waste assimilation.

Hendricks et al. (2000) made a balance of substances in Vienna to evaluate the dependence of this city on its surrounding environment; they confirmed the aforementioned tendency of cities to consume resources globally and to dispose wastes regionally, and claimed that material flow accounting is a useful tool for early resource depletion detection and environmental management.

Kennedy et al. (2007) gathered eight metropolitan regions studies (Brussels, Tokyo, Hong Kong, Sidney, Toronto, Vienna, London and Cape Town) from different dates to review changes in material and energy consumption and waste generation patterns across time; they concluded that the majority of the reviewed cities showed an increment in per capita energy, material and water consumption and also in wastewater generation.

Browne et al. (2011) evaluated the raw material entries and the waste outputs in the Irish city-region of Limerick to analyse, among other things, if material consumption and waste generation were related to economic growth and income, which proved to be, but to a certain extent; they reported that in the Republic of Ireland material flow accounting is limited for city-level studies due to a lack of disaggregated data, which is a common limiting factor in many urban regions of the world not only for the utilization of this methodology but also for other methodological approaches.

1.3.3 Life-cycle energy analysis

Life-cycle energy analysis (LCEA) is a tool derived from life-cycle assessment that has been applied to the building sector for the last few decades, with the particularity of using energy as the only measure of environmental impact to ease energy efficiency-related decision-making; essentially, a building LCEA covers the energy used for its construction and embedded in the materials (embodied energy) and the operational energy used over its lifespan (Fay et al., 2000). This approach is easily extended to take into account the energy used for the transport of the buildings occupants, including transport-embodied energy if necessary.

Sartori and Hestnes (2007) conducted a literature review comprehending 60 LCEA from 9 countries, including embodied and operational energy of residential and non-residential buildings; they found a linear correlation between total energy used and operational energy, which remained even with differences in climatic conditions. Ramesh et al. (2010) carried out a critical review including 73 LCEA from 13 nations (mainly, developed and/or cold countries), encompassing residential and office buildings; they found that operational energy and embodied energy stood for 80 to 90% and 10 to 20% of total used energy, respectively.

Steemers (2003) examined the share of energy use in buildings and transport based on the premise that urban form has an important influence on their balance and that these two components are significantly touched by urban planning schemes and policies. For the case of dwellings, he found that the consequences of densification are a balance between the benefits from reduced heat losses and the non-benefits from lack of daylight. Also, for temperate climates, he found that, although transport consumes globally less than half of the buildings energy, the environmental benefits of better transportation systems would bring more buildings to natural ventilation, which are less energy-squanderers than the ones with artificial ventilation.

Perkins et al. (2009) estimated transport and housing energy used (including the embodied energy of both), and the associated greenhouse gas (GHG) emissions, from dwellings in apartment buildings in Adelaide's (Australia) downtown and in houses in the suburbs to examine if urban density had an influence on the environmental impacts. With respect to total energy use, they found that it was higher for the houses than for the apartments mainly because of car use, while regarding GHG, they found that average per capita emissions from the apartments were higher than those from the suburbs due to occupancy rates and operational and embodied energy. They concluded that is not clear if centralized higher densities translate into less per capita emissions when a comprehensive housing and transport energy analysis is conducted.

1.4 Emergy evaluation

Emergy synthesis, also known as emergy analysis or emergy evaluation, is part of this 'life-cycle energy family' of approaches, which has the distinctive feature of putting the emphasis on the environmental support that provides the resource flows sustaining the economy, in this case of a given urban area under study, as well as the associated supporting ecosystem services (Sciubba and Ulgiati, 2005; Zhang et al., 2010).

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); in other words, it is the 'solar energy footprint through time'. Emergy evaluation is an interesting methodology for evaluating and comparing the sustainability of cities, as it integrates the different types of flows interacting in urban ecosystems (Ascione et al., 2011).

1.4.1 Methodological framework

Odum's concept of energy hierarchy comprehends the principles of energy transformation and quality for which 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 and Ulgiati, 2004a).

In the center of this hierarchy lies the concept of the unit emergy value or emergy intensity, that is, the quantity of emergy needed to produce one unit of output (Figure 1.8). The unit emergy most widely used, "transformity" (expressed in seJ/J), is defined as the amount of seJ required to produce one joule of available energy at the output of a given product, service or process, an it is also a measure of the process efficiency: the lower the transformity, the more efficient the conversion (Brown and Ulgiati, 2004a). Other emergy intensities frequently used are specific emergy (expressed seJ/g) and emergy per unit of currency (expressed in 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).

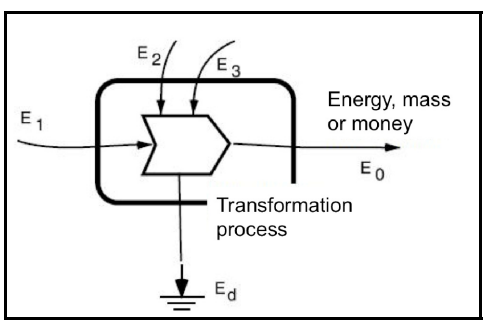

Figure 1.8 The emergy intensity concept [En: inputs; E0: output; Ed: degraded energy]
From Odum (1996, p. 17)

An emergy evaluation begins with the preparation of the diagram of the system under analysis (Figure 1.9), including the main input and output flows of materials, energy, currency, labor, etc. In urban regions, sunlight, rain, wind, surface an groundwater, tides, and primary production in nearby forests and permanent farmland may be considered among the

main renewable input flows; topsoil and materials from local stone quarries may be accounted among the main locally non-renewable input flows; fuels, electricity, building materials, food, goods and services, supplies for the manufacturing industries, spending by visitors, imports, and money from exports may be considered among the purchased input flows (mainly from non-renewable origins), while exports, money paid for imports, supplies, goods and services, municipal solid waste, wastewater and atmospheric emissions may be accounted among the main output flows.

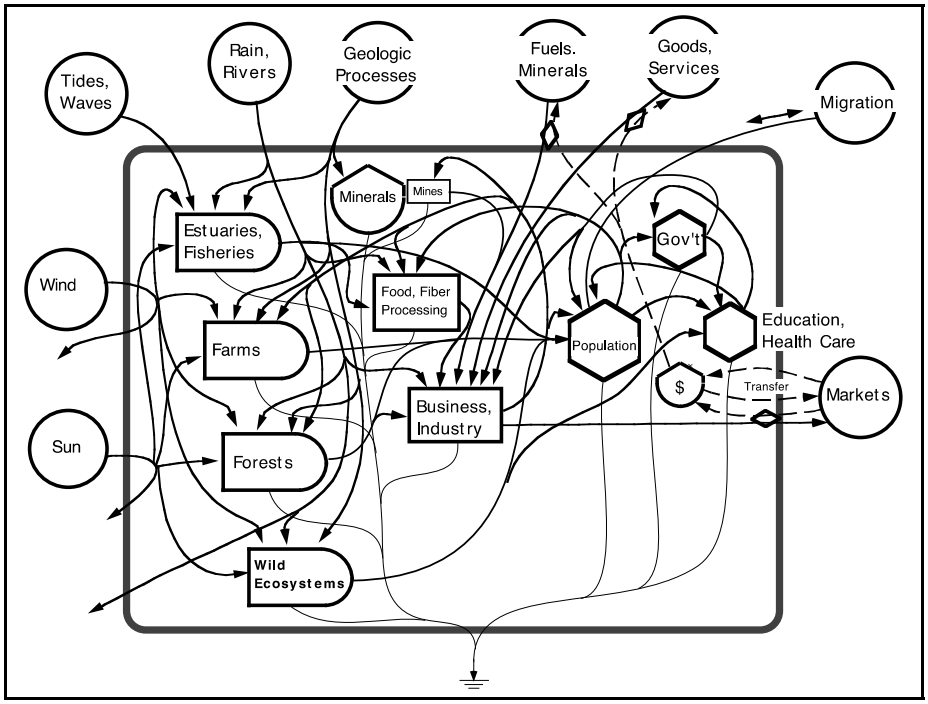

Figure 1.9 Emergy diagram for a generic nation or country
From Brown (2011, p. 11)

Once the diagram is created, a table with the raw data is integrated to calculate the corresponding emergy flows, which are obtained through a multiplication by the appropriate unit emergy values (Brown and Ulgiati, 2004b). Finally, from the aggregate emergy flows obtained (renewable, non-renewable, imported, etc.), performance indicators are calculated for their final interpretation as support mechanisms in decision-making processes (Brown and Ulgiati, 1997; Ulgiati et al., 1995).

1.4.2 Emergy-based indicators

As mentioned above, usually, flows are grouped as renewable (*R*), local non-renewable (*N*), imports (*F*), exports (*Exp*) and waste (*W*), and then, performance indicators are estimated to aid decision-making efforts (Figure 1.10). This work focused mainly on resource utilization, so emphasis was placed on indicators that consider the intensity of resource use, such as empower density, per capita emergy use and emergy-to-money ratio, in order to observe their possible relation with parameters commonly used in urban planning.

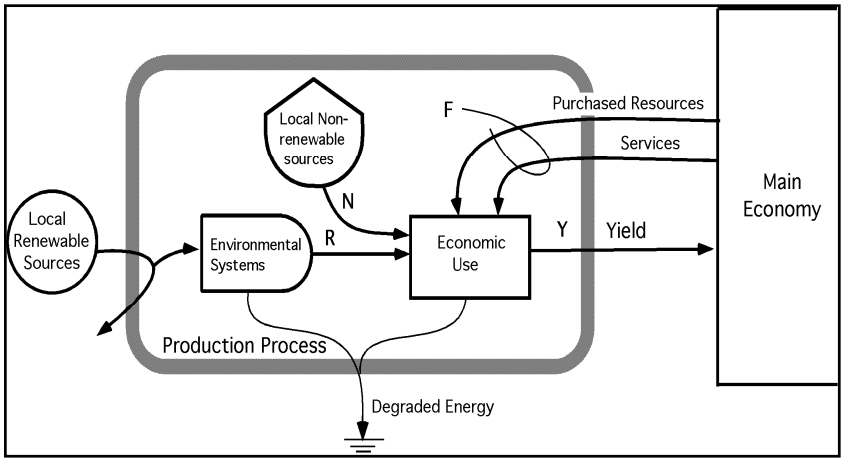

Figure 1.10 Scheme for the estimation of the emergy-based indicators
From Brown and Ulgiati (2004b, p. 333)

The main emergy-based indicators used in the thesis are presented in Table 1.1. Total emergy used (*U*) was considered as the overall indicator of the environmental support (including the external socio-economic system) for the well being of citizens and for the production of goods and services, which in turn generate wastes. *U* was taken as a measure of the yield of the system (city, residential unit and/or borough) for calculating the environmental yield ratio (*EYR*). An *EYR* value much greater than 1 indicates that the analyzed urban system generates more new resources (emergy) than those that were available as inputs; otherwise, the system is a consumer-transformer of resources (Ascione et al., 2009).

Table 1.1 Summary of the emergy-based indicators used in the work

Indicator	Calculation	Unit	Indication
Per capita emergy (U_{cap})	*U*/number of residents in a residential unit, zone or city	seJ/person·year	Standard of living
Empower per household (*EH*)	*U*/number of households in a residential unit, zone or city	seJ/household·year	Quality of living
Empower density of the habitable area (ED_{Hab})	*U*/total habitable area in a residential unit or zone	seJ/m^2·year	Intensity of resource utilization
Emergy-to-money ratio (*EMR*)	*U*/GDP or *U*/Total Income of a household, residential unit or zone	seJ/USD	Ecological economic efficiency
Environmental loading ratio (*ELR*)	[*N*+*F*]/*R*	-	Balance non-renewable to renewable resources
Per capita support area (SA_{cap})	([*N*+*F*]/[*ELR**(*R*/area)]$_{City}$)/number of residents in the residential unit	m^2/person·year	Emergy-based ecological footprint
Emergy sustainability index (*ESI*)	[*U*/*F*]/[(*N*+*F*)/*R*]	-	Long term sustainability
Emergy of wastes per household (*WH*)	*W*/number of households in a residential unit or zone	seJ/household·year	Environmental loading

The environmental loading ratio (*ELR*) is the ratio of non-renewable and imported emergy to renewable emergy. It evaluates the balance between non-renewable and renewable resources: the higher its value, the less sustainable the urban system under study (Brown and Ulgiati, 2001).

Empower density (*ED*) is the total emergy used in a given area per unit time. It is an indicator of the intensity of utilization of resources, with high values for industrial activities and urban centers (Brown and Ulgiati, 2001). It may also denote the scarcity of available land or the need for support land (Ascione et al., 2009).

On the other hand, emergy analysis suggests that money is an incomplete measure of wealth and that the emergy used to produce a service or product is a better measure of real wealth, estimated through the emergy-to-money ratio (*EMR*) using the Gross Domestic Product (Odum, 1996). *EMR* is an indicator of the capacity of money to buy emergy in a determined region: the higher its value, the greater the quantity of emergy the region's economy buys (Zhang et al., 2011). It may also be an indicator of ecological economic efficiency, when regions are compared: lower values of *EMR* correspond to higher levels of emergy use efficiency (Cai et al., 2009).

Carrying capacity may be estimated by means of the support land area (*SA*) required to obtain enough inputs to fulfill the emergy requirements of a given population, within a local economic and environmental system, based on the region's intensity of development (Brown and Ulgiati, 2001).

The emergy sustainability index (*ESI*) is the ratio between *EYR* and *ELR*; it can inform about the possible degree of contribution of the system under analysis to the regional system with respect to the environmental burden inflicted (Ascione et al., 2009). *ESI* gives an appraisal of long-term sustainability; in general, the higher its value the higher the dependence on renewable resources and the lower the environmental burden (Brown and Ulgiati, 1997).

1.4.3 Emergy studies in urban environments

At the city level, emergy analysis has been applied to urban areas since more than two decades ago, being one of the seminal works the one reported by Huang (1998) for the Taipei metropolitan region in Taiwan. Since then, several emergy papers related to urban environments have been published; in most of the cases, the overall objective was to carry out sustainability assessments, whether for a given year of study or for a time period in which evolution of the environmental and emergetic trends were observed and evaluated. A few of them, among the best-documented ones, are outlined here.

Lei et al. (2008) analyzed Macao, China, in 2004, considering *R*, *N*, *F*, *W* and *Exp*. Given the prominent role played by tourism, the emergy balance for this sector was estimated in detail, taking as input the money spent by tourists, and as output the actual emergy consumed by them, founding that input emergy was almost 5 times the output emergy. The emergy from wastes included their treatment (services, labour and equipment depreciation), which resulted in a difference of +2.5% of the emergy 'embodied' in the wastes.

Ascione et al. (2009) studied Rome, Italy, in 2002, considering *R*, *N*, and *F* and including certain specific sectors (tourism and government support). Emergy imported from labour was

taken into consideration, assuming that daily commuters made up about 10% of the population, and also it was estimated that 6% of the emergy of services and labour for imports was renewable.

Zhang et al. (2011) examined *R*, *N*, *F* and *Exp* in Beijing, China, for several years of study (from 1990 to 2004, with a time span separation of two years). *Exp* was calculated both from actual products and from costs. Local agriculture and forestry were not included in the overall emergy use because they were mainly supported by free environmental flows. Similarly to what was observed for Macao and Rome, the authors found that Beijing relies heavily on resources purchased from abroad (imports); they also noted that this dependence increased during the studied period.

With respect to the residential land use, at the housing unit level, few emergy evaluations, with a rather accentuated building materials or energy performance-based approach, have been conducted at the scale of single buildings. Other studies have been carried out in housing units so large that might be considered small cities by their own.

Brown and Buranakarn, (2003) evaluated emergy consumption in the life cycles of the main building materials used in a 1,012 m^2 building located in the state of Florida, United States, including waste disposal and recycling and estimating the associated emergy intensities and recycling indices. Their results suggest that recycle of metals, plastic and glass may present benefits over wood and such advantages seem to be greater for material recycle systems, followed by reuse and by-product reuse systems.

Pulselli et al. (2007) used emergy analysis for calculating material and energy inputs during the construction and operation (including maintenance) phases of a 2,700 m^2 multi-storey building in central Italy to gain insights for the evaluation and selection of building materials and technologies. They estimated that nearly 50% of the building's emergy consumption corresponded to the manufacturing phase (considering a lifetime of 50 years), 35% to maintenance activities, and 15% to the operation (use) of the building, on a yearly basis.

For their part, Li and Wang (2009) used a mixed life-cycle assessment and emergy analysis approach to evaluate a large-scale suburban residential area of more than 152 thousand people and almost 62 thousand households in Beijing, China; in their emergy evaluation, they focused mainly on building materials use, leaving aside housing operation. They observed that the bulk of emergy consumption came from the building manufacturing and the housing operation phases and that the most important environmental impact was due to photochemical oxidant creation potentials.

Finally, it is important to remark that, while all emergy evaluations in urban areas may be related somewhat to urban planning domains, studies directly related to land use planning are scarce. In this regard, the most thoroughly studied urban agglomeration is the Taipei metropolitan region in Taiwan. Huang and colleagues (2007) have worked in this aspect mostly aiming at exploring the spatial energetic hierarchy in urban landscape systems, through the follow-up of urban growth and land use change at a municipal disaggregation level. They developed a simulation model that included the natural area, agricultural area and urban area subsystems, which results depicted a spatial pattern of convergence, with an increasing energy hierarchy towards the central districts of Taipei.

CHAPTER 2

AN EMERGY ANALYSIS FOR URBAN ENVIRONMENTAL SUSTAINABILITY ASSESSMENT, THE ISLAND OF MONTREAL, CANADA

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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.

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

2.1 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 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 et al., 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 et al., 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 90s, 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 and Asano, 1999; Kennedy et al., 2007; Newman, 1999; Sahely et al., 2003, etc.). 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 and Chen, 2012).

Further, material flow accounting (Decker et al., 2000; Hendricks et al., 2000), ecological footprint (Folke et al., 1997; Muñiz and Galindo, 2005; Rees and Wackernagel, 1996), and energetic life cycle analysis (Perkins et al., 2009; Pullen, 2000; Steemers, 2003; Treloar et al., 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 et al., 2011a; Sciubba et al., 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 and 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 and Ulgiati, 2005; Zhang et al., 2010), rather than other aspects, such as thermodynamic and utilization efficiencies (Liu et al., 2011b).

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 et al., 2011). This methodology has been successfully applied to studies of several urban areas, such as Taipei (Huang, 1998), Macao (Lei et al., 2008), Rome (Ascione et al., 2009), and Beijing (Zhang et al., 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.

2.2 Methodology

2.2.1 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 and 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 one joule of available energy at the output. It is a measure of the process

efficiency: the lower the transformity, the more efficient the conversion (Brown and 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, labor, etc. Figure 2.1 shows the main flows interacting in Montreal.

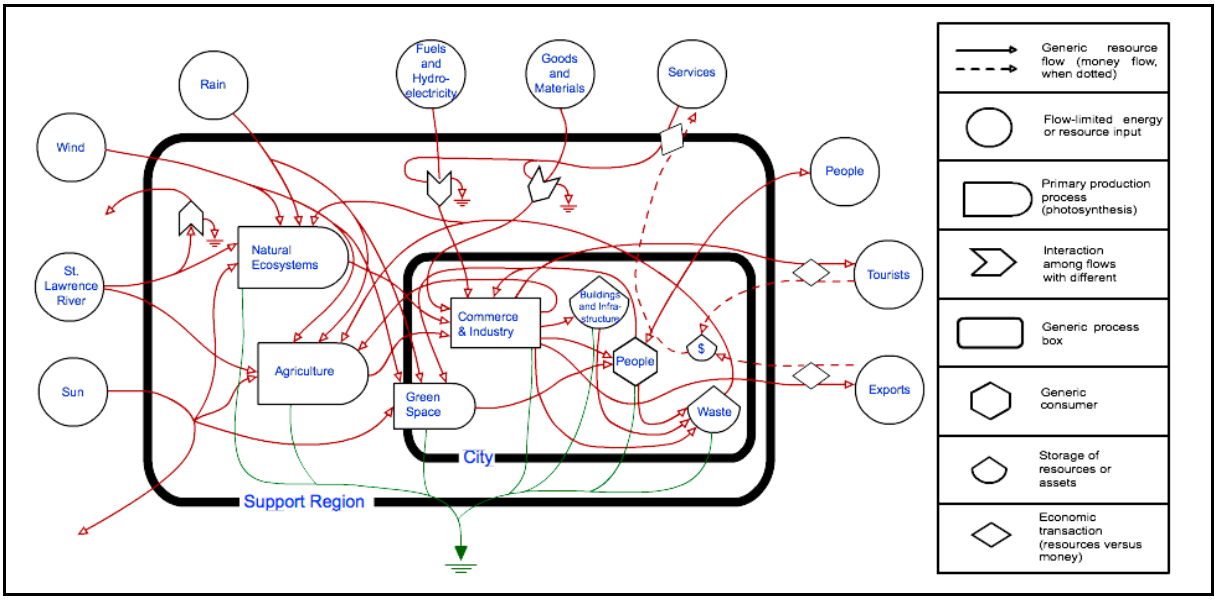

Figure 2.1 Diagram of the main flows on the Island of Montreal
Adapted from Brown (2011, p. 3)

The St. Lawrence River, with its mean annual flow ranging from 7,800 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/hr. (Environment Canada, 2011).

In 2005, there were about 3500 hectares of forest and 4100 hectares of permanent farmland on the Island (City of Montreal, 2006; Hodder et al., 2001).

A major component of the energy flows entering Montreal was the 30508 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) were generated in the year of study.

Also, in 2005, the GDP was 74.7 billion USD, which accounted for 36% of Quebec's GDP and exports (ISQ, 2011), with revenues from exports and tourism standing at about 20 billion USD (City of Montreal 2010a) and 2 billion USD (City of Montreal 2010b), respectively.

Once the diagram is created, a table with raw data is integrated to calculate the corresponding emergy flows (Table 2.1), which are obtained through a multiplication by the appropriate unit emergy values (Brown and Ulgiati, 2004b).

Finally, from the aggregate emergy flows obtained (renewable, non-renewable, imported, etc.), performance indicators are calculated for their final interpretation as support mechanisms in decision-making processes (Brown and Ulgiati, 1997; Ulgiati et al., 1995).

The global emergy budget (15.83×10^{24} seJ/year) used in this study was calculated from solar insolation, deep earth heat and tidal energy, all expressed in seJ (Brown and Ulgiati, 2004b; Odum, 2000).

Table 2.1 Emergy synthesis of material, energy and money flows on the Island of Montreal

	Element	Quantity	Unit	Transformity (seJ/J,g,$)	Reference (transformity)	Emergy (seJ/year)
	Renewable resources					
1	Solar radiation	$2.21x10^{18}$	J/year	1.00	Odum, 1996	$2.21x10^{18}$
2	Wind	$1.78x10^{16}$	J/year	$2.45x10^{03}$	Odum, 2000	$4.37x10^{19}$
3	Rain (evapotranspiration)	$3.59x10^{14}$	J/year	$3.10x10^{04}$	Odum, 2000	$1.11x10^{19}$
4	St. Lawrence River	$7.84x10^{16}$	J/year	$4.70x10^{04}$	Odum, 2000	$3.68x10^{21}$
5	Surface heat flux	$7.09x10^{14}$	J/year	$1.07x10^{04}$	After Odum, 2000	$7.59x10^{18}$
	Local non-renewable resources					
6	Topsoil loss	$4.01x10^{10}$	g/year	$2.29x10^{09}$	Odum, 2000; Huang and Chen, 2005	$9.17x10^{19}$
	Imports					
7	Cereals	$1.66x10^{11}$	g/year	$9.82x10^{08}$	Odum, 1996; Pulselli, 2010	$1.63x10^{20}$
8	Fruits	$1.48x10^{11}$	g/year	$1.23x10^{09}$	Odum, 1996; Pulselli, 2010	$1.82x10^{20}$
9	Vegetables	$2.86x10^{11}$	g/year	$5.96x10^{09}$	Odum, 1996; Brandt-Williams, 2001	$1.70x10^{21}$
10	Meat	$1.74x10^{11}$	g/year	$3.17x10^{10}$	Odum, 1996; Brandt-Williams, 2001; Bastianoni et al., 2005	$5.53x10^{21}$
11	Fish	$1.73x10^{10}$	g/year	$1.53x10^{11}$	Odum, 1996; Bastianoni et al., 2005	$2.64x10^{21}$
12	Milk and other diaries	$2.47x10^{11}$	g/year	$2.41x10^{10}$	Odum, 1996; Brandt-Williams, 2001	$5.94x10^{21}$
13	Eggs	$1.95x10^{10}$	g/year	$1.07x10^{11}$	Brandt-Williams, 2001	$2.09x10^{21}$
14	Sugars and syrups	$6.24x10^{10}$	g/year	$1.55x10^{08}$	Brandt-Williams, 2001; Brown and Ulgiati, 2004b	$9.67x10^{18}$
15	Potable water	$6.99x10^{14}$	g/year	$3.00x10^{06}$	Pulselli, 2010	$2.10x10^{21}$
16	Sand and gravel	$1.60x10^{13}$	g/year	$1.68x10^{09}$	Odum, 2000	$2.69x10^{22}$
17	Portland cement	$7.32x10^{11}$	g/year	$2.56x10^{09}$	Brown and Buranakarn, 2003; Pulselli et al., 2008	$1.87x10^{21}$
18	Asphalt	$4.34x10^{11}$	g/year	$2.83x10^{09}$	Bastianoni et al., 2009	$1.23x10^{21}$
19	Aluminum	$1.88x10^{11}$	g/year	$7.76x10^{08}$	Ascione et al., 2009	$1.46x10^{20}$
20	Iron and steel	$9.99x10^{11}$	g/year	$3.27x10^{09}$	Campbell et al., 2005; Ascione et al., 2009	$3.27x10^{21}$
21	Copper	$9.62x10^{10}$	g/year	$3.36x10^{09}$	Brown et Ulgiati, 2004b	$3.23x10^{20}$
22	Wood	$4.07x10^{12}$	g/year	$6.48x10^{08}$	Campbell et al., 2005; Castellini et al., 2006	$2.63x10^{21}$
23	Paper	$1.33x10^{12}$	g/year	$4.65x10^{09}$	Ulgiati et al., 1994; Odum, 1996; Pulselli, 2010	$6.18x10^{21}$
24	Paper (journal)	$1.70x10^{11}$	g/year	$8.46x10^{09}$	Pulselli, 2010	$1.44x10^{21}$
25	Glass	$2.49x10^{11}$	g/year	$2.55x10^{09}$	Brown and Bardi, 2001; Ascione et al., 2009	$6.35x10^{20}$
26	Plastics	$3.86x10^{11}$	g/year	$4.54x10^{09}$	Brown and Bardi, 2001; Castellini et al., 2006	$1.75x10^{21}$
27	Textiles	$3.67x10^{10}$	g/year	$1.24x10^{11}$	Odum, 1996; Campbell et al., 2005	$4.55x10^{21}$
28	Chemical products	$8.78x10^{11}$	g/year	$3.42x10^{09}$	Ulgiati et al., 1994; Odum, 1996; Campbell et al., 2005	$3.00x10^{21}$
29	Fertilizers	$1.29x10^{11}$	g/year	$3.99x10^{09}$	Brandt-Williams, 2001; Campbell et al., 2005	$5.16x10^{20}$
30	Hydroelectricity	$1.10x10^{17}$	J/year	$6.23x10^{04}$	Brown and Ulgiati, 2002	$6.84x10^{21}$
31	Gasoline	$1.47x10^{12}$	g/year	$2.92x10^{09}$	Bastianoni et al., 2009	$4.29x10^{21}$
32	Diesel	$6.65x10^{11}$	g/year	$2.83x10^{09}$	Bastianoni et al., 2009	$1.88x10^{21}$
33	Fuel oil	$7.78x10^{11}$	g/year	$2.66x10^{09}$	Bastianoni et al., 2009	$2.07x10^{21}$
34	Coal	$2.20x10^{15}$	J/year	$4.00x10^{04}$	Odum, 2000	$8.78x10^{19}$
35	Natural gas	$4.88x10^{16}$	J/year	$4.00x10^{04}$	Bastianoni et al., 2009	$1.95x10^{21}$
36	Liquid petroleum gas	$7.40x10^{10}$	g/year	$3.11x10^{09}$	Bastianoni et al., 2009	$2.30x10^{20}$
37	Services for imports	$1.21x10^{10}$	$/year	$1.61x10^{12}$	After Lei et al., 2008; ERS-USDA, 2011	$1.94x10^{22}$
	Exports					
38	Exportations (incomes)	$1.94x10^{10}$	$/year	$1.54x10^{12}$	Calculated here	$2.99x10^{22}$
39	Tourism (tourists' expenses)	$2.12x10^{09}$	$/year	$1.61x10^{12}$	After Lei et al., 2008; ERS-USDA, 2011	$3.41x10^{21}$
	Wastes					
40	Municipal solid wastes	$3.89x10^{15}$	J/year	$1.80x10^{06}$	Huang and Chen, 2005	$7.00x10^{21}$
41	Construction wastes	$1.41x10^{11}$	g/year	$1.79x10^{09}$	Huang and Hsu, 2003	$2.53x10^{20}$
42	Wastewater	$4.63x10^{15}$	J/year	$6.66x10^{05}$	Huang and Chen, 2005	$3.08x10^{21}$

2.2.2 Interpretation of emergy-based indicators

Flows were grouped according to most of the literature published by emergy analysts: renewable resources (*R*), local non-renewable resources (*N*), imports (*F*), exports (*Exp*) and waste (*W*). Likewise, commonly reported emergy indicators were calculated to evaluate the environmental sustainability of Montreal. As the present work focused mainly on the resources, the emphasis was placed on the indicators that consider the intensity of the use of such resources, such as empower density and per capita emergy, in order to observe their possible relation with parameters commonly used in urban planning, such as density.

Total emergy used (*U*) was considered as the overall indicator of the environmental support (including the external socio-economic system) for the well-being of residents and production of goods and services, which in turn generated waste in Montreal. *U* was taken as a measure of the yield of the system for calculating the environmental yield ratio (*EYR*). An *EYR* value much greater than 1 indicates that the analyzed urban system generates more new resources (emergy) than those that were available as inputs; otherwise, the system is a consumer-transformer of resources (Ascione et al., 2009). The environmental loading ratio (*ELR*) is the ratio of non-renewable and imported emergy to renewable emergy. It evaluates the balance between non-renewable and renewable resources: the higher its value, the less sustainable the urban system under study (Brown and Ulgiati, 2001). Empower density (*ED*) is the total emergy used in a given area per unit time. It is an indicator of the intensity of utilization of resources, with high values for industrial activities and urban centers (Brown and Ulgiati, 2001). It may also denote the scarcity of available land or the need for support land (Ascione et al., 2009). On the other hand, emergy analysis suggests that money is an incomplete measure of wealth and that the emergy used to produce a service or product is a better measure of real wealth, estimated through the emergy-to-money ratio (*EMR*) using the Gross Domestic Product (Odum, 1996). *EMR* is an indicator of the capacity of money to buy emergy in a determined region: the higher its value, the greater the quantity of emergy the region's economy buys (Zhang et al., 2011). It may also be an indicator of ecological

economic efficiency, when regions are compared: lower values of *EMR* correspond to higher levels of emergy use efficiency (Cai et al., 2009).

This work explores the possibility of some parameters, such as population density and available space, being related to the intensity of resource utilization, measured as per capita emergy (U_{cap}) and empower density (in both cases, higher values of U_{cap} and *ED* indicate a higher intensity of resource consumption and/or utilization). This hypothesis is based on the behavior observed in some social insects, such as ants, which change their energy consumption under crowded conditions or with variations in colony size (Cao and Dornhaus, 2008; Fonck and Jaffe, 1996). To explore this potential relationship, a comparison was carried out with selected cities drawn from published studies. Possible scenarios expected were that population density either could not or would weakly affect the intensity of resource use, or at least, that at some interval of density, the intensity of resource utilization would be affected. Moreover, it was expected that the higher the total emergy used, the higher the GDP, and that the greater the U_{cap}, the higher the per capita GDP.

2.2.3 Data collection and elaboration

The main sources of information used in this study came from the statistics and databases of Statistics Canada, Institute of Statistics of Quebec, Montreal in Statistics, Environment Canada, Ministry of Natural Resources and Wildlife of Quebec, Hydro-Québec and the Communauté Métropolitaine de Montréal. Unavailable data for the year of study, especially those for the manufacturing sector, were brought to present value of 2005 from CANSIM, the socioeconomic database of Statistics Canada, and by applying price indices. Finally, information from the case studies that were used in the cities comparison was obtained from Ascione et al. (2009), Lei et al. (2008) and Zhang et al. (2009, 2011).

Although, as mentioned above, one of the key gaps that emergy analysis tries to bridge is that of the incompleteness of currency as a measure of wealth, one of the most criticized points of the methodology is the assessment of monetary flows. Emergy analysis may treat such flows

indistinctly as actual physical flows or proceed by replacing unavailable data of actual physical flows of materials and energy by their respective costs (Hau and Bakshi, 2004). In this work, the use of direct monetary data to estimate emergy flows was avoided as much as possible; with emergy of services for imports, exports and tourism being the only flows estimated from money flows. By their nature, services for imports were calculated from the cost of imports, similarly to practically all the papers reviewed in the literature, while exports and tourism were estimated from aggregated city-level data.

For the estimation of the emergy of renewable and local non-renewable resources, data was obtained from averages of several decades; for the calculation of wind, for example, the mean annual speed for 1971 to 2000 provided by the Montreal International Airport Station (Environment Canada, 2011) was used, while for the geo-potential of the St. Lawrence River, the historic mean annual flow was used (Environment Canada, 2010). The emergy of food was the only set of items calculated from national per capita averages (for urban regions) of actual physical flows (Statistics Canada, 2006).

Emergy flows of potable water, sand and gravel, hydroelectricity, gasoline, diesel, municipal solid waste, construction waste, and wastewater were calculated from actual physical flow aggregated city-level data. The emergy of Portland cement, wood, chemical products, fuel oil, coal, natural gas, and liquid petroleum gas was estimated from actual physical flows available from aggregated province-level data, taking as the main criterion for scaling down the data, the proportional share of the acquisition cost of the raw materials and energy used in the manufacturing sector in Montreal versus the total for the Province of Quebec in 2005 (ISQ, 2009).

Emergy flows of asphalt, aluminum, iron and steel, copper, paper, newspaper, glass, plastics, textiles, and fertilizers were calculated from the prices and acquisition costs of those materials available from aggregated province-level data, taking as the main criterion for scaling down the data the proportional share of the acquisition cost of the raw materials used

in the manufacturing sector in Montreal versus the total for the Province of Quebec in 2005 (ISQ, 2009).

2.3 Results

2.3.1 Island of Montreal

Table 2.2 summarizes the main emergy flows and the performance indicators calculated for the Island of Montreal from Table 1.

Table 2.2 Emergy flows and indicator calculated for the Island Montreal

Flows and indicators		Quantity	Unit
	Emergy flows		
R	Renewable emergy (maximum among items 1-5)	3.68×10^{21}	seJ/year
N	Non-renewable emergy (item 6)	9.17×10^{19}	seJ/year
F	Imported emergy (food, materials, goods, services)	1.12×10^{23}	seJ/year
U	Total emergy used	1.15×10^{23}	seJ/year
Exp	Emergy of exports	3.33×10^{22}	seJ/year
W	Emergy of wastes	1.03×10^{22}	seJ/year
	Emergy-based indicators		
U_{cap}	Per capita emergy, U/population	6.25×10^{16}	seJ/per·year
ED	Empower density, U/area	2.31×10^{14}	seJ/m^2·year
EMR	Emergy to money ratio, U/GDP	1.54×10^{12}	seJ/$
R/U	Renewable emergy to total emergy used ratio	3.19	%
W/U	Emergy of wastes to total emergy used ratio	8.96	%
SA_R	Support area (based on renewable resources)	15136	km^2
EYR	Emergy yield ratio, U/F	1.034	-
ELR	Environmental loading ratio, (N+F)/R	30.321	-

The total emergy used in Montreal in 2005 was 1.15×10^{23} seJ; locally renewable emergy was 3.68×10^{21} seJ, and imported (purchased) emergy totaled 1.12×10^{23} seJ.

As shown in Figure 2.2, construction materials constituted the most significant emergy flow entering the Island (3.00×10^{22} seJ/year), followed by goods and commodities (2.45×10^{22}

seJ/year), food and water ($2.04x10^{22}$ seJ/year), services for imports ($1.95x10^{22}$ seJ/year) and fuels and electricity ($1.73x10^{22}$ seJ/year). Finally, emergy from exports was $3.33x10^{22}$ seJ/year and emergy of the wastes generated in 2005 was $1.03x10^{22}$ seJ/year (representing 9% of the total emergy used in 2005).

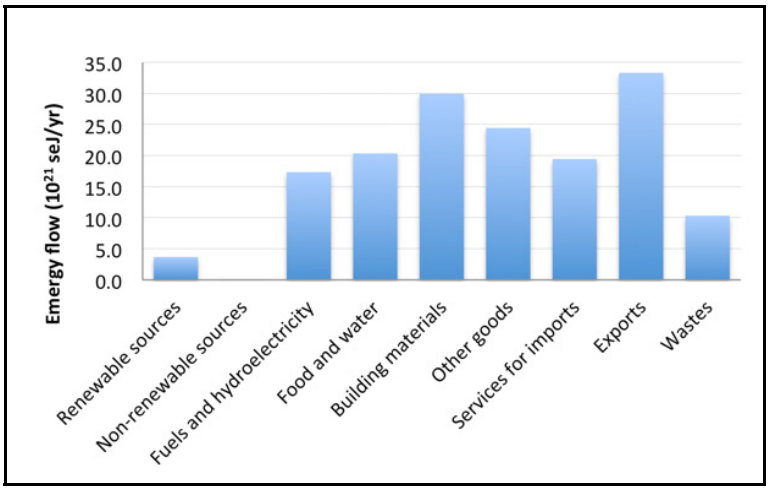

Figure 2.2 Main aggregated emergy flows for the Island of Montreal in 2005 (seJ/year)

2.3.2 Emergy assessment in the selected cities

All the studies in the reviewed literature aggregated flows as *R*, *N*, *F*, and *W* and *Exp*: in all cases, *F* was the largest flow, the *R/U* ratio ranged from 0.011 to 0.035, and the *W/U* ratio, from 0.07 to 0.18.

In the analysis of Beijing, *R*, *N*, *F* and *Exp* were evaluated for several years of study (the most recent, 2004, was used in the comparison presented here). Exports were calculated both from actual products and from costs. Local agriculture and forestry were not included in the overall emergy use because they were mainly supported by free environmental flows. The calculated indicators were the emergy self-support ratio [*(R+N)/U*], *ELR, ED, EMR* and U_{cap}, and the last three were used in the comparison performed in this work. Primary data were obtained from the Beijing Statistical Office and the Editorial Committee for China Environment Year-Book (Zhang et al., 2011).

In the 2004 Macao study, *R*, *N*, *F*, *W* and *Exp* were considered. Given the prominent role played by tourism, its emergy was estimated in detail, taking as input the money spent by tourists, and as output the actual emergy consumed by them (the emergy input was almost 5 times the emergy output). The emergy of waste included services, labor and equipment depreciation (this resulted in a difference of +2.5% of the emergy 'embodied' in waste), and because of the significance of the trade between Macao and China, trading partners were divided into China and 'other regions'. In addition to traditionally reported indicators, the authors developed the net emergy ratio, which was not used in the comparison presented here. Actual physical and monetary local-level data used in the calculations came from the Yearbook of Statistics 2004 of the Statistics and Census Service of the Macao Special Administration Region (Lei et al., 2008).

In Rome, *R*, *N*, *F* and specific sectors (tourism and government support) were estimated for 2002. Emergy imported from labor was taken into consideration, assuming that daily commuters made up about 10% of the population, and it was estimated that 6% of the emergy of services and labor for imports was renewable. The indicators calculated were *EMR*, U_{cap}, *ED, EYR, ELR* and the emergy index of sustainability (*ESI* = *EYR/ELR*); the first three were used in the comparison, taking the total emergy with services and labor. It was reported that most of the data was available in reports published by the City Administration (Ascione et al., 2009).

In the studies of Guangzhou and Shanghai, *R*, *N*, *F*, *W* and *Exp* were assessed for 2004; exports were calculated from the cost of goods and services, with solid waste and wastewater included. Imports and outside sources were broken down only into goods, services and fuels, and the former two were estimated from their costs. The calculated indicators were U_{cap}, *ED* and *EMR*, which were used in the comparison performed in this work. Data were obtained from the Guangzhou and Shanghai Statistical Bureau and the Editorial Committee for China Environment Year-Book (Zhang et al., 2009).

Data and emergy-based indicators for San Juan (1992) and Taipei (1990) were used as reported by Ascione et al. (2009); data and emergy-based indicators for Miami-Dade (1990) and Zhongshan (2000) were used as reported by Lei et al. (2008). Table 2.3 summarizes the data used in the comparison of the cities.

Table 2.3 Emergy-based indicators and parameters for the selected cities

City	Pop. den. (per/km^2)	Population (persons)	Surface (m^2)	GDP (USD)	GDP$_{capita}$ (USD/per)	*U* (seJ/yr)	U_{cap} (seJ/per·yr)	*ED* (seJ/m^2·yr)	*EMR* (seJ/USD)
Miami-Dade (1990)	$0.38x10^{03}$	$1.94x10^{06}$	$5.06x10^{09}$	$7.15x10^{09}$	$3.69x10^{03}$	$6.61x10^{22}$	$3.41x10^{16}$	$1.31x10^{13}$	$9.24x10^{12}$
Zhongshan (2000)	$0.74x10^{03}$	$1.34x10^{06}$	$1.80x10^{09}$	$3.78x10^{09}$	$2.82x10^{03}$	$2.74x10^{22}$	$2.04x10^{16}$	$1.52x10^{13}$	$7.25x10^{12}$
Beijing (2004)	$0.89x10^{03}$	$14.90x10^{06}$	$16.80x10^{09}$	$53.50x10^{09}$	$3.59x10^{03}$	$65.10x10^{22}$	$4.36x10^{16}$	$3.88x10^{13}$	$12.20x10^{12}$
Guangzhou (2004)	$0.99x10^{03}$	$7.38x10^{06}$	$7.43x10^{09}$	$51.50x10^{09}$	$6.97x10^{03}$	$30.80x10^{22}$	$4.17x10^{16}$	$4.14x10^{13}$	$5.98x10^{12}$
Rome (2002)	$1.97x10^{03}$	$2.54x10^{06}$	$1.29x10^{09}$	$69.00x10^{09}$	$27.20x10^{03}$	$14.00x10^{22}$	$5.50x10^{16}$	$10.80x10^{13}$	$2.03x10^{12}$
Shanghai (2004)	$2.13x10^{03}$	$13.50x10^{06}$	$6.34x10^{09}$	$101.00x10^{09}$	$7.46x10^{03}$	$62.20x10^{22}$	$4.60x10^{16}$	$9.81x10^{13}$	$6.16x10^{12}$
Taipei (1990)	$2.80x10^{03}$	$6.53x10^{06}$	$2.33x10^{09}$	$119.00x10^{09}$	$18.20x10^{03}$	$12.40x10^{22}$	$1.90x10^{16}$	$5.32x10^{13}$	$1.04x10^{12}$
San Juan (1992)	$3.18x10^{03}$	$1.71x10^{06}$	$0.54x10^{09}$	$22.90x10^{09}$	$13.40x10^{03}$	$3.76x10^{22}$	$2.20x10^{16}$	$7.00x10^{13}$	$1.64x10^{12}$
Montreal (2005)	$3.70x10^{03}$	$1.85x10^{06}$	$0.50x10^{09}$	$74.70x10^{09}$	$40.50x10^{03}$	$11.50x10^{22}$	$6.25x10^{16}$	$23.10x10^{13}$	$1.54x10^{12}$
Macao (2004)	$16.90x10^{03}$	$0.47x10^{06}$	$0.03x10^{09}$	$1.03x10^{09}$	$2.21x10^{03}$	$2.46x10^{22}$	$5.29x10^{16}$	$89.50x10^{13}$	$23.90x10^{12}$

It should be noted that the Beijing, Macao and Rome evaluations presented a more detailed breakdown of the items included in the calculation of the different emergy flows, similarly to the analysis conducted in this work. In the other studies, such as those of Guangzhou and Shanghai, imported flows were grouped into broader categories, and the corresponding emergy of goods was estimated from monetary flows. In addition, besides the lack of availability of data of actual flows at the most detailed level of aggregation, the dates on which the studies were carried out could have an effect on the results, as the more recent the analyses performed, the more refined the practice of the method, and the greater the number of transformities calculated for various goods, products, processes and services. Moreover,

when analyses conducted on different dates are used in such comparisons, there is a degree of risk in not considering external factors, such as regional economic crises, which may affect not only the local patterns of consumption, but also the export incomes and the purchasing power parities, albeit in different ways. Finally, the comparison made in this paper, which was based on the intensity of resource utilization, rather than on the urban system's outputs, minimized the impacts of differences and gaps in the estimation of exports and tourism. These differences become more significant when evaluating and comparing overall performance.

2.3.3 Emergy of monetary flows: exchange rates versus purchasing power parities

Paid services to bring goods, materials, fuels, etc. constituted a significant fraction of the emergy imported in 2005, which amounted to 21% of the actual material flows emergy. Since currency exchange rates often change abruptly over a short time frame, a sensitivity analysis was performed, with data drawn from the Organization for Economic Co-operation and Development (OECD, 2011), comparing the application of yearly average exchange rates and purchasing power parities (PPP), to the conversion of Canadian dollars to USD for the services for imports. By applying the average 2005 exchange rate, 1.21×10^{10} USD was calculated (item 37, Table 1), whereas 1.28×10^{10} USD was obtained when 2005 PPP were applied, representing a 5.2% increase. This difference would be more meaningful if the currency of a developing country, for example, the Mexican peso (MEX), was used as the reference currency. In this case, by applying the average 2005 exchange rate, 1.32×10^{11} MEX is calculated, whereas 1.05×10^{11} MEX is obtained if the 2005 PPP are used, representing a 25.9% decrease, and confirming the general premise that when the PPP are used rather than exchange rates, the differences between developing and developed countries are lessened (Schreyer and Koechlin, 2002). The outcomes in this hypothetical scenario could result in a variation of about 5% in the total emergy use calculation.

2.4 Discussion

2.4.1 Island of Montreal

Like most modern cities, the day-to-day operations of Montreal are based on material and energy imports, most of which come from non-renewable sources, as evidenced by an *EYR* of 1.03 and an ELR of 30.32. As mentioned earlier, the latter is an indicator of the pressure of non-renewable resource utilization; in urbanized areas with strong economic activity, the ELR may be greater than 1000 (Brown and Ulgiati, 2001). The relatively low *ELR* of the Island of Montreal confirms the St. Lawrence River as a key element of the regional system. Its high contribution as a renewable emergy source, providing more than 3% of the total amount used, corresponds to the geo-potential of its rate of flow, which, the with help of its tributary, the Ottawa River, reaches a historical annual mean of 9550 m^3/s at the analysis location (Environment Canada, 2010). Figure 2.3 shows a ternary resource flow lines diagram depicting the relative proportion of *R, N* and *F*, given by the lengths of the perpendiculars from the vertex to the opposite side of the triangle (Almeida et al., 2007).

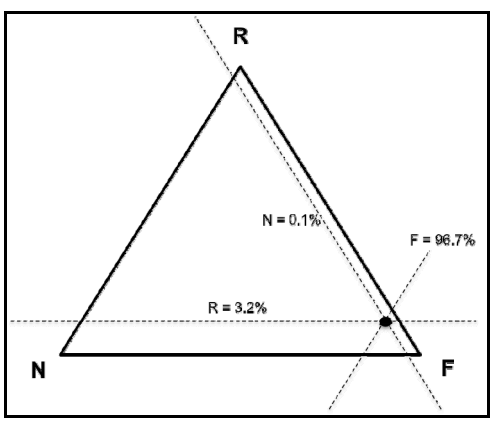

Figure 2.3 Resource flow ternary diagram of renewable resources, local non-renewable resources and imported emergy for the Island of Montreal in 2005

The relatively low emergy contribution of the energy flows entering the Island (fuels and electricity) is due to the fact that in Quebec, 98% of the electricity produced is of hydraulic origin (Hydro-Québec, 2011). On the other hand, the average price of electricity in Montreal

is among the lowest of the twenty largest cities in North America, and significantly below the prices in cities in the northeastern United States; in 2005, the average cost per kWh in Montreal was 0.0517 USD (Hydro-Québec, 2005). This low price, coupled with Montreal's strategic geographical position, lend it competitive advantages for the development of economic activities and exports from the Island at a lower emergy cost, which is reflected in an EMR of 1.54×10^{12} seJ/USD·year.

As noted in Section 2.2.2, *ED* is an indicator of the intensity of activity or of utilization of resources (one of which is land itself) in a given area per unit time. Its value may exceed 1.0×10^{14} seJ/m^2·year in large urban centers (Brown and Ulgiati, 2001), but Montreal's 2.31×10^{14} seJ/m^2·year reflects a significant lack of available land, considering that, of the 499.1 km^2 of the Island's land area, about 87% was already built-up by 2000 (ISQ, 2010).

2.4.2 Comparison with the selected cities

The comparison with the selected cities found in the literature was carried out using intensity indicators (values per unit area, per capita parameters) rather than total quantities, in order to attenuate the differences of each urban region's specific features, the influence of the urban system size, and to some extent, to address the implications of the dates on which the studies were performed (Ascione et al., 2009). The exploratory exercise that follows represents a search for trends that should be viewed with caution, given the particularities of each urban region, such as location, demographic profile, economic structure, nature and intensity of trade relations, as well as the differences attributable to the assessment procedures detailed in Section 2.3.2. As mentioned above, Table 2.3 presents the characteristics of the selected cities, shown in increasing order of population density.

From Figure 2.4, a correlation between population density and empower density is confirmed (Ascione et al., 2009), which in turn seems to have its origin in the correlation between population size and total emergy used (Figure 2.5). In both cases, linear regressions were calculated by ordinary least squares (the value of the coefficient of determination, R^2, was

included in the graphs). In Figure 2.4a, all ten selected cities were included, and in Figure 2.4b, the outlier (Macao) was not considered in order to observe the effect on the R^2 value. Although R^2 falls when Macao is removed, a relatively strong correlation is confirmed.

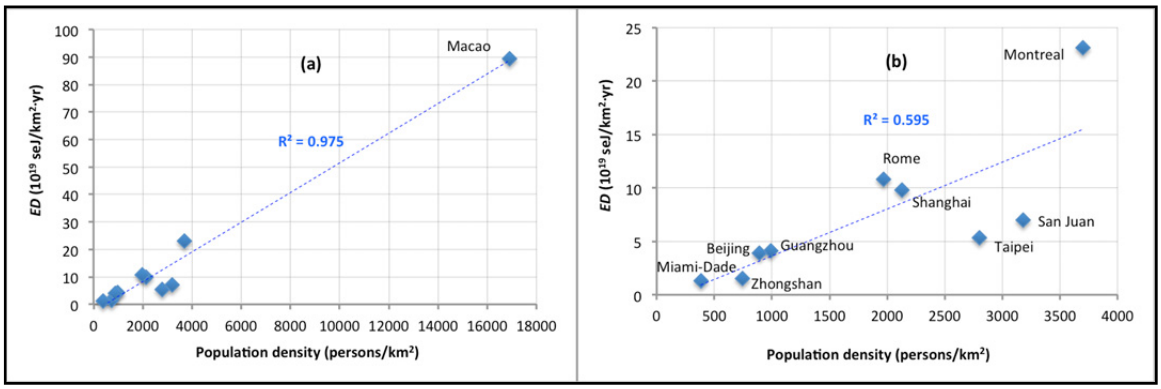

Figure 2.4 (a) Population density and empower density in the selected cities and (b) population density and empower density in the selected cities without outliers (Macao)

Likewise, when outliers (Beijing and Shanghai) are not considered in the population-to-total emergy graph, R^2 falls, but a comparatively strong correlation is also confirmed (Figure 2.5). It is of note that, except for Taipei, populations of 2.5 million or less seem to reduce the total emergy used, which is interesting, given that cities of less than 500,000 inhabitants and cities with populations of 1 to 5 million will continue to absorb most of the world's urban population, with 53% and 22% of the total (LEAD International, 2008), respectively.

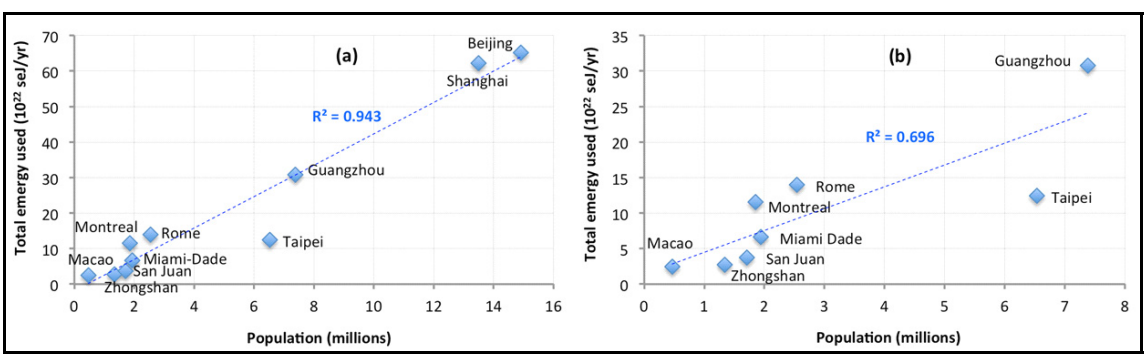

Figure 2.5 (a) Population and total emergy used in the selected cities and (b) population and total emergy used in the selected cities without outliers (Beijing and Shanghai)

In Figure 2.6, a power-type regression by least squares was calculated from the per capita available space-to-empower density graph. It can be seen that *ED* decreases considerably when each inhabitant has about 300 m^2 of available land or more (roughly, the equivalent of a population density of 3300 persons/km^2 or less). When all the cities are included for the estimation of R^2, an important correlation is seen, and when Macao is not considered in the calculation, R^2 decreases, but not significantly (from 0.886 to 0.770). Thus, in future work, it will be fundamental to analyze urban regions with densities ranging between those of Macao and the Island of Montreal, ideally around 10,000 inhabitants/km^2.

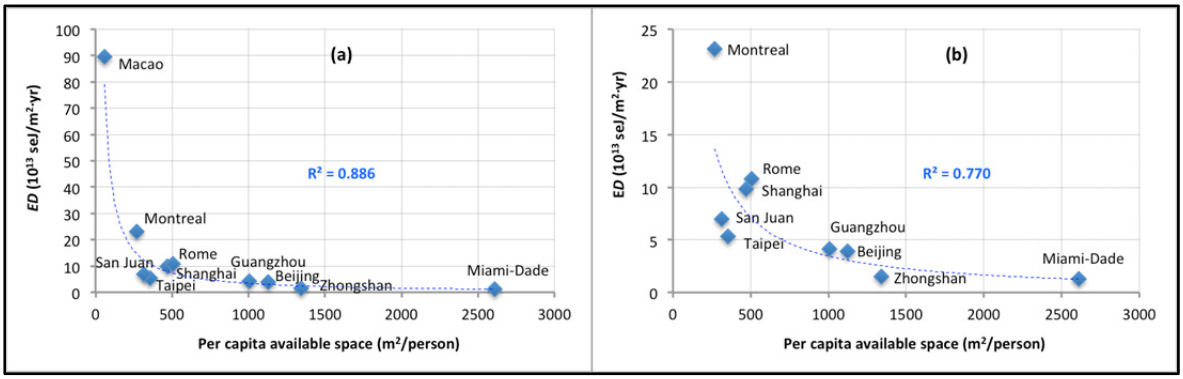

Figure 2.6 (a) Available space per inhabitant and empower density in the selected cities and (b) available space per inhabitant and empower density in the selected cities without outliers (Macao)

Although no significant correlation was found between total population and per capita emergy utilization, much like the case of per capita energy consumption in some social insects (Fonck and Jaffé, 1996) and per capita electricity consumption in human populations (Cabrera and Jaffé, 1998), the trend in the selected cities suggests that, to a certain extent, population density may be correlated to U_{cap} (Macao is a rare case of high population density; therefore, to facilitate the visualization of the comparison of population density and U_{cap}, this city was not displayed in Figure 2.7). Although the curve best representing the relationship was a polynomial-type degree four curve (which is excessive for explaining the variation in the data), the U_{cap} drop that takes place in the region of the graph between Rome-Shanghai and Taipei-San Juan, and the subsequent rise, observed not in isolation but in combination with Figure 2.6, may deserve a more detailed analysis in future work. The

influence of urban form on resource utilization, for example, in terms of energy consumption, is complex and linked to the debate on urban density and energy demand (Safirova et al., 2007). The causal mechanism involved is not entirely clear, but at a global level, densely populated cities use less transport energy per person and per passenger-kilometer than do low density cities (Rickwood et al., 2008). However, several Chinese cities showed that the higher the compactness, the lower the energy consumption, but that when certain density thresholds are exceeded, environmental performance declines (Liu et al., 2012).

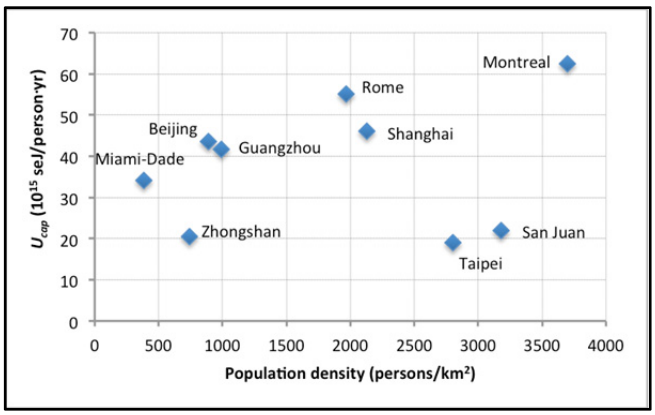

Figure 2.7 Population density and per capita emergy in the selected cities without outliers (Macao)

When the relationship between per capita GDP, as a measure of well-being, and U_{cap}, which can also be considered as an indirect standard of living measure, was reviewed, a general trend was found: a higher U_{cap} corresponds to a higher per capita GDP (Figure 2.8b). While the authors recognize the limitations of monetary indicators of well-being, this relationship was explored mainly because per capita GDP is a widespread indicator due to the availability and reliability of data for international comparison (Boarini et al., 2006). If absolute amounts of U and GDP are plotted (Figure 2.8a), it can be seen that no clear pattern or trend exists. However, if the same parameters are considered on a per capita basis, with a polynomial regression curve of degree two, it would appear that the greater the per capita emergy, the higher the per capita GDP will be (R^2 = 0.893), with San Juan and Taipei being the most significant exceptions. These two urban areas are among those with a notably higher emergy use efficiency, denoted by their low level of *EMR*, and the others being Montreal and Rome

(Table 2.3). In these 4 cities, as well as Macao, the highest per capita GDPs are also observed, but the latter shows the highest *EMR*, i.e., the high per capita GDP and the related high U_{cap} appear to bring along the 'cost' of a low ecological economic efficiency. These facts, besides being attributable to each city's geographical location and economic system structure and nature, could also indirectly be influenced by other variables, such as population density, as suggested for the case of per capita income and population density in the Pearl River Delta (Andrianoff, 2010). That is because, as seen previously, when only general absolute amounts are compared, then the higher the population, the greater the emergy use (Figure 2.5a) and, further, a larger population often results in higher GDP generation (Table 2.3).

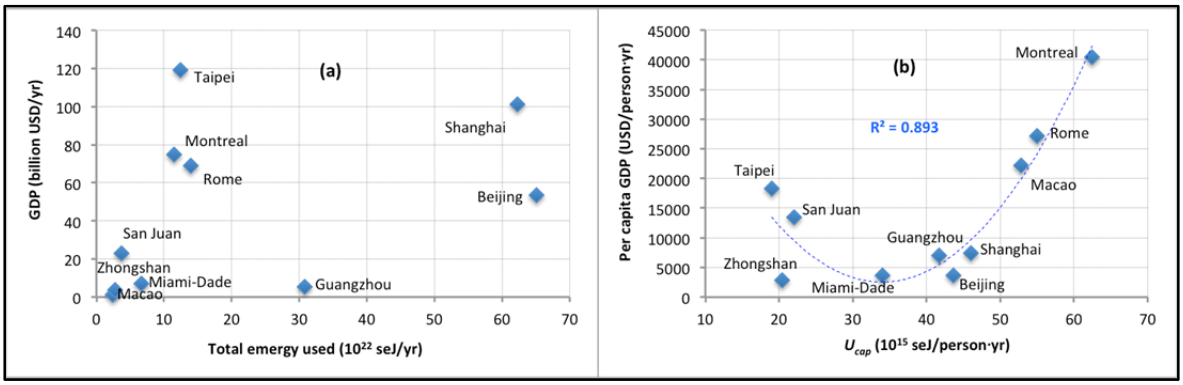

Figure 2.8 (a) Total emergy used and GDP in the selected cities and
(b) per capita emergy and per capita GDP in the selected cities

2.5 Conclusions

Emergy analysis has proved to be a useful tool for evaluating the environmental sustainability of the Island of Montreal. The Island shows a high level of emergy consumption, mostly based on resource imports, typical of present day urban centers, especially those developing a technology and information sector, as well as high per capita emergy, also common in cities in developed countries. The support area required, using only renewable resources, would be 30 times the area of the Island, even though the percentage of renewable resources-to-total emergy used is relatively high. Although the ratio of waste-to-

total emergy used was relatively low, this indicates the need for Montreal to improve its environmental performance.

In the comparison of the selected cities, relatively strong correlations were confirmed between population density and empower density and between population size and total emergy used. It was also observed that empower density fell considerably when each person has about 300 m^2 of available land or more: however, the case of densely populated cities, ideally those with around 10,000 inhabitants/km^2, needs to be studied more thoroughly. For its part, population density may be related to per capita emergy consumption, but more urban regions, with densities ranging between 1500 and 4000 inhabitants/km^2, should be analyzed in greater detail. Finally, in the cities reviewed, with the exception of San Juan and Taipei, it appears that the greater the per capita emergy, the higher the per capita GDP. In that regard, it would be interesting to confirm whether this trend holds when using statistics of actual individual (or household) income, rather than of per capita GDP.

The use of PPP, rather than average exchange rates, to estimate the emergy of monetary flows, may lead to significant variations in the calculation of total emergy used, and so it is therefore relevant to explore the use of PPP when data exists for their application, especially in developing countries. Also, given the widespread availability of information in economic databases and the frequent lack of data on actual input and output flows of materials in urban systems, it would be interesting to adapt a methodology, based on economic information and indices, to obtain and update non-existent actual materials data.

The high empower density of the Island of Montreal indicates that, to optimize the use of the available space in an environmentally sound manner, projects involving the re-development of grayfields and recovered brownfields should be fostered, along with the implementation and rehabilitation of green areas associated with such projects. One future research avenue should include ways of allocating the appropriate development densities to projects that reuse recovered spaces, in order to minimize disruption in the hierarchy of distribution of emergy flows in a city and to provide guidelines for planning instruments, such as urban

development plans. To that end, the next step should be to explore the intensity of occupation at the urban zoning planning level, calculating and comparing transformities of various types of neighborhoods, districts or boroughs, especially those belonging to cities accommodating population densities in the aforementioned interval, ranging from 1500 to 4000 inhabitants/km^2.

2.6 References

Almeida, C.M.V.B., Barrella, F.A., Giannetti, B.F., 2007. *Emergetic ternary diagrams: five examples for application in environmental accounting for decision-making*. Journal of Cleaner Production 15 (1), p. 63-74.

Andrianoff, T., 2010. *Does denser mean richer?* http://timandrianoff.com/mapping/mapping_PRD.pdf. Accessed November 14, 2011.

Ascione, M., Bargigli, S., Campanella, L., Ulgiati, S., 2011. *Exploring an urban system's dependence on the environment as a source and a sink: the city of Rome (Italy) across space and time scales*. ChemSusChem 4 (5), p. 613-627.

Ascione, M., Campanella, L., Cherubini, F., Ulgiati, S., 2009. *Environmental driving forces of urban growth and development. An emergy-based assessment of the city of Rome, Italy*. Landscape and Urban Planning 93 (3-4), p. 238-249.

Bastianoni, S., Campbell, D.E., Ridolfi, R., Pulselli, F.M., 2009. *The solar transformity of petroleum fuels*. Ecological Modelling 220 (1), p. 40-50.

Bastianoni, S., Marchettini, N., Niccolucci, V., Pulselli, F.M., 2005. *Environmental accounting for the lagoon of Venice and the case of fishing*. Annali di Chimica 95 (3-4), p. 143-152.

Boarini, R., Johansson A., Mira d'Ercole, M., 2006. *Alternative measures of well-being*. Statistics Brief OECD, No. 11, May 2006, p. 8.

Brandt-Williams, S.L., 2001. *Handbook of emergy evaluation. Folio #4. Emergy of Florida Agriculture*. http://www.emergysystems.org/downloads/Folios/Folio_4.pdf. Accessed September 14, 2010.

Brown, M.T., 2011. *Sample system diagrams of ecosystems and regional systems*. http://www.emergysystems.org/downloads/System_DIAGRAM.zip. Accessed Sept. 22, 2011.

Brown, M.T., Bardi, E., 2001. *Handbook of Emergy Evaluation. Folio #3. Emergy of Ecosystems*. http://www.emergysystems.org/downloads/Folios/Folio_3.pdf. Accessed September 14, 2010.

Brown, M.T., Buranakarn, V., 2003. *Emergy indices and ratios for sustainable material cycles and recycle options*. Resources, Conservation and Recycling 38 (1), p. 1-22.

Brown, M.T., Ulgiati, S., 2004a. *Energy quality, emergy and transformity: H. T. Odum's contributions to quantifying and understanding systems*. Ecological Engineering 178 (1-2), p. 201-213.

Brown, M.T., Ulgiati, S., 2004b. *Emergy analysis and environmental accounting* in: Cleveland, C. J. (Eds.), Encyclopedia of Energy, Elsevier Academic, Oxford, p. 329-354.

Brown, M.T., Ulgiati, S., 2002. *Emergy evaluations and environmental loading of electricity production systems*. Journal of Cleaner Production 10 (4), p. 321-334.

Brown, M.T., Ulgiati, S., 2001. *Emergy measures of carrying capacity to evaluate economic investments*. Population and Environment 22 (5), p. 471-501.

Brown, M.T., Ulgiati, S., 1997. *Emergy-based indices and ratios to evaluate sustainability: monitoring economies and technology towards environmentally sound innovation*. Ecological Engineering 9 (1-2), p. 51-69.

Burgess, E.W., 1925. *The growth of the city: An introduction to a research project*, in: Marzluff, J. M., Shulenberger, E., Endlicher, W., Alberti, M., Bradley, G., Ryan, C., ZumBrunnen, C., Simon, U. (Eds.), Urban Ecology. An International Perspective on the Interaction Between Humans and Nature. Springer Science+Bussiness Media, LLC., New York, 2008, p. 71-78.

Cabrera, S., Jaffé, K., 1998. *On the energetic cost of human societies: Energy consumption as an econometric index*. Interciencia 23 (6), p. 350-354.

Cai, Z.F., Zhang, L.X., Zhang, B., Chen, Z.M., 2009. *Emergy-based analysis of Beijing-Tianjin-Tangshan region in China*. Communications in Nonlinear Science and Numerical Simulation 14 (12), p. 4319-4331.

Campbell, D.E., Brandt-Williams, S.L., Meisch, M.E.A., 2005. *Environmental accounting using emergy: Evaluation of the State of West Virginia*. http://www.epa.gov/nheerl/publications/files/wvevaluationposted.pdf. Accessed September 29, 2010.

Cao, T.T., Dornhaus, A., 2008. *Ants under crowded conditions consume more energy*. Biology Letters 4 (6), p. 613-615.

Castellini, C., Bastianoni, S., Granai, C., Dal Bosco, A., Brunetti, M., 2006. *Sustainability of poultry production using the emergy approach: comparison of conventional and organic rearing systems*. Agriculture, Ecosystems and Environment 114 (2-4), p. 343-350.

Chen, S., Chen, B., 2012. *Network environ perspective for urban metabolism and carbon emissions: A case study of Vienna, Austria*. Environmental Science and Technology 46 (8), p. 4498-4506.

City of Montreal, 2011. *The Montreal economy*. http://www.montreal2025.com/decouvrir_economie.php?lang=en. Accessed October 27, 2011.

City of Montreal, 2010a. *Établissements exportateurs et valeur des exportations, agglomération de Montréal (Exporting establishments and value of exports, agglomeration of Montreal)*. http://ville.montreal.qc.ca/portal/page?_pageid=6897,67885697&_dad=portal&_schema=PORTAL [in French]. Accessed April, 12, 2011.

City of Montreal, 2010b. *Volume et dépenses des touristes, agglomération de Montréal (Volume and expending by tourists, agglomeration of Montreal)*. http://ville.montreal.qc.ca/portal/page?_pageid=6897,67889573&_dad=portal&_schema=PORTAL [in French]. Accessed April, 12, 2011.

City of Montreal, 2009. *Profil sociodémographique. Agglomération de Montréal. Édition 2009 (Socio-demographic profile. Montreal Agglomeration. 2009 Edition)*, p. 27.

City of Montreal, 2006. *Politique de protection et de mise en valeur des milieux naturels de Montréal. Bilan et orientations (Protection and enhancement policy for the natural environment of Montreal. Assessment and directions)*, p. 24.

City of Montreal, 2005. *Plan de transport de Montréal. Portrait et diagnostic. Note technique 9: Transport des marchandises (Montreal transportation plan. Portrait and diagnostics. Technical note 9: Transport of goods)*, p. 21.

Communauté Métropolitaine de Montréal (CMM), 2011. *Quantités gérées par les municipalités de l'agglomération de Montréal. Tableau de borde du Plan métropolitaine de gestion des matières résiduelles (Quantities handled by the municipalities of the agglomeration of Montreal. Dashboard of the waste management metropolitan plan)*. http://tbpmgmr.cmm.qc.ca/swf/MesureIndicateurs.php [in French]. Accessed April 6, 2011.

Decker, E.H., Elliott, S., Smith, F.A., Blake, D.R., Rowland, F.S., 2000. *Energy and material flow through the urban ecosystem*. Annual Review of Energy and the Environment 25, p. 685-740.

Economic Research Service of the United States Department of Agriculture (ERS-USDA), 2011. *International macroeconomic data set. Real GDP (2005 dollars) Historical*. http://www.ers.usda.gov/Data/Macroeconomics/Data/HistoricalRealGDPValues.xls. Accessed October, 20, 2011.

Environment Canada, 2011. *Canadian climate normals or averages 1971-2000. Montreal Pierre Elliot Trudeau international airport station*. http://climate.weatheroffice.gc.ca/climate_normals/results_e.html?stnID=5415&lang=e&dCode=1&StationName=MONTREAL&SearchType=Contains&province=ALL&provBut=&month1=0&month2=12. Accessed November 22, 2011.

Environment Canada, 2010. *Flows of the St. Lawrence River and its main tributaries*. http://www.ec.gc.ca/stl/default.asp?lang=En&n=B82B3625-1. Accessed December 9, 2010.

Folke, C., Jansson, A., Larsson, J., Constanza, R., 1997. *Ecosystem appropriation by cities*. Ambio 26 (3), p. 167-172.

Fonck, C., Jaffé, K., 1996. *On the energetic cost of sociality*. Physiology and Behavior 59 (4-5), p. 713-719.

Forkes, J., 2007. *Nitrogen balance for the urban food metabolism of Toronto, Canada*. Resources, Conservation and Recycling 52 (1), p. 74-94.

Hau, J.L. and Bakshi, B.R., 2004. *Promise and problems of emergy analysis*. Ecological Modelling 178 (1-2), p. 215-225.

Hendriks, C., Obernosterer, R., Müller, D., Kytzia, S., Baccini, P., Brunner, P.H., 2000. *Material Flow Analysis: A tool to support environmental policy decision making. Case studies on the city of Vienna and the Swiss lowlands*. Local Environment 5 (3), p. 311-328.

Hermanowicz, S.W., Asano, T., 1999. *Abel Wolman's the metabolism of cities revisited: A case for water recycling and reuse*. Water Science and Technology 40 (4-5), p. 29-36.

Hodder, D., Thiffault C., Saia, M.-A., 2001. *Atlas des bois de Montréal (Atlas of Montreal's woods)*, p. 87.

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

Huang, S.-L., Chen, C.-W., 2005. *Theory of urban energetics and mechanisms of urban development*. Ecological Modelling 189 (1-2), p. 49-71.

Huang, S.-L., Hsu, W.-L., 2003. *Materials flow analysis and emergy evaluation of Taipei's urban construction*. Landscape and Urban Planning 63 (2), p. 61-74.

Hydro-Québec, 2011. *Rapport annuel 2010 (Annual report 2010)*, p. 118.

Hydro-Québec, 2009. *Profil régional des activités d'Hydro-Québec. Région de Montréal (Hydro-Québec regional profile. Montreal area)*, p. 110.

Hydro-Québec, 2005. *Comparaison des prix de l'électricité dans les grandes villes nord-americaines (Comparison of electricity prices in major North American cities)*, p.74.

Institute of Statistics of Quebec (ISQ), 2011. *Produit intérieur brut aux prix de base par région administrative, Québec, 2003-2007 (Gross domestic product at basic prices by Quebec administrative region, 2003-2007)*. http://www.stat.gouv.qc.ca/donstat/econm_finnc/conjn_econm/compt_econm/pib_ra_2003-2007.htm [in French]. Accessed September 15, 2011.

Institute of Statistics of Quebec (ISQ), 2010. *Bulletin statistique régional Montréal, Édition 2010 (Montreal regional statistics bulletin, 2010 edition)*, p. 32.

Institute of Statistics of Quebec (ISQ), 2009. *Coûts des matières premières et de l'énergie utilisés dans le secteur de la fabrication, par région administrative et sous-secteur du SCIAN, Québec, 2005 (Cost of the raw materials and energy used in the manufacturing sector, by administrative region and NAICS subsector, Québec, 2005)*. http://www.stat.gouv.qc.ca/donstat/econm_finnc/sectr_manfc/profil_secteur/ra_2005_scian3_couts.htm [in French]. Accessed February 21, 2011.

Kennedy, C., Cuddihy, J., Engel-Yan, J., 2007. *The changing metabolism of cities*. Journal of Industrial Ecology 11 (2), p. 43-59.

Kennedy, C., Pincetl, S., Bunje, P., 2011. *The study of urban metabolism and its applications to urban planning and design*. Environmental Pollution 159 (8-9), p. 1965-1973.

LEAD International, 2008. *Megacities and climate change. Sustainable urban living in a changing world*. First ed. LEAD International, London, p. 56.

Lei, K., Wang, Z., Ton, S., 2008. *Holistic emergy analysis of Macao*. Ecological Engineering 32 (1), p. 30-43.

Lin, L., Liu, M., Luo, F., Wang, K., Zhang, Q., Xiang, W.-N. (2012a). *Comment on "The study of urban metabolism and its applications to urban planning and design" by Kennedy et al. (2011)*. Environmental Pollution, 167, p. 184-185.

Lin, L., Liu, M., Luo, F., Wang, K., Zhang, Q., Xiang, W.-N. (2012b). *Response to authors' reply regarding "The study of urban metabolism and its applications to urban planning and design" by Kennedy et al. (2011)*. Environmental Pollution, 167, p. 187.

Liu, G.Y., Yang, Z.F., Chen, B., Su, M.R., Zhang, Y., Zhang, L.X., Jiang, M.M., 2011a. *Extended exergy analysis of urban socioeconomic system: a case study of Beijing, 1996-2006*. International Journal of Exergy 9 (2), p. 168-191.

Liu, G.Y., Yang, Z.F., Chen, B., Zhang, Y., 2011b. *Ecological network determination of sectoral linkages, utility relations and structural characteristics on urban ecological economic system*. Ecological Modelling 222 (15), p. 2825-2834.

Liu, Y., Song, Y., Arp, H.P., 2012. *Examination of the relationship between urban form and urban eco-efficiency in China*. Habitat International 36 (1), p. 171-177.

Ministry of Natural Resources and Wildlife of Quebec (MNRW), 2011. *Granulats : sable et gravier (Aggregates: sand and gravel)*. http://www.mrnf.gouv.qc.ca/mines/industrie/industrie-substances-sable.jsp [in French]. Accessed January 28, 2011.

Muñiz, I., Galindo, A., 2005. *Urban form and the ecological footprint of commuting. The case of Barcelona*. Ecological Economics 55 (4), p. 499-514.

Newman, P.W.G., (1999). *Sustainability and cities: extending the metabolism model*. Landscape and Urban Planning 44 (4), p. 219-226.

Organisation for Economic Co-operation and Development (OECD), 2011. *2005 Purchasing Power Parities (PPP) Benchmark Results. Table 1.12 PPP in national currencies per US dollar (United States = 1.00)*. http://stats.oecd.org/Index.aspx?DataSetCode=PPP2005. Accessed October 4, 2011.

Odum, H.T., 1996. *Environmental accounting: Emergy and environmental decision making*. First ed., John Wiley, New York, p. 370.

Odum, H.T., 2000. *Handbook of Emergy Evaluation. Folio #2. Emergy of Global Processes*. http://www.emergysystems.org/downloads/Folios/Folio_2.pdf. Accessed September 14, 2010.

Perkins, A., Hamnett, S., Pullen, S., Zito, R., Trebilcock, D., 2009. *Transport, Housing and Urban Form: The Life Cycle Energy Consumption and Emissions of City Centre Apartments Compared with Suburban Dwellings*. Urban Policy and Research 27 (4), p. 377-396.

Pullen, S.F., 2000. *Energy used in the construction and operation of houses*. Architectural Science Review 43 (2), p. 87-94.

Pulselli, R.M., 2010. *Integrating emergy evaluation and geographic information systems for monitoring resource use in the Abruzzo region (Italy)*. Journal of Environmental Management 91 (11), p. 2349-2357.

Pulselli, R.M., Simoncini, E., Ridolfi, R., Bastianoni, S., 2008. *Specific emergy of cement and concrete: an energy-based appraisal of building materials and their transport*. Ecological Indicators 8 (5), p. 647-656.

Purenne, P., 2007. Rapport annuel 2005. *Analyse de la qualité des eaux brutes et de l'eau traitée à la Station d'épuration et évaluation du rendement des installations (Annual report 2005. Analysis of the quality of raw and treated water at the treatment plant and evaluation of the facilities' performance)*, p. 55.

Rees, W., Wackernagel, M., 1996. *Urban ecological footprints: why cities cannot be sustainable - and why they are a key to sustainability*. Environmental Impact Assessment Review 16 (4-6), p 223-248.

Rickwood, P., Glazebrook, G., Searle, G., 2008. *Urban Structure and Energy - A Review*. Urban Policy and Research 26 (1), p. 57-81.

Safirova, E., Houde, S., Harrington, W., 2007. Spatial development and energy consumption. Resources For The Future. Discussion paper, p. 47.

Sahely, H.R., Dudding, S., Kennedy, C.A., 2003. *Estimating the urban metabolism of Canadian cities: Greater Toronto Area Case Study*. Canadian Journal of Civil Engineering 30 (2), p. 468-483.

Schreyer, P., Koechlin F., 2002. *Purchasing power parities – measurement and uses*. Statistics Brief OECD, No. 3, March 2002, p. 8.

Sciubba, E., Bastianoni, S., Tiezzi, E., 2008. *Exergy and extended exergy accounting of very large complex systems with an application to the province of Siena, Italy*. Journal of Environmental Management 86 (2), p. 372-382.

Sciubba, E., Ulgiati, S., 2005. *Emergy and exergy analyses: Complementary methods or irreducible ideological opinions?* Energy 30 (10), p. 1953-1988.

Statistics Canada, 2006. *Food Statistics 2005*, p. 46.

Steemers, K., 2003. *Energy and the city: density, buildings and transport*. Energy and Buildings 35 (1), p. 3-14.

Treolar, G.J., Love, P.E.D., Holt, G.D., 2001. *Using national input-output data for embodied energy analysis of individual residential buildings*. Construction Management and Economics 19 (1), p. 49-61.

Ulgiati, S., Brown, M.T., Bastianoni, S., Marchettini, N., 1995. *Emergy-based indices and ratios to evaluate the sustainable use of resources*. Ecological Engineering 5 (4), p. 519-531.

Ulgiati, S., Odum, H.T., Bastianoni, S., 1994. *Emergy use, environmental loading and sustainability. An emergy analysis of Italy*. Ecological Modelling 73 (3-4), p. 215-268.

United Nations Human Settlements Programme (UN-HABITAT), 2011. Cities and Climate Change: Global Report on Human Settlements 2011. 1st ed. United Kingdom; United States of America: Earthscan Publications Ltd, p. 279.

United Nations Human Settlements Programme (UN-HABITAT), 2006. *State of the World's Cities 2006/2007*. 1st ed. United Kingdom; United States of America: Earthscan Publications Ltd, p. 202.

Wolman, A., 1965. *The metabolism of cities*. Scientific American 213 (3), p. 179-190.

Zhang, Y., Singh, S., Bakshi, B.R., 2010. *Accounting for Ecosystem Services in Life Cycle Assessment, Part I: A Critical Review*. Environmental Science and Technology 44 (7), p. 2232-2242.

Zhang, Y., Yang, Z., Liu, G., Yu, X., 2011. *Emergy analysis of the urban metabolism of Beijing*. Ecological Modelling 222 (14), p. 2377-2384.

Zhang, Y., Zhao, Y.W., Yang, Z.F., Chen, B., Chen, G.Q., 2009. *Measurement and evaluation of the metabolic capacity of an urban ecosystem*. Communications in Nonlinear Science and Numerical Simulation 14 (4), p. 1758-1765.

CHAPTER 3

EMERGY EVALUATION OF THE ENVIRONMENTAL SUPPORT OF RESIDENTIAL UNITS IN THE ISLAND OF MONTREAL, CANADA

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Abstract

The sustainability of cities, in general, and the environmental implications of the high resource consumption in households, in particular, are growing concerns related to urban regions. Suitable urban planning is an essential tool to help in the task and, for that, an important aspect to consider is the influence of the urban form (density, house typology, distance to downtown, etc.) on the intensity of resource utilization. Emergy analysis, an energetic methodological approach that allows the integration of natural and human flows interacting in urban environments, was used to evaluate five typical present-day housing units in the Island of Montreal. The main flows considered were: natural resources, food, water, acquired products and services, electricity, fuels, materials in the structure of buildings, municipal solid wastes and wastewater. As expected, total emergy used was positively correlated to the size of the residential units both with respect to the number of occupants and to the size of the dwellings. Results suggest that variables affecting markedly the intensity of emergy utilization are per household income and per capita habitable space and, while a higher income increased per capita emergy in all cases, increasing the availability of space per resident did not result in a decrease of empower density after 50

m^2/person. Future work should consider residential units with lower and higher densities and levels of aggregation at the scale of urban planning zones.

Keywords. Residential unit; Urban form; Resource utilization; Emergy synthesis; Emergy-based performance.

3.1 Introduction

One of every two persons in the world lives in a city since 2007; at present, about one of every three city-dwellers lives in a slum and current trends indicate that the number of urban residents will continue to increase to more than 60% of total world population by 2030 (UN-HABITAT, 2011). Among the main local level to global scale environmental problems related to urban growth, often also associated to inadequate planning, are decline in agricultural and forest land, drying out of marshes, extraction of construction materials in large quantities, pollution of water courses by untreated wastewater, air pollution and large emissions of greenhouse gases from motor vehicles and industries (UNEP, 2002; UN-HABITAT, 2008), hence, the evolution and development of cities has become a growing concern.

High resource utilization is a common feature of modern day cities that must be addressed. For instance, operation of buildings in urban areas requires a substantial fraction of the energy used in the world, reaching up to 50, 41 and 36% in the United Kingdom, the European Union and the United States, respectively, on a national basis (Steemers, 2003), and fractions corresponding to the transport and industry sectors should also be added. Likewise, domestic consumption from households is a major source of carbon emissions in urban areas, along with the industry and urban agricultural sectors (Chen and Chen, 2012). An important aspect to take into account is the knowledge of the influence of the urban form, which is a key issue to better inform planning decisions on future development of urban areas with less environmental burden (Perkins et al., 2009), e.g., densely populated cities use less energy from transport per person than cities with low density, even though the debate

continues on the causal mechanisms involved (Rickwood et al., 2008). For the housing sector, the concepts of urban form involve spatial distribution of the dwellings, housing typology (Bramley and Power, 2009; Perkins et al., 2009) and other aspects related to the urban macro structure, such as distance to central business districts (CMHC, 2000).

For their part, material flow accounting (Decker et al., 2000; Hendricks et al., 2000), ecological footprint (Muñiz and Galindo, 2005; Rees and Wackernagel, 1996), and energetic life cycle analysis (Norman et al., 2006; Perkins et al., 2009; Treloar et al., 2001) are widely used methods to account for the flows interacting in urban environments. Emergy synthesis is part of the energy 'family' of methodologies, but it additionally provides a way to incorporate in the same base of comparison natural flows and other flows, such as currency and labor, through a common unit of measure, the solar emergy joule (seJ), that takes into consideration the 'free' work that the environment carries out and the quality of the used resources: "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 has proved to be an interesting methodology to evaluate and compare sustainability of cities, since it integrates the different types of flows that interact in urban ecosystems (Ascione et al., 2011). This work resorted to emergy synthesis as the analysis was intended from a deep sustainability perspective (Kennedy et al., 2011), emphasizing the environmental support that provides the resource flows sustaining the operation a housing unit (Sciubba and Ulgiati, 2005). Few emergy evaluations, with a rather accentuated building materials and/or energy performance-based approach, have been conducted at the scale of a building (Brown and Buranakarn, 2003; Pulselli et al., 2007) and at the scale of a residential unit, although the latter were carried out either from a generic perspective, since this point was not the central issue of the study (Brown and Vivas, 2005), or in housing units so large that might be considered small cities by their own (Li and Wang, 2009).

In this context, the environmental sustainability of five residential units in the Island of Montreal, located in the southeastern part of Canada (45°30' N, 73°30' W), from the viewpoint of the environmental support required for their day by day running, was evaluated.

In 2011, the Island had a population density of around 3900 persons by square kilometer (ISQ, 2012). The city has a diversified economy based on a consolidated industrial sector and on the growing services, technology and knowledge sectors, being an important part of the industrial and commercial region of eastern North America (City of Montreal, 2011a). The Island has an average net residential density (total number of dwellings divided by lot area, without including roads and public and institutional related infrastructure) of 38.5 dwellings per hectare (dw/ha), rising to more than 120 dw/ha in some districts of the city center, while to the west of the island, districts present usual densities of suburban residential areas, with values of less than 16 dw/ha (CMM, 2011). The general objective of the present work was to assess the environmental performance of typical present-day residential units in the Island of Montreal through the analysis of their material, energetic and economic flows, using the emergy method, to explore the applicability of emergy-based indicators to guidelines for urban planning, such as housing density and other related occupation parameters.

3.2 Material and methods

According to Odum's idea of energy hierarchy, in which all energy transformations can be arranged in a hierarchy from sunlight to electrical power (requiring many joules of the first one to obtain a joule of the latter), a central concept is the unit emergy value, the amount of emergy needed to produce one unit of output (Brown and Ulgiati, 2004a). Transformity, defined as the amount of seJ required to produce one joule of available energy at the output, is the most widely accepted unit emergy value, but other values such as specific emergy (expressed in seJ/g) and emergy per unit of currency (seJ/$), are also frequently used (Brown and Ulgiati, 2004b). From the unit emergy values of rain, wind, fossil fuels, minerals and so on, other natural and human-made products have been analyzed and many more unit values have been estimated, which in turn have been used in more detailed analyses of different kinds (Ascione et al., 2009; Brandt-Williams, 2001; Odum, 2000).

Usually, an emergy evaluation begins with the definition of the diagram of the studied system (Figure 3.1), including the main input and output flows of materials, energy, money etc.

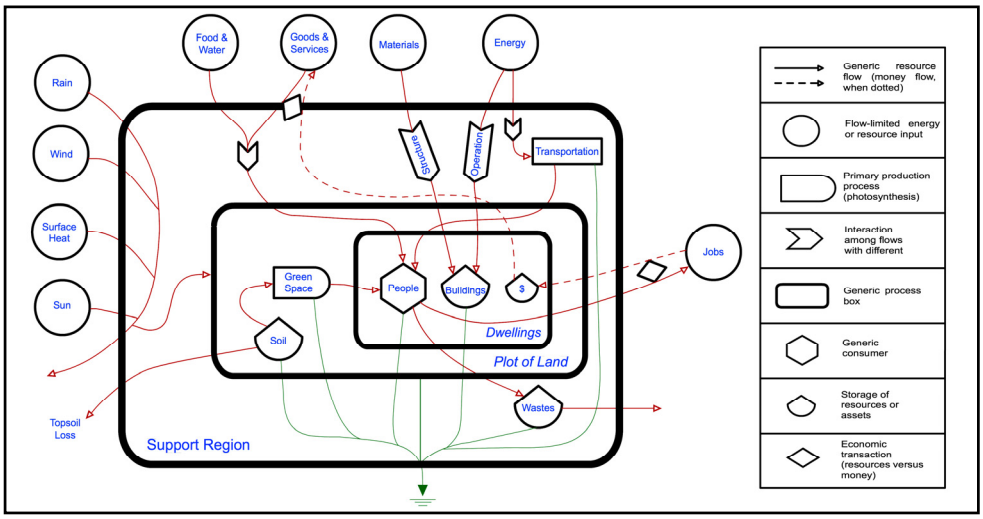

Figure 3.1 Diagram of the main flows considered in the analysis of the residential units
Adapted from Brown (2011, p. 3)

For the analysis of the housing units, the main flows considered were sunlight, kinetic energy from wind, evapotranspiration from rain, local topsoil loss, food, water, basic consumer items acquired, electricity, fuels, municipal solid wastes, wastewater and building materials in the structure. Although other materials present in dwellings, like non-structural materials and finishes, and related infrastructure, such as streets, sewers and other facilities, are important components contributing to total emergy used, they were not considered in this study because, unlike structural materials, they are present in similar proportions in virtually all cases, and maintenance and other constructive stages appear to have low significance (Norman et al., 2006) and, for its part, the structure may represent up to 80% of the bulk of a typical construction (Buckley et al., 2010).

After the formulation of the diagram, a table is integrated with the raw data to calculate the corresponding emergy flows (Table 3.1), which are obtained by multiplying the former by the appropriate unit emergy values (Brown and Ulgiati, 2004b).

Table 3.1 Emergy synthesis of material, energy and economic flows in the residential units (Outremont borough's case)

	Item	Quantity	Unit	Transformity (seJ/J,g,$)	Reference (transformity)	Emergy (seJ/year)
	Renewable resources (R)					
1	Solar radiation	5.96E+12	J/year	1.00	Odum, 1996	5.96E+12
2	Wind	4.80E+10	J/year	2.45E+03	Odum, 2000	3.92E+13
3	Rain (evapotranspiration)	2.54E+09	J/year	3.10E+04	Odum, 2000	2.88E+13
4	Surface heat flux	1.91E+09	J/year	1.07E+04	After Odum, 2000	2.04E+13
	Local non-renew. resources (N)					
5	Topsoil loss	1.13E+04	g/year	2.29E+09	Odum, 2000; Huang and Chen, 2005	2.59E+13
	Purchased resources (F)					
6	Cereals	4.63E+06	g/year	9.82E+08	Odum, 1996; Pulselli, 2010	4.55E+15
7	Fruits	4.14E+06	g/year	1.23E+09	Odum, 1996; Pulselli, 2010	5.08E+15
8	Vegetables	7.98E+06	g/year	5.96E+09	Odum, 1996; Brandt-Williams, 2001	4.75E+16
9	Meat	4.87E+06	g/year	3.17E+10	Brandt-Williams, 2001; Bastianoni et al., 2005	1.54E+17
10	Fish	4.84E+05	g/year	1.53E+11	Odum, 1996; Bastianoni et al., 2005	7.38E+16
11	Milk and other diaries	6.90E+06	g/year	2.41E+10	Odum, 1996; Brandt-Williams, 2001	1.66E+17
12	Eggs	5.46E+05	g/year	1.07E+11	Brandt-Williams, 2001	5.84E+16
13	Sugars and syrups	1.74E+06	g/year	1.55E+08	Brandt-Williams, 2001; Brown and Ulgiati, 2004b	2.70E+14
14	Potable water	8.26E+09	g/year	3.00E+06	Pulselli, 2010	2.48E+16
15	Natural gas	1.88E+12	J/year	4.00E+04	Bastianoni et al., 2009	7.52E+16
16	Electricity	4.70E+11	J/year	6.23E+04	Brown and Ulgiati, 2002	2.93E+16
17	Gasoline	8.89E+06	g/year	2.92E+09	Bastianoni et al., 2009	2.59E+16
18	Diesel	8.89E+05	g/year	2.83E+09	Bastianoni et al., 2009	2.52E+15
19	Electricity (transport)	1.01E+10	J/year	6.23E+04	Brown and Ulgiati, 2002	6.30E+14
20 a	Building structure (steel)	2.54E+06	g/year	3.27E+09	Campbell et al., 2005; Ascione et al., 2009	8.32E+15
20 b	Building structure (wood)	3.27E+06	g/year	6.48E+08	Campbell et al., 2005; Castellini et al., 2006	2.12E+15
21	Basic costumer items (spending)	3.05E+05	$/year	1.54E+12	Vega-Azamar et al., 2013	4.71E+17
	Wastes (W)					
22	Municipal solid wastes	5.81E+10	J/year	1.80E+06	Huang and Chen, 2005	1.05E+17
23	Wastewater	3.31E+10	J/year	6.66E+05	Huang and Chen, 2005	2.20E+16

Total emergy used (*U*) was calculated as the sum of the emergy from items 5 to 21 and the highest renewable emergy input among items 1 to 4 (Table 3.1), to avoid double counting (Campbell et al., 2005; Zhang et al., 2011). The global emergy budget (15.83×10^{24} seJ/year) used in this study was calculated from solar insolation, deep earth heat and tidal energy (Brown and Ulgiati, 2004b; Odum, 2000). Finally, from the aggregate emergy flows estimated (*R*, *N*, *F* and *W*), performance indices and indicators, which are dealt with in the discussion section, are calculated for their interpretation as a support in decision-making processes (Brown and Ulgiati, 1997).

3.3 Calculation and data used

Emergy-based indicators (Table 3.2) help to compare the performance of the considered housing units with an emphasis on the environmental support (estimated through the emergy from the used resources) needed for the daily running of the households. Based on the requirements for the estimation of these indicators, the appropriated data was selected and elaborated.

Table 3.2 Emergy-based indicators considered in the study cases

Indicator	Calculation	Unit	Indication
Per capita emergy (U_{cap})	*U*/number of residents in the residential unit	seJ/person·year	Standard of living
Empower per household (*EH*)	*U*/number of households in the residential unit	seJ/household·year	Quality of living
Empower density of the habitable area (ED_{Hab})	*U*/total habitable area in the residential unit	seJ/m^2·year	Intensity of resource utilization
Emergy to money ratio (*EMR*)	*U*/total income of the residential unit	seJ/USD	Ecological economic efficiency
Environmental loading ratio (*ELR*)	[N+F]/R	-	Balance non-renewable to renewable resources
Per capita support area (SA_{cap})	$([N+F]/[ELR*(R/\text{area})]_{\text{Montreal}})$/number of residents in the residential unit	m^2/person	Emergy-based ecological footprint
Emergy of wastes per household (*WH*)	*W*/number of households in the residential unit	seJ/household·year	Environmental loading

Five residential units, located in five different boroughs of the City of Montreal, were analyzed. The housing types of the units are four-storey apartment buildings, two and three-storey townhouses and three-storey plexes in the unit in the borough of Rosemont, four-storey multifamily building in Outremont, three-storey multifamily building in Plateau Mont-Royal (M-R), seven-storey multifamily building in Saint-Laurent and five-storey multifamily building in Saint-Leonard, with lot coverage ratios of 42, 80, 52, 28 and 50%, respectively (Leloup and Séraphin, 2009). Distance to downtown was considered as that of the straight line between the location of the residential units and the corner of two of the most significant streets in the business and commercial heart of the city and was estimated with the help of ArcView 3.3 GIS software. Table 3.3 shows the main attributes used in the analysis of the residential units, presented in ascending order of net density (number of dwellings divided by lot area).

Table 3.3 Main features of the residential units

Case	Net den. (dw/ha)	Lot Area (m^2)	Habitable Area (m^2)	Number of Dwellings	Number of Residents	Structure's material	Dist. to DT (km)
Rosemont	85	25579	24747	217	510	Concrete/wood	7.0
Outremont	171	1346	2671	23	48	Steel/wood	4.9
Plateau M-R	180	1995	3041	36	89	Wood	2.3
Saint-Laurent	271	3067	4904	83	208	Concrete	7.7
Saint-Leonard	323	1454	2749	47	94	Concrete	7.9

The year of study was 2008, however, some information came from sources of slightly different dates, such as the studies related to energy consumption in buildings, the electoral districts statistics profiles (in the City of Montreal, the average number of electoral districts by borough is three), given that all data were scaled down to the most detailed level of disaggregation possible as one of the highest priorities and challenges (Codoban and Kennedy, 2008), and natural resources data, owing to environmental inputs of regional systems are frequently calculated using long-term averages (Campbell et al., 2005). Also, unavailable data for the year of study, especially those belonging to monetary flows (all currency values are expressed in U.S. dollars), were brought to present value by applying price indexes (Norman et al., 2006; Statistics Canada, 2012). Table 3.4 shows the way in which data were processed and the main sources from which they came.

Table 3.4 Data elaboration and sources

Item	Elaboration	Sources
Natural resources	Long period averages	Davies and Davies (2010), Environment Canada (2011), NASA (2000)
Food	Per capita averages for urban regions adjusted by food spending in boroughs and electoral districts' per household income	City of Montreal (2012 and 2009), Statistics Canada (2009)
Water	Per capita treated drinking water adjusted by consumption by house type	City of Montreal (2011b), CMHC (2001)
Electricity and natural gas from house operations	Energy consumption by house type	Baouendi et al. (2005), CWC (2004), Liu (2007)
Fuels and electricity from transport	Split mode, average trip length, vehicle and public transport performance	AMT (2010), Codoban and Kennedy (2008), NRC-OEE (2007), Paez et al. (2010)
Building materials in the structure	Materials take-off estimation	American Society of Professional Estimators (2009 and 2010), Pulselli et al. (2006)
Basic consumer items	Household expenditure adjusted by electoral districts' per household income	City of Montreal (2012 and 2009)
Municipal solid wastes	Per capita generation of municipal solid wastes in boroughs	City of Montreal (2011c)
Wastewater	Treated wastewater adjusted by water consumption estimated for the units	City of Montreal (2011b), CMHC (2001), Purenne (2009)

3.4 Results

As expected, total emergy used (*U*) varied according to the size of the residential units, both with respect to the number of occupants and to the size of the buildings, and purchased emergy (*F*) was the dominant flow sustaining the housing units.

3.4.1 Aggregated emergy flows

Purchased (imported) emergy (*F*) averaged 99.99% of total emergy used, while renewable emergy (*R*), local non-renewable emergy (*N*) and emergy from wastes (*W*) averaged about 0.0074%, 0.0026% and 15.1% of *U*, respectively. Table 3.5 shows the main emergy flows calculated for the five cases (presented in ascending order of net density).

Table 3.5 Total emergy used (*U*) and aggregated emergy flows as percentage of total emergy used for the residential units

Case	*U* (x10^{18} seJ/yr)	Renewable (*R*)	Non-renew (*N*)	Purchased (*F*)	Wastes (*W*)
Rosemont	9.31	0.0171%	0.0053%	99.98%	16.70%
Outremont	1.15	0.0034%	0.0023%	99.99%	11.01%
Plateau M-R	1.47	0.0070%	0.0026%	99.99%	18.33%
Saint-Laurent	4.44	0.0035%	0.0013%	99.99%	12.42%
Saint-Leonard	1.75	0.0061%	0.0016%	99.99%	17.10%

R corresponded to the kinetic energy from wind for the housing unit in Outremont borough, where the lot coverage ratio was the highest (80%), and to the chemical potential of rain (evapotranspiration of the grass in green areas) for the rest of the cases, while *N* corresponded to topsoil loss for the construction of the housing units.

3.4.2 Purchased emergy and emergy from wastes

Comparisons among cases with different characteristics are usually carried out favoring the utilization of intensity indicators (e.g. values per unit area or per capita parameters) instead of

total quantities to attenuate such differences (Ascione et al., 2009). In this work, the emergy requirements was considered on a per occupant basis and on a per unit area of habitable space basis, in both cases, higher values of U_{cap} and ED_{Hab} indicating higher intensity of resource consumption and/or utilization. Figure 3.2 shows the itemized flows that were analyzed in the five residential units.

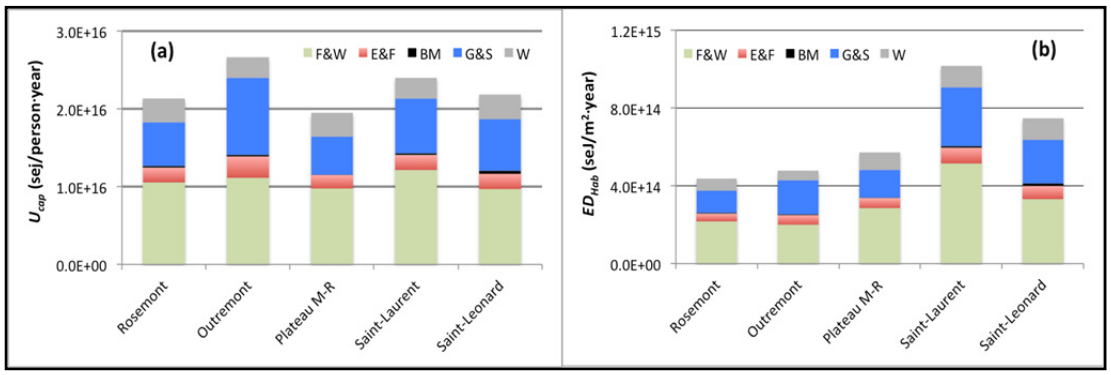

Figure 3.2 Emergy requirements of the five residential units: (a) on a per capita basis, and (b) per square meter of habitable space [F&W: food and water; E&F: electricity and fuels; BM: building materials in the structure; G&S: basic goods and services acquired; W: wastes]

Emergy from food and water averaged 54% of U in the housing units; the units in Saint-Laurent and in Saint-Leonard presented the largest and smallest per resident uses (12100×10^{12} and 9700×10^{12} seJ/person·year, respectively) and the units in Saint-Laurent and in Outremont showed the highest and lowest per square meter consumption values (515×10^{12} and 200×10^{12} seJ/m^2·year, respectively).

Emergy from basic goods and services averaged nearly 34% of U in the housing units; Outremont exhibited the highest per capita use (9800×10^{12} seJ/person·year) and Plateau M-R the lowest (4900×10^{12} seJ/person·year) and Saint-Laurent and Rosemont showed the largest and smallest per square meter uses (300×10^{12} and 115×10^{12} seJ/m^2·year, respectively).

In all five cases, emergy from electricity and fuels, for both the operation of the dwellings and the transport of the residents, ranged around 10% of U in the housing units; Outremont presented the highest per occupant use (2780×10^{12} seJ/person·year) and Plateau M-R the

lowest ($1750x10^{12}$ seJ/person·year), while, once again, Saint-Laurent and Rosemont exhibited the largest and smallest per square meter uses ($81x10^{12}$ and $39x10^{12}$ seJ/m^2·year, respectively).

As mentioned above (Table 3.5), the highest percentage of emergy from generated wastes corresponded to the unit in Plateau M-R; the highest per resident emergy from wastes corresponded to the unit in Saint-Leonard ($3190x10^{12}$ seJ/person·year) and the highest per floor area value corresponded to that in Saint-Laurent ($113x10^{12}$ seJ/m^2·year), while the lowest per capita amount corresponded to the unit in Saint-Laurent ($2650x10^{12}$ seJ/person·year) and the lowest per square meter of habitable area value corresponded to that in Outremont ($47x10^{12}$ seJ/m^2·year).

The contribution of the structural components of the buildings was no significant in terms of emergy utilization when compared to the other analyzed flows; it only averaged 1.2% of *U* in the housing units. The highest percentage corresponded to the unit in Saint-Leonard (2%), which structure is made out of concrete, and the lowest to that in Plateau M-R (0.3%), which structure is made out of wood. This trend did not vary when the basis of comparison was changed (per capita or per square meter) and, when concrete and steel were combined with wood (Rosemont and Outremont, respectively), emergy from the structure decreased markedly. Finally, Table 3.6 summarizes the main indicators estimated from the above-mentioned emergy flows (U_{cap} in seJ/person·year, *EH* and *WH* in seJ/household·year, ED_{Hab} in seJ/m^2·year, *EMR* in seJ/USD, *ELR* is dimensionless and SA_{cap} in m^2/person·year).

Table 3.6 Emergy-based indicators calculated for the residential units

Case	U_{cap}	*EH*	ED_{Hab}	*EMR*	*ELR*	SA_{cap}	*WH*
Rosemont	1.83E+16	4.29E+16	3.76E+14	1.07E+12	5864	81.58	7.16E+15
Outremont	2.40E+16	5.00E+16	4.31E+14	6.48E+11	29321	107.13	5.51E+15
Plateau M-R	1.65E+16	4.07E+16	4.82E+14	1.03E+12	14317	73.68	7.47E+15
Saint-Laurent	2.14E+16	5.35E+16	9.06E+14	8.75E+11	28913	95.49	6.65E+15
Saint-Leonard	1.87E+16	3.73E+16	6.38E+14	9.03E+11	16431	83.39	6.38E+15

3.5 Discussion

3.5.1 Density and distance to downtown and emergy from electricity and fuels

One of the main aspects defining urban form is density of occupation, expressed through the number of dwellings per unit area, which is why many studies consider this parameter among the variables to analyze (Bramley and Power, 2009). In this regard, net density of the residential units did not seem to influence the per capita emergy use corresponding to electricity and fuels for the operation of the dwellings and for the transport of the residents, while it appeared to slightly affect the per square meter use (Figure 3.3), which confirms that, when normalizing the emergy flows, the choice of a per capita basis or per unit area is important to interpret the overall effects (Norman et al., 2006).

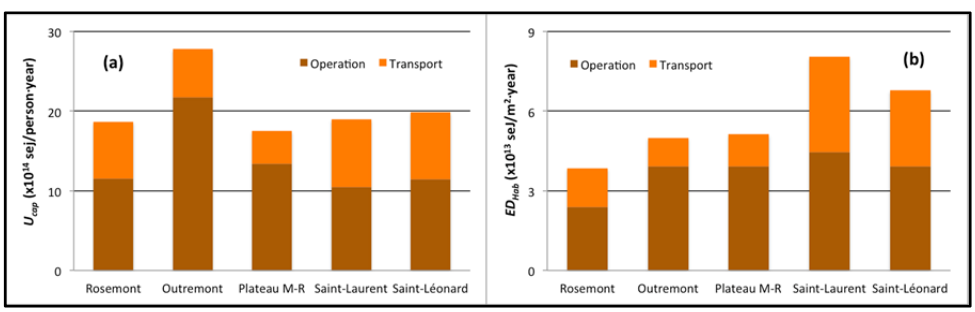

Figure 3.3 Emergy from dwellings operation and from dwellers transport: (a) on a per capita basis, and (b) by square meter of habitable area

With regard to the emergy required for the operation of the housing units, with the exception of the unit in Outremont, the outcomes on a per capita basis contrast with findings of life cycle energy consumption studies in which energy utilization from buildings operations in low-density areas are approximately from 1.5 times to twice of that of high-density areas, although per unit area they do not differ or the differences are small (Norman et al., 2006; Perkins et al., 2009). This may be attributed to the particular characteristics of the residential units (mainly, the selected densities, the house types and the number of occupants per dwelling) and to differences in the transformities of the 'mixing' of fuels and electricity (in Montreal its origin is hydraulic) considered in the present work.

As expected, emergy from fuels and electricity for the transport of residents is more influenced by the distance to the city center rather than other variables like density (Figure 3.3), similar to other studies suggesting that distance to central districts is more important than variables such as housing typology and density and road layout (CMCH, 2000). The units in Saint-Laurent and Saint-Leonard exhibit the highest values both on a per capita basis and per square meter of built-up area; both are the furthest away from downtown (Table 3.3) and have the highest percentage of car use, 66.5% and 65.7% respectively (AMT, 2010). The relatively high and low consumption of the units in Rosemont and Plateau Mont-Royal may also be explained by the combination of distance to downtown and automobile mode split (48.1% and 33% respectively).

3.5.2 Per household income and available space per person

Empower per household may be an indicator of living quality in housing areas (Li and Wang, 2009) and, in the same way, per capita emergy may also be an indirect indicator of standard of living. For this reason, it was explored whether an equivalent economic indicator at the 'micro' level, per household income, could be related to per capita emergy consumption and to empower per household, expecting that higher household incomes corresponded to higher U_{cap} and EH. This general trend was found, although more markedly for the two units with higher incomes, since the other three units have nearly equal incomes (Figure 3.4a).

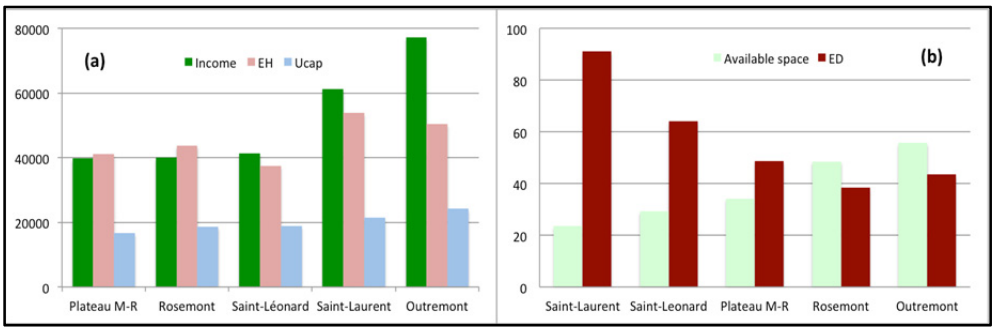

Figure 3.4 (a) Per household income (USD/year), empower per household (x10^{12} seJ/household·year) and per capita emergy (x10^{12} seJ/person·year), and (b) Per capita available space (m^2/person) and empower density of the habitable space (x10^{13} seJ/m^2·year)

It was also observed that increasing the available space per resident, which occurs frequently as a result of the decrease of both housing density and accommodation of occupants by dwelling, decreases the intensity of emergy utilization, measured as empower density of the living space, but up to some point: from around more than 50 m^2/person, increasing the availability of space per occupant did not result in a decrease of ED_{Hab} (Figure 3.4b). Empower density is the total emergy used in a given area (in this case, the habitable area) per unit time, it is an indicator of the intensity of utilization of resources with high values for industrial activities and urban centers (Brown and Ulgiati, 2001) and it also may denote the scarcity of available land or the need of support land (Ascione et al., 2009). U_{cap}, *EH* and ED_{Hab} besides indicating both welfare and intensity of resource utilization, may also denote 'abuse' of resource consumption, depending on the origin of the emergy flows.

3.5.3 Emergy-based performance

As mentioned in Table 2, *ELR* is the ratio of non-renewable and purchased emergy to renewable emergy, it evaluates the balance between non-renewable and renewable resources, so the higher its value, the less sustainable the system under study (Brown and Ulgiati, 2001). On the other hand, *EMR* besides indicating the capacity of money to buy emergy (Zhang et al., 2011), may be an indicator of ecological economic efficiency when regions are compared, with lower values of *EMR* corresponding to higher levels of emergy use efficiency (Cai et al., 2009). For its part, carrying capacity may be estimated by means of the area (*SA*) required to obtain enough inputs to fulfill the emergy requirements of a given population, in this case that of the analyzed residential units, within a local economic and environmental system, in this case the Island of Montreal, based on the intensity of development of the system, specifically through its *ELR* (Brown and Ulgiati, 2001).

With respect to these indicators, given that for each one lower values correspond to better executions, in addition to their individual values, in Figure 3.5, the combined performance of the three indicators may be observed by considering the accumulated area of the three bars of each housing unit. Rosemont has the lowest *ELR*, which may be explained by the

contribution of renewable resources coming from the green areas (second lowest lot coverage ratio) and by the proportion of habitable area to lot area (the lowest). Outremont presents the lowest *EMR*, which seems to happen because its high level of income results also in a high emergy consumption rate. The relatively low per capita and per household emergy consumption of Plateau Mont-Royal is reflected in a smaller need of support area per resident. The best-combined performances corresponded to Rosemont and Plateau Mont-Royal, followed by Saint-Leonard.

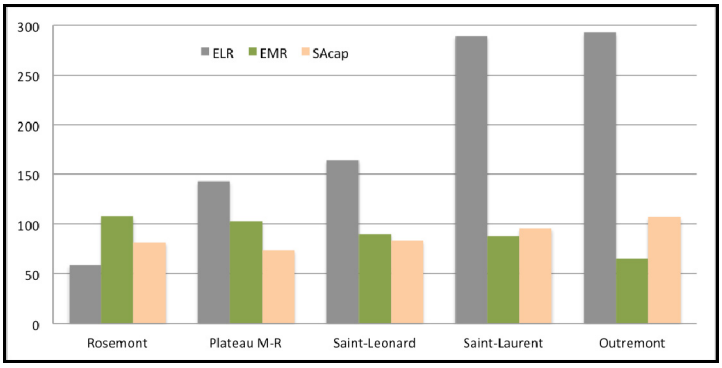

Figure 3.5 Environmental loading ratio (x10^2, dimensionless), emergy to money ratio (x10^{10} seJ/USD) and per capita support area (m^2/person·year) for the five residential units

As mentioned above, per household empower may inform on living quality in housing areas. For its part, emergy from the wastes generated in the housing units, in the present study both municipal solid wastes and wastewater, divided by the total number of households in each unit is an indicator of their environmental load. In the first case, high values correspond to higher availability of resources, whereas in the latter, high values indicate greater impacts.

In Figure 3.6, the ratios *EH* to *WH* obtained for the residential units are plotted. This ratio may assist for assigning a ranking of sustainability (in this case, of the analyzed units' waste generation performance on a per household base); in the graphic, a higher slope indicates a larger proportion of acquired commodities and services to generated pollutants (Li and Wang, 2009). In the studied units, the ranking, in descending order, was: Outremont, Saint-Laurent, Rosemont, Saint-Leonard and Plateau Mont-Royal, mainly due to the fact that the

higher incomes of Outremont and Saint-Laurent, which give them greater ability to acquire emergy, do not seem to translate into a markedly greater amount of per household emergy from wastes.

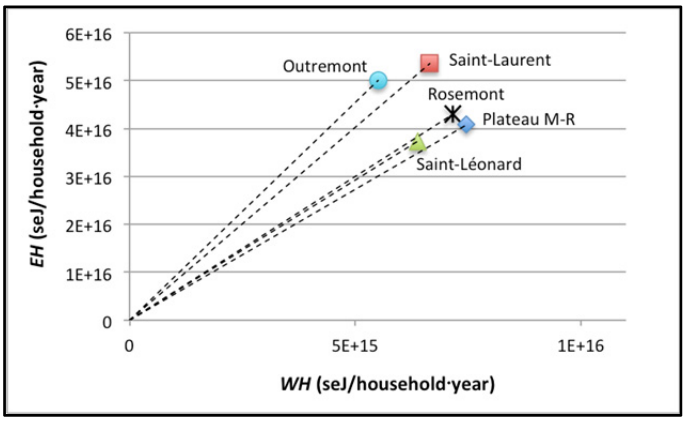

Figure 3.6 Empower per household and emergy from wastes per household

3.6 Conclusions

As expected, total emergy used, and the associated total emergy-based ecological footprint, is a function of the size of housing units both with respect to the number of occupants and to the size of the buildings.

For all the itemized flows analyzed, with the exception of wastes and building materials in the structure, the highest per capita emergy consumptions corresponded to the housing units with the highest per household incomes. Also, the highest emergy consumption per unit floor area always corresponded to the dwelling unit with the smallest available space per person, and the lowest emergy utilizations per square meter of habitable area corresponded to the units with the lowest net housing densities. The contribution of these flows to total emergy use, in descending order, was: food and water, goods and services, and electricity and fuels.

With regard to emergy from wastes, on a per capita basis, greater amounts generated coincided with lower per household incomes in the analyzed residential units. This trend was

confirmed when the ratio per household emergy from wastes to empower per household was examined; the best efficiencies were found for high-income housing units. In turn, the unit that generated the lowest emergy from wastes per unit floor area was the one with the highest available space per person.

Although the contribution of the structural components of the analyzed buildings was no significant in terms of emergy utilization, it was found that concrete was the material with the highest emergy by square meter of constructed area, despite having an intermediate transformity (when compared to wood and steel). Notably, when concrete and steel were combined with wood, emergy from the structure decreased, confirming the suitability of using environmentally sound building materials.

The residential units that presented the best simultaneous emergy-based performances were the ones in the boroughs of Rosemont and Plateau Mont-Royal. The first one combined moderate U_{cap}, SA_{cap} and *EH-WH* ratio, the lowest ED_{Hab} and *ELR*, but also the highest *EMR*. This may be due to a relatively high habitable space per dweller, to the floor area to lot area ratio and the lot coverage percentage with the related greater contribution of renewable flows (green spaces), to the variety of the housing types and the relatively low density, and to a moderate level of income that translates into a limited ability to acquire emergy but also into a relatively low economic-emergetic efficiency at the same time. The latter combined the lowest U_{cap} and SA_{cap}, moderate *EH-WH* ratio, ED_{Hab} and *ELR*, but also a relatively high *EMR*. This may be attributed to its low per capita and per household emergy consumption, among other aspects.

The results suggest that, from the variables considered, the most important ones affecting the intensity of emergy utilization are per household income, per capita habitable space and, to a lesser extent, distance to downtown. In the analyzed residential units, while access to a higher level of income increased per capita emergy in all cases, increasing the availability of space per occupant did not result in a decrease of empower density after 50 square meters per person.

Finally, it will be very important to examine more cases to confirm or discard the apparent trends found in this work, including residential units with lower and higher densities of occupation than those considered here. From a wider perspective, future work should consider levels of aggregation at the scale of urban planning unities (urban zoning, boroughs, districts or even neighborhoods).

3.7 References

Agence métropolitaine de transport (AMT), 2010. *Mobilité des personnes dans la région de Montréal Enquête Origine-Destination 2008, version 08.2a (Mobility of people in the Montreal area Origin-Destination Survey 2008, version 08.2a)*. (Data processing: Ricardo Vega.) http://www.enquete-od.qc.ca/docs/EnqOD08_Mobilite.pdf [in French]. Accessed March 21, 2012.

Ascione, M., Bargigli, S., Campanella, L., Ulgiati, S., 2011. *Exploring an urban system's dependence on the environment as a source and a sink: the city of Rome (Italy) across space and time scales*. ChemSusChem 4 (5), p. 613-627.

Ascione, M., Campanella, L., Cherubini, F., Ulgiati, S., 2009. *Environmental driving forces of urban growth and development. An emergy-based assessment of the city of Rome, Italy*. Landscape and Urban Planning 93 (3-4), p. 238-249.

Baouendi, R., Zmeureanu, R., Bradley, B., 2005. *Energy and emission estimator: A prototype tool for designing canadian houses*. Journal of Architectural Engineering 11 (2), p. 50-59.

Bastianoni, S., Campbell, D.E., Ridolfi, R., Pulselli, F.M., 2009. *The solar transformity of petroleum fuels*. Ecological Modelling 220(1), p. 40-50.

Bastianoni, S., Marchettini, N., Niccolucci, V., Pulselli, F.M., 2005. *Environmental accounting for the lagoon of Venice and the case of fishing*. Annali di Chimica 95 (3-4), p. 143-152.

Bonenfant, R.R. Jr. 2009. *How to estimate the cost of structural steel*. American Society of Professional Estimators' Technical Paper. Estimating Today, January 2009, p. 15-22.

Bramley, G., Power, S., 2009. *Urban form and social sustainability: the role of density and housing type*. Environment and Planning B: Planning and Design 36 (1), p. 30-48.

Brandt-Williams, S.L., 2001. *Handbook of Emergy Evaluation. Folio #4. Emergy of Florida Agriculture*. http://www.emergysystems.org/downloads/Folios/Folio_4.pdf. Accessed September 14, 2010.

Brown, M.T., 2011. *Sample system diagrams of ecosystems and regional systems*. http://www.emergysystems.org/downloads/System_DIAGRAM.zip. Accessed Sept. 22, 2011.

Brown, M.T., Buranakarn, V., 2003. *Emergy indices and ratios for sustainable material cycles and recycle options*. Resources, Conservation and Recycling 38 (1), p. 1-22.

Brown, M.T., Ulgiati, S., 2004a. *Energy quality, emergy and transformity: H. T. Odum's contributions to quantifying and understanding systems*. Ecological Engineering 178 (1-2), p. 201-213.

Brown, M.T., Ulgiati, S., 2004b. *Emergy analysis and environmental accounting* in: Cleveland, C. J. (Eds.), Encyclopedia of Energy, Elsevier Academic, Oxford, p. 329-354.

Brown, M.T., Ulgiati, S., 2002. *Emergy evaluations and environmental loading of electricity production systems*. Journal of Cleaner Production 10 (4), p. 321-334.

Brown, M.T., Ulgiati, S., 2001. *Emergy measures of carrying capacity to evaluate economic investments*. Population and Environment 22 (5), p. 471-501.

Brown, M.T., Ulgiati, S., 1997. *Emergy-based indices and ratios to evaluate sustainability: monitoring economies and technology towards environmentally sound innovation*. Ecological Engineering 9 (1-2), p. 51-69.

Brown, M. T., Vivas, B., 2005. *Landscape development intensity index*. Environmental Monitoring and Assessment 101 (1-3), p. 289-309.

Buckley, M., Halsall, R., Vollering, B., Webber, D., 2010. *Considering sustainability in the selection of structural systems*. Halsall Associates Limited. Toronto, p. 9.

Cai, Z.F., Zhang, L.X., Zhang, B., Chen, Z.M., 2009. *Emergy-based analysis of Beijing-Tianjin-Tangshan region in China*. Communications in Nonlinear Science and Numerical Simulation 14 (12), p. 4319-4331.

Campbell, D.E., Brandt-Williams, S.L., Meisch, M.E.A., 2005. *Environmental accounting using emergy: Evaluation of the State of West Virginia*. http://www.epa.gov/nheerl/publications/files/wvevaluationposted.pdf. Accessed September 29, 2010.

Canada Mortgage and Housing Corporation (CMHC), 2001. *Analysis of the annual energy and water consumption of apartment buildings in the CMHC HiSTAR Database*. Research Highlight, p. 4.

Canada Mortgage and Housing Corporation (CMHC), 2000. *Greenhouse gas emissions from urban travel: tool for evaluating neighbourhood sustainability*. Research Report, p. 60.

Canadian Wood Council (CWC), 2004. *Energy and the Environment in Residential Construction*. Sustainable Building Series No. 1, p. 15.

Castellini, C., Bastianoni, S., Granai, C., Dal Bosco, A., Brunetti, M., 2006. *Sustainability of poultry production using the emergy approach: comparison of conventional and organic rearing systems*. Agriculture, Ecosystems and Environment 114 (2-4), p. 343-350.

Chen, S., Chen, B., 2012. *Network environ perspective for urban metabolism and carbon emissions: A case study of Vienna, Austria*. Environmental Science and Technology 46 (8), p. 4498-4506.

City of Montreal, 2011a. *The Montreal economy*. http://www.montreal2025.com/decouvrir_economie.php?lang=en. Accessed October 27, 2011.

City of Montreal, 2011b. Eau potable traitée, agglomération de Montréal, moyenne annuelle (Treated drinking water, Agglomeration of Montreal, annual average). http://ville.montreal.qc.ca/portal/page?_pageid=6897,67889708&_dad=portal&_schema=PORTAL [in French]. Accessed March 29, 2011.

City of Montreal, 2011c. *Portrait 2010 des matières résiduelles de l'agglomération de Montréal (2010 Portrait of municipal solid wastes of the Montreal Agglomeration)*, p. 52.

City of Montreal, 2009. *Profils des 58 districts électoraux de la ville de Montréal. Édition 2009 (City of Montreal's 58 Electoral Districts Profiles. 2009 Edition)*, p. 136.

Codoban, N., Kennedy, C. A., 2008. *Metabolism of neighborhoods*. Journal of Urban Planning and Development 134 (1), p. 21-31.

Communauté Métropolitaine de Montréal (CMM), 2011. Les forms d'habitat et la planification des densités résidentielles (Housing types and planning of residential densities), p. 24.

Davies, J. H., Davies, D. R., 2010. *Earth's surface heat flux*. Solid Earth, vol. 1, p. 15-24.

Decker, E.H., Elliott, S., Smith, F.A., Blake, D.R., Rowland, F.S., 2000. *Energy and material flow through the urban ecosystem*. Annual Review of Energy and the Environment 25, p. 685-740.

Environment Canada, 2011. *Canadian climate normals or averages 1971-2000. Montreal Pierre Elliot Trudeau international airport station*. http://climate.weatheroffice.gc.ca/climate_normals/results_e.html?stnID=5415&lang=e&dCode=1&StationName=MONTREAL&SearchType=Contains&province=ALL&provBut=&month1=0&month2=12. Accessed November 22, 2011.

Farnsworth, E. 2010. *How to estimate the cost of a timber framed structure*. American Society of Professional Estimators. Technical Paper. Estimating Today, December 2010, p. 6.

Hendriks, C., Obernosterer, R., Müller, D., Kytzia, S., Baccini, P., Brunner, P.H., 2000. *Material Flow Analysis: A tool to support environmental policy decision making. Case studies on the city of Vienna and the Swiss lowlands*. Local Environment 5 (3), p. 311-328.

Hermanowicz, S.W., Asano, T., 1999. *Abel Wolman's the metabolism of cities revisited: A case for water recycling and reuse*. Water Science and Technology 40 (4-5), p. 29-36.

Huang, S.-L., Chen, C.-W., 2005. *Theory of urban energetics and mechanisms of urban development*. Ecological Modelling 189 (1-2), p. 49-71.

Institute of Statistics of Quebec (ISQ), 2012. *Bulletin statistique régional Montréal, Édition 2012 (Montreal Regional Statistical Bulletin, 2012 Edition)*, p. 27.

Kennedy, C., Cuddihy, J., Engel-Yan, J., 2007. *The changing metabolism of cities*. Journal of Industrial Ecology 11 (2), p. 43-59.

Kennedy, C., Pincetl, S., Bunje, P., 2011. *The study of urban metabolism and its applications to urban planning and design*. Environmental Pollution 159 (8-9), p. 1965-1973.

LEAD International, 2008. *Megacities and climate change. Sustainable urban living in a changing world*. First ed. LEAD International, London, p. 56.

Leloup, X., Séraphin, I., 2009. *Étude post occupation de projets résidentiels pour familles en milieu urbain dense (Post occupancy study of residential projects for families in dense urban environment)*. Institut National de la Recherche Scientifique (National Institute for Scientific Research), p. 120.

Li, D., Wang, R., 2009. *Hybrid Emergy-LCA (HEML) based metabolic evaluation of urban residential areas: the case of Beijing, China*. Ecological Complexity 6 (4), p. 484-493.

Liu, R., 2007. *Energy consumption and energy intensity in multi-unit residential buildings in Canada*. Canadian Building Energy End-Use Data and Analysis Center, p. 20.

Muñiz, I., Galindo, A., 2005. *Urban form and the ecological footprint of commuting. The case of Barcelona*. Ecological Economics 55(4), p. 499-514.

National Aeronautic and Space Administration (NASA), 2000. *Insolation Levels. Surface meteorology and Solar Energy Data Set* (taken from: Whitlock, Charles H., D. E. Brown, W. S. Chandler, R. C. DiPasquale, N. Meloche, G. J. Leng, S. K. Gupta, A. C. Wilber, N. A. Ritchey, A. B. Carlson, D. P. Kratz, et P. W. Stackhouse. 2000. Release 3 NASA Surface Meteorology and Solar Energy Data Set For Renewable Energy Industry Use. Proceedings of Rise and Shine 2000, the 26th Annual Conference of the Solar Energy Society of Canada Inc. and Solar, Oct. 21-24, 2000, Halifax, Nova Scotia, Canada).

Natural Resources Canada. Office of Energy Efficiency (NRC-OEE). 2007. *Fuel Consumption Guide 2008*, p. 65.

Nocus, S. F. 2009. *How to estimate the cost of load bearing wood framed walls.* American Society of Professional Estimators' Technical Paper. Estimating Today, April 2009, p. 11.

Norman, J., MacLean, H. L., Kennedy, C. A., 2006. *Comparing high and low residential density: life-cycle analysis of energy use and greenhouse gas emissions*. Journal of Urban Planning and Development 132 (1), p. 10-21.

Odum, H.T., 1996. *Environmental accounting: Emergy and environmental decision making*. First ed., John Wiley, New York, p. 370.

Odum, H.T., 2000. *Handbook of Emergy Evaluation. Folio #2. Emergy of Global Processes*. http://www.emergysystems.org/downloads/Folios/Folio_2.pdf. Accessed September 14, 2010.

Paez, A., Mercado, R. G., Farber, S., Morency, C., Roorda, M. 2010. *Accessibility to health care facilities in Montreal Island: an application of relative accessibility indicators from the perspective of senior and non-senior residents*. International Journal of Health Geographics, 2010, 9:52. DOI: 10.1186/1476-072X-9-52.

Perkins, A., Hamnett, S., Pullen, S., Zito, R., Trebilcock, D., 2009. *Transport, Housing and Urban Form: The Life Cycle Energy Consumption and Emissions of City Centre Apartments Compared with Suburban Dwellings*. Urban Policy and Research 27 (4), p. 377-396.

Pulselli, R.M., 2010. *Integrating emergy evaluation and geographic information systems for monitoring resource use in the Abruzzo region (Italy)*. Journal of Environmental Management 91 (11), p. 2349-2357.

Pulselli, R. M., Pulselli, F. M., Marchettini, N., Bastianoni, S. *2006. Environmental accounting of buildings: outcomes from the emergy analysis*. WIT Transactions on Ecology and the Environment 93 (The Sustainable City IV: Urban Regeneration and Sustainability), p. 489-498.

Pulselli, R. M., Simoncini, E., Pulselli, F. M., Bastianoni, S., 2007. *Emergy analysis of building manufacturing, maintenance and use: Em-building indices to evaluate housing sustainability*. Energy and Buildings 39 (5), p. 620-628.

Purenne, P., 2009. Rapport annuel 2008. *Analyse de la qualité des eaux brutes et de l'eau traitée à la Station d'épuration et évaluation du rendement des installations (Annual Report 2008. Analysis of the quality of raw and treated water at the treatment plant and evaluation of the facilities' performance)*, p. 58.

Rees, W., Wackernagel, M., 1996. *Urban ecological footprints: why cities cannot be sustainable - and why they are a key to sustainability*. Environmental Impact Assessment Review 16 (4-6), p. 223-248.

Rickwood, P., Glazebrook, G., Searle, G., 2008. *Urban Structure and Energy - A Review*. Urban Policy and Research 26 (1), p. 57-81.

Schlesier, B. E. 2010. *How to estimate the cost of concrete construction*. American Society of Professional Estimators' Technical Paper. Estimating Today, March 2010, p. 12.

Sciubba, E., Ulgiati, S., 2005. *Emergy and exergy analyses: Complementary methods or irreducible ideological opinions?* Energy 30(10), p. 1953-1988.

Statistics Canada, 2012. *Consumer Price Indexes, historical summary*. http://www.statcan.gc.ca/tables-tableaux/sum-som/l01/cst01/econ46a-eng.htm. Accessed July 12, 2012.

Statistics Canada, 2009. *Food Statistics 2008*, p. 42.

Steemers, K., 2003. *Energy and the city: density, buildings and transport*. Energy and Buildings 35 (1), p. 3-14.

Treolar, G.J., Love, P.E.D., Holt, G.D., 2001. *Using national input-output data for embodied energy analysis of individual residential buildings*. Construction Management and Economics 19 (1), p. 49-61.

United Nations Environment Programme (UNEP), 2002. *Global Environmental Outlook 3 (GEO-3)*. 1st ed. United Kingdom: Earthscan Publications Ltd., p. 446.

United Nations Human Settlements Programme (UN-HABITAT), *2011.Cities and Climate Change: Global Report on Human Settlements 2011*. 1st ed. United Kingdom; United States of America: Earthscan Publications Ltd, p. 279.

United Nations Human Settlements Programme (UN-HABITAT), 2008. *State of World Cities 2008/2009, Harmonious cities*. 1st ed. United Kingdom ; United States of America: Earthscan Publications Ltd., p. 259.

Vega-Azamar, R.E., Glaus, M., Hausler, R., Oropeza-García. N.A., Romero-López, R., 2013. *An emergy analysis for urban environmental sustainability assessment, the Island of Montreal, Canada*. Landscape and Urban Planning 118, p. 18-28.

Zhang, Y., Yang, Z., Liu, G., Yu, X., 2011. *Emergy analysis of the urban metabolism of Beijing*. Ecological Modelling 222(14), p. 2377-2384.

CHAPTER 4

EMERGY-BASED PERFORMANCE OF THE RESIDENTIAL LAND USE IN SEVEN BOROUGHS OF THE ISLAND OF MONTREAL, CANADA

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Abstract

High resource utilization in the residential sector, and the associated environmental impacts, are central issues in the growth of urban regions. Land-use urban planning is a primary instrument for the proper development of cities; for better supporting it, an important point is the consideration of the influence of the urban form (density, house typology, location of land uses, etc.) on the intensity of resource utilization. Emergy synthesis, an energy-based methodological approach that allows the quantification and integration of natural and human-generated flows interacting in urban environments, was used to assess the environmental performance of the residential land use of seven boroughs in the Island of Montreal, a Canadian urban region with a population density of 3900 inhabitants per square kilometer. Natural resources, food, water, acquired goods and services, electricity, fuels, municipal solid wastes and wastewater were the main flows considered in the analysis. Results suggest that income, household size and distance to downtown are the variables affecting more noticeably the intensity of emergy utilization. Further studies should consider emergy modeling at the scale of urban planning unities based on the variables that were found to affect more significantly the intensity of resource utilization.

Keywords. Intensity of resource utilization; Borough; Residential land use; Urban form; Urban Planning; Emergy-based performance.

4.1 Introduction

Since 2007, one out of two persons in the world lives in a city and current trends point out that urban population will continue to rise to about 5 billion by 2030 (UN-HABITAT, 2011); more than 75% of this population lives in settlements of five million residents or less, and, for a long time, it will be this type of urban regions which will continue to absorb the majority of the urban population in the world (LEAD International, 2008). Given that urban regions are among the main originators of local to global scale environmental problems, many of which are directly or indirectly associated to poor planning (UN-HABITAT, 2008), the proper development of cities are in the center of current concerns.

High resource use is a common feature of modern day cities that must be addressed. A major contributor to this utilization rate is the residential, or domestic, sector. Around 30% of energy use in the world goes to housing (Pulselli et al., 2007), operation of buildings reach up to 50, 41 and 36% in the United Kingdom, the European Union and the United States, respectively, on a national basis (Steemers, 2003). In countries like Canada, household water utilization accounts for around 30% of all the water used (Statistics Canada, 2013). Likewise, domestic consumption from households is a major source of carbon emissions in urban areas (Chen and Chen, 2012). Several works have found food, mobility of people, housing and energy-using products, among the main domestic related aspects affecting sustainability, accounting, aggregately, for almost 80% of the environmental impacts in industrialized nations (Tukker et al., 2010).

Also, land-use planning is the primary policy intervention influencing the form of urban settlements (Bramley and Power, 2009) that continues to be among the most powerful management instruments for design and control used by urban planners; one of its main objectives is to look for simultaneous territorial integrity for both the human subsystem and

natural subsystem (Campbell, 1996). One key point for this is the knowledge of the interrelationships between the socio-economic drivers and the environmental performance at the land use level (Pauleit and Duhme, 2000). Hence, an important aspect to better inform planning decisions on future development of urban areas with less environmental burden is the influence of the nature and the intensity of occupation of the city's territory (Perkins et al., 2009); for instance, is widely acknowledged that densely populated cities use less energy from transport per person than cities with low density, even though the debate continues on the causal mechanisms involved (Rickwood et al., 2008). For the residential sector, the concepts of urban form involve, besides density, spatial distribution of dwellings, housing typology (Bramley and Power, 2009; Perkins et al., 2009) and other aspects related to the urban macro structure, such as distance to central business districts (CMHC, 2000).

For their part, material flow accounting (Decker et al., 2000; Hendricks et al., 2000), ecological footprint (Muñiz and Galindo, 2005; Rees and Wackernagel, 1996), and energetic life cycle analysis (Norman et al., 2006; Perkins et al., 2009; Treloar et al., 2001) are widely used methods to account for the flows interacting in urban environments. Emergy synthesis is part of the energy 'family' of methodologies, which additionally provides a way to incorporate in the same base of comparison natural and human-generated flows, such as currency and labor, through a common unit of measure, the solar emergy joule (seJ), that takes into account the 'free' work that the environment carries out and the quality of the used resources: "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 has showed to be an appropriated methodology to evaluate and compare sustainability of cities, since it integrates the different types of flows that interact in urban ecosystems (Ascione et al., 2011). This work resorted to emergy synthesis as the analysis was intended from a deep sustainability perspective (Kennedy et al., 2011), emphasizing the environmental support that provides the resource flows sustaining, in this case, the daily activities in a borough (Sciubba and Ulgiati, 2005).

In this context, environmental sustainability of the residential land use of seven boroughs in the Island of Montreal, located in the southeastern part of Canada (45°30' N, 73°30' W), from the perspective of the environmental support required for their daily activities, was evaluated. In 2011, the Island had more than 1.9 million inhabitants in its 499 km^2, implying a population density of around 3900 persons by square kilometer (ISQ, 2012). The city has a diversified economy based on a consolidated industrial sector and on the growing services, technology and knowledge sectors, being an important part of the industrial and commercial region of eastern North America (City of Montreal, 2011a). The Island has an average gross residential density of 48.1 dwellings per hectare (dw/ha), rising to more than 150 dw/ha in some boroughs of the city center, while in the suburbs, the boroughs present values of less than 20 dw/ha (CMM, 2011). The main objective of the present work was to assess the environmental performance of the residential land use at the borough level in the Island of Montreal, through the quantification and analysis of the material, energetic and economic flows by means of the emergy synthesis method to explore the response of emergy-based indicators to the variation of urban planning and management parameters.

4.2 Materials and methods

According to Odum's idea of energy hierarchy, in which all energy transformations can be arranged in a hierarchy from sunlight to electrical power (requiring many joules of the first one to obtain a joule of the latter), a central concept is the unit emergy value, the amount of emergy needed to produce one unit of output (Brown and Ulgiati, 2004a). Transformity, defined as the amount of seJ required to produce one joule of available energy at the output, is the most widely accepted unit emergy value, but other values such as specific emergy (expressed in seJ/g) and emergy per unit of currency (seJ/$), are also frequently used (Brown and Ulgiati, 2004b). From the unit emergy values of rain, wind, fossil fuels, minerals and so on, other natural and human-made products have been analyzed and many more unit values have been estimated, which in turn have been used in more detailed analyses of different kinds (Ascione et al., 2009; Brandt-Williams, 2001; Odum, 2000).

An emergy evaluation begins with the definition of the system diagram under analysis (Figure 4.1), including the main input and output flows of materials, energy, money etc. For the analysis of the boroughs, the main flows considered were sunlight, kinetic energy from wind, evapotranspiration from rain, surface heat flux, local topsoil loss, food, water, acquired goods and services, electricity and fuels, for both the operation of the dwellings and the transport of the residents, municipal solid wastes and wastewater.

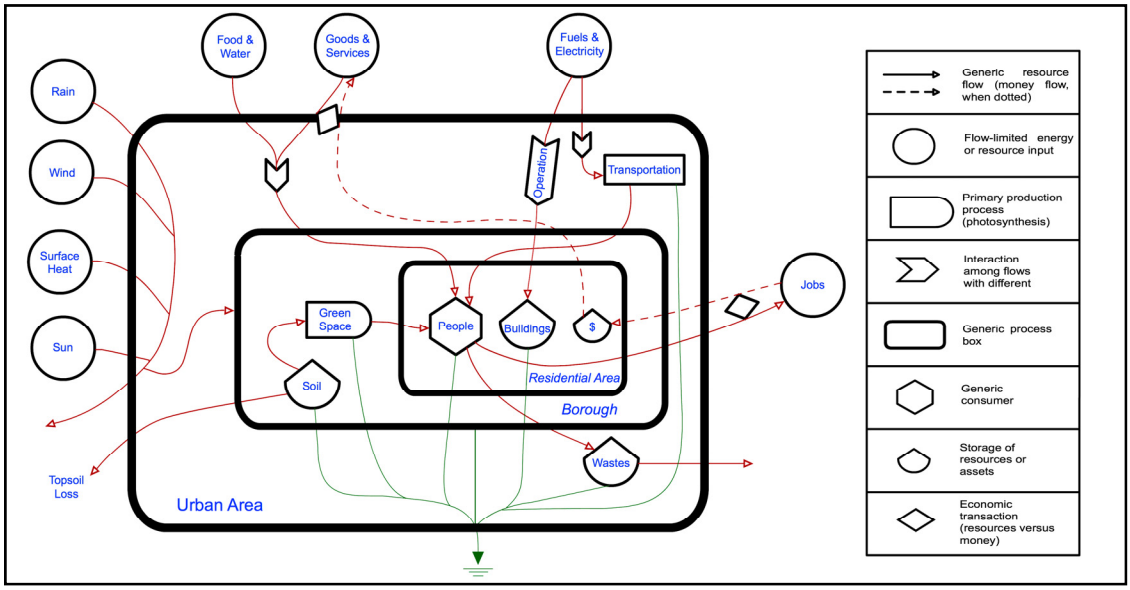

Figure 4.1 Diagram of the main flows considered in the analysis of the boroughs
Adapted from Brown (2011, p. 3)

After the formulation of the diagram, a table is integrated with the raw data to calculate the corresponding emergy flows (Table 4.1), which are obtained through a multiplication by the appropriate unit emergy values (Brown and Ulgiati, 2004b). Total emergy used (*U*) was calculated as the sum of the emergy from items 5 to 20 and the highest emergy input among items 1 to 4 (Table 4.1), to avoid double counting (Campbell et al., 2005; Zhang et al., 2011). The global emergy budget (15.83×10^{24} seJ/year) used in this study was calculated from solar insolation, deep earth heat and tidal energy (Brown and Ulgiati, 2004b; Odum, 2000). Finally, from the aggregate emergy flows estimated (*R*, *N*, *F* and *W*), performance indices and indicators, which are dealt with in the discussion section, are calculated for their

interpretation as a support in decision-making processes (Brown and Ulgiati, 1997), in this case, in the urban planning and management context.

Table 4.1 Emergy synthesis of material, energy and economic flows in the borough of Ville-Marie

	Item	Quantity	Unit	Transformity (seJ/J,g,$)	Reference (transformity)	Emergy (seJ/year)
	Renewable resources (R)					
1	Solar radiation	7.31E+16	J/year	1.00	Odum, 1996	7.31E+16
2	Wind	1.96E+14	J/year	2.45E+03	Odum, 2000	4.81E+17
3	Rain (evapotransp.)	1.76E+13	J/year	3.10E+04	Odum, 2000	5.45E+17
4	Surface heat flux	2.34E+13	J/year	1.07E+04	After Odum, 2000	2.51E+17
	Local non-ren. resources (N)					
5	Topsoil loss	9.60E+07	g/year	2.29E+09	Odum, 2000; Huang and Chen, 2005	2.20E+17
	Purchased resources (F)					
6	Cereals	6.44E+09	g/year	9.82E+08	Odum, 1996; Pulselli, 2010	6.32E+18
7	Fruits	5.76E+09	g/year	1.23E+09	Odum, 1996; Pulselli, 2010	7.05E+18
8	Vegetables	1.11E+10	g/year	5.96E+09	Odum, 1996; Brandt-Williams, 2001	6.60E+19
9	Meat	6.76E+09	g/year	3.17E+10	Brandt-Williams, 2001; Bastianoni et al., 2005	2.15E+20
10	Fish	6.72E+08	g/year	1.53E+11	Odum, 1996; Bastianoni et al., 2005	1.03E+20
11	Milk and other diaries	9.58E+09	g/year	2.41E+10	Odum, 1996; Brandt-Williams, 2001	2.30E+20
12	Eggs	7.58E+08	g/year	1.07E+11	Brandt-Williams, 2001	8.11E+19
13	Sugars and syrups	2.42E+09	g/year	1.55E+08	Brandt-Williams, 2001; Brown and Ulgiati, 2004b	3.75E+17
14	Potable water	8.84E+12	g/year	3.00E+06	Pulselli, 2010	2.65E+19
15	Natural gas	2.42E+15	J/year	4.00E+04	Bastianoni et al., 2009	9.66E+19
16	Electricity	6.04E+14	J/year	6.23E+04	Brown and Ulgiati, 2002	3.76E+19
17	Gasoline	8.02E+09	g/year	2.92E+09	Bastianoni et al., 2009	2.34E+19
18	Diesel	7.66E+08	g/year	2.83E+09	Bastianoni et al., 2009	2.17E+18
19	Electricity (transport)	1.85E+13	J/year	6.23E+04	Brown and Ulgiati, 2002	1.15E+18
20	Acquired goods and services (spending)	3.94E+08	$/year	1.54E+12	Vega-Azamar et al., 2013	6.09E+20
	Wastes (W)					
21	Municipal solid wastes	1.77E+14	J/year	1.80E+06	Huang and Chen, 2005	3.19E+20
22	Wastewater	3.98E+13	J/year	6.66E+05	Huang and Chen, 2005	2.65E+19

4.3 Calculation

Emergy-based indicators (Table 4.2) help to compare the environmental performance of the boroughs stressing the support needed for the dwellers activities, estimated by means of the emergy from the used resources. Based on the requirements for the estimation of these indicators, the appropriated data was selected and elaborated.

Table 4.2 Emergy-based indicators considered in the study cases

Indicator	Calculation	Unit	Indication
Empower per household (EH)	U/borough's number of households	seJ/household·year	Quality of living
Per capita emergy (U_{cap})	U/borough's number of dwellers	seJ/person·year	Standard of living
Empower density of the habitable area (ED_{Hab})	U/borough's total residential floor area	seJ/m^2·year	Intensity of resource utilization
Emergy to money ratio (EMR)	U/total income of borough's households	seJ/USD	Ecological economic efficiency
Per capita support area (SA_{cap})	$([N+F]_{borough}/[(N+F)/area]_{Montreal})$/borough's number of dwellers	m^2/person	Emergy-based ecological footprint
Emergy sustainability index (ESI)	[U/F]/[(N+F)/R]	-	Long term sustainability
Emergy of wastes per household (WH)	W/borough's number of households	seJ/household·year	Environmental loading

Seven boroughs of the City of Montreal (Le Plateau-Mont-Royal, Le Sud-Ouest, Pierrefonds-Roxboro, Rivière-des-Prairies-Pointe-aux-Trembles, Rosemont-La Petite-Patrie, Ville-Marie and Villeray-Saint-Michel-Parc-Extension), with different characteristics such as housing types, green area coverage, per household income, number of residents per dwelling and distance to downtown, were analyzed. One of the most important aspects defining urban form is density of occupation, expressed through the number of dwellings per unit area (Bramley and Power, 2009). Accordingly, the gross residential density of the boroughs ranged around three values: above 150, about 100 and below 35 dwellings per hectare. Table 4.3 shows the main attributes used in the analysis of the boroughs, presented in descending order of gross residential density.

Table 4.3 Main characteristics of the broroughs

Case	Gross den. (dw/ha)	Area (ha)	Household income (USD/yr)	Total households	Floor area (ha)	Total dwellers	Dist. to DT (km)	% Green areas
Ville-Marie	161	1652	46511	43250	859	74265	0.8	30.8
Plateau M-R	151	813	40684	56045	890	98275	2.9	9.4
Villeray	103	1649	33138	62865	975	141765	7.3	12.4
Rosemont	99	1585	37501	70085	1129	130570	5.9	15.3
Sud-Ouest	94	1568	35715	33005	559	68080	3.7	17.7
Riv. Prairies	30	4228	49004	40635	885	102470	17.4	12.7
Pierrefonds	19	2706	57415	23730	821	64285	23.3	16.4

Residential floor area in each borough was estimated through the reported gross residential density (CMM, 2011) and the weighted mean of the floor area ratio, i.e. floor space/plot area, established in the Master Plan of Montreal (City of Montreal, 2004), estimated with the help of ArcView 3.3 GIS software.

Distance to downtown was considered as that of the straight line between the centroid of each borough and the corner of two of the most significant streets in the business and commercial heart of the city, it was estimated also with the help of ArcView 3.3 GIS software. Similarly, distance to two of the major employment areas, one located to the east and the other to the west of the island, was examined. Green area coverage was also compiled from the reported in the Master Plan of Montreal (City of Montreal, 2004).

Two of the main sources of statistical data were the City of Montreal's socio-demographic profiles of boroughs (City of Montreal, 2009) and economic profiles of boroughs (City of Montreal, 2012). It is important to note that the calculations in this paper were made taking into account only the population housed in private homes (total dwellers in Table 4.3, which means around 95% of total population in the boroughs) and the occupied dwellings (total households in Table 4.3).

Unavailable data at the borough level were scaled down, as in the case of food consumption, for which national averages for urban regions were adjusted through the expenditure on food in each borough.

For the estimation of emergy from natural resources, data coming from long periods were used; owing to environmental inputs of regional systems are frequently calculated using long-term averages (Campbell et al., 2005). Also, data corresponding to monetary flows (all currency values are expressed in US dollars) were brought to present value by applying price indexes when needed (Norman et al., 2006; Statistics Canada, 2012). Table 4.4 shows the way in which data were processed and the main sources from which they came.

Table 4.4 Data elaboration and sources

Item	Elaboration	Sources
Natural resources	Long period averages	Davies and Davies (2010), Environment Canada (2011), NASA (2000)
Food	Per capita averages for urban regions adjusted by food spending in the boroughs	City of Montreal (2012), Statistics Canada (2009)
Water	Consumption by house type	CMHC (2001), Troy et al. (2005)
Electricity and natural gas from house operations	Average of energy consumption by house type and by number of residents	Statistics Canada (2010)
Fuels and electricity from transport	Split mode, average trip length, vehicle and public transport performance	AMT (2010), Codoban and Kennedy (2008), NRC-OEE (2007), Paez et al. (2010)
Goods and services	Household expenditure in the boroughs	City of Montreal (2012)
Municipal solid wastes	Total generation of municipal solid wastes in the boroughs	City of Montreal (2011b)
Wastewater	Proportion of water consumption estimated for the boroughs	CMHC (2001), Troy et al. (2005)

4.4 Results

Total emergy used (*U*) varied depending on the number of residents, size of the households, income, distance to downtown and mixing of house types, among other aspects, in the analyzed boroughs.

As expected, purchased (imported) emergy (*F*) was the dominant flow sustaining the day-by-day activities in each borough with an average of 99.94% of *U*, while renewable emergy (*R*), local non-renewable emergy (*N*) and emergy from wastes (*W*) averaged about 0.04%, 0.02% and 27.84% of *U*, respectively.

R corresponded to the chemical potential of rain (evapotranspiration of the grass in parks and green areas) for the borough of Ville-Marie, where the green areas coverage was the highest (almost 31%), and to the kinetic energy from wind for the rest of the boroughs, while *N* corresponded to topsoil loss in areas other than parks and green areas.

Figure 4.2 shows the main aggregated emergy flows, as a percentage of *U*, calculated for the seven cases, they are presented in descending order of gross residential density.

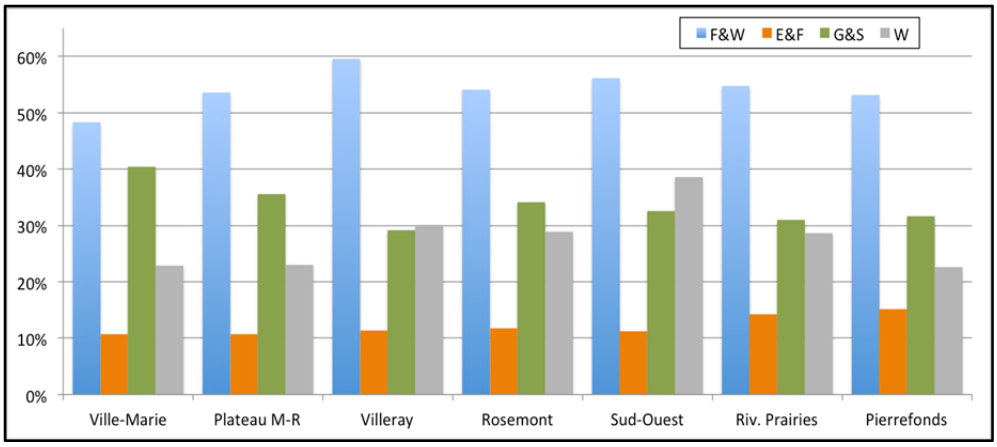

Figure 4.2 Purchased emergy and emergy from wastes, as percentage of the total emergy used, in the seven boroughs [F&W: food and water; E&F: electricity and fuels; G&S: goods and services acquired; W: wastes]

Comparisons among cases with different characteristics are usually carried out favoring the utilization of intensity indicators instead of total quantities to attenuate such differences (Ascione et al., 2009). In this work, the emergy requirements were considered mainly on a per occupant basis and on a per unit area of habitable space basis, in both cases, higher values of U_{cap} and ED_{Hab} indicating higher intensity of resource consumption and/or utilization.

Emergy from food and water averaged 54% of U in the boroughs. Plateau M-R and Ville-Marie presented the largest and smallest per resident uses (9.88×10^{15} and 9.70×10^{15} seJ/person·year, respectively) and Villeray and Pierrefonds showed the highest and lowest per square meter of floor area consumption values (1.43×10^{14} and 7.69×10^{13} seJ/m^2·year, respectively). Emergy from acquired goods and services averaged 33%, with Ville-Marie exhibiting the highest per capita use (8.20×10^{15} seJ/person·year) and Villeray the lowest (4.80×10^{15} seJ/person·year), and Plateau M-R and Pierrefonds showing the largest and smallest per square meter uses (7.25×10^{13} and 4.57×10^{13} seJ/m^2·year, respectively).

For its part, emergy from total electricity and fuels consumption ranged around 12% of U in the boroughs; Pierrefonds presented the highest per occupant use (2.80×10^{15} seJ/person·year)

and Villeray the lowest ($1.86x10^{15}$ seJ/person·year), while, Rivière Prairies and Ville-Marie exhibited the largest and smallest per square meter uses ($2.95x10^{13}$ and $1.87x10^{13}$ seJ/m^2·year, respectively). The average percentage of emergy from generated wastes, with respect to *U,* was nearly 28%; the highest and lowest per resident value corresponded to Sud-Ouest and Pierrefonds ($6.78x10^{15}$ and $4.18x10^{15}$ seJ/person·year, respectively), while the highest and lowest per square meter of habitable area rates corresponded to Villeray and Pierrefonds ($7.03x10^{20}$ and $2.69x10^{20}$ seJ/m^2·year, respectively). Table 4.5 summarizes the main indicators estimated from the analysis of the emergy flows (U_{cap} in seJ/person·year, *EH* and *WH* in seJ/household·year, ED_{Hab} in seJ/m^2·year, *EMR* in seJ/USD, SA_{cap} in m^2/person·year and *ESI* is dimensionless).

Table 4.5 Emergy-based indicators calculated for the seven boroughs

Case	U_{cap}	*EH*	ED_{Hab}	*EMR*	SA_{cap}	*ESI*	*WH*
Ville-Marie	2.01E+16	3.45E+16	1.74E+14	7.41E+11	89.8	0.00037	7.98E+15
Plateau M-R	1.84E+16	3.23E+16	2.04E+14	7.95E+11	82.4	0.00013	7.45E+15
Villeray	1.65E+16	3.72E+16	2.40E+14	1.12E+12	73.7	0.00021	1.12E+16
Rosemont	1.82E+16	3.40E+16	2.11E+14	9.06E+11	81.5	0.00019	9.81E+15
Sud-Ouest	1.75E+16	3.62E+16	2.13E+14	1.01E+12	78.4	0.00038	1.40E+16
Riv. Prairies	1.79E+16	4.52E+16	2.08E+14	9.23E+11	80.1	0.00067	1.30E+16
Pierrefonds	1.85E+16	5.01E+16	1.45E+14	8.72E+11	82.6	0.00066	1.13E+16

4.5 Discussion

This section presents an exploratory search for trends that must be viewed with caution, given the peculiarities of the Island of Montreal, such as location, socioeconomic structure, relationships with the rest of the metropolitan region, among other factors, in addition to the limited number of boroughs analyzed.

4.5.1 Per capita and per household emergy utilization

Empower per household may be an indicator of quality of living in residential areas (Li and Wang, 2009) and, similarly, per capita emergy may also be an indirect indicator of standard of living. For this reason, it was explored if per household income, an economic measure of well-being, could be related to per capita emergy consumption and to empower per household, expecting that higher household incomes corresponded to higher U_{cap} and *EH*, see Figures 4.3 and 4.4.

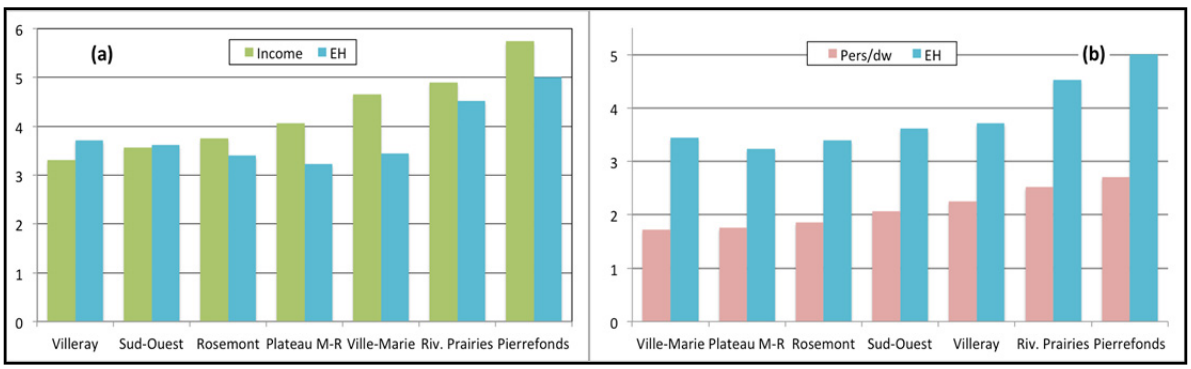

Figure 4.3 (a) Per household emergy (x10^{16} seJ/dwelling·year) and per household income (x10^{04} USD/year); (b) per household emergy (x10^{16} seJ/dwelling·year) and household size (persons/dwelling)

From Figure 4.3a, a nonlinear trend of empower per household variation with respect to household income may be noted, presenting a minimum *EH* for the borough of Plateau M-R, which has a medium income level and the second lowest household size (number of occupants per dwelling), with 1.75 residents.

Figure 4.3b depicts a positive linear correlation between occupancy per dwelling and empower per household was confirmed; the coefficient of determination value (R^2) estimated for the seven cases was 0.904. The central borough of Ville-Marie, which matches the smallest household size with the highest per capita emergy consumption (associated to its considerable rate of acquisition of goods and services, Figure 4.2), breaks the trend. The

highest per household emergy utilisations corresponded to Rivière Prairies and Pierrefonds, the boroughs with the highest incomes and the highest resident occupancies.

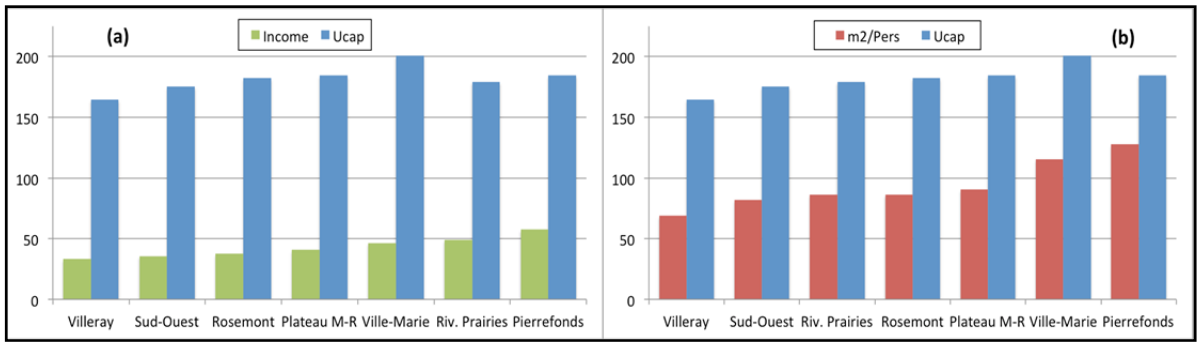

Figure 4.4 (a) Per capita emergy (x10^{14} seJ/person·year) and per household income (x10^{03} USD/year); (b) per capita emergy (x10^{14} seJ/person·year) and available living space per person (m^2/person)

For its part, although the range of variation of U_{cap} was not broad, a gradual increment was detected when per household income increased, with a peak for Ville-Marie and a small drop for the two boroughs with the highest incomes (Figure 4.4a). The highest per capita emergy utilization value, registered in Ville-Marie, is associated to the aforementioned emergy from goods and services, while, in turn, Rivière Prairies and Pierrefonds presented the highest household sizes (2.52 and 2.71 persons per dwelling, respectively), which slightly attenuates the parameters estimated on a per capita basis.

A certain influence of per resident habitable space on per capita emergy consumption was also observed. In general, a greater availability of floor area per person corresponded to a higher U_{cap} (Figure 4.3b). This is partly explained by the significant positive linear correlation between income and availability of living space (R^2=0.731, estimated for the seven cases). Again, the district notoriously breaking the trend is Ville-Marie, which may be explained by the combination of high emergy consumption with the low resident occupancy rate (1.72 persons per dwelling, the smallest).

4.5.2 Emergy from electricity and fuels

As mentioned above, one of the main aspects defining urban form is density (Bramley and Power, 2009). On this point, gross residential density of the boroughs seem to have some influence on both per capita and per square meter of floor area emergies corresponding to total energy consumption. Figure 4.5 depicts the per capita and the per square meter emergies of total electricity and fuels (*E&F*) used for both the operation of dwellings and the transport of residents estimated for the seven boroughs, presented in descending order of gross residential density.

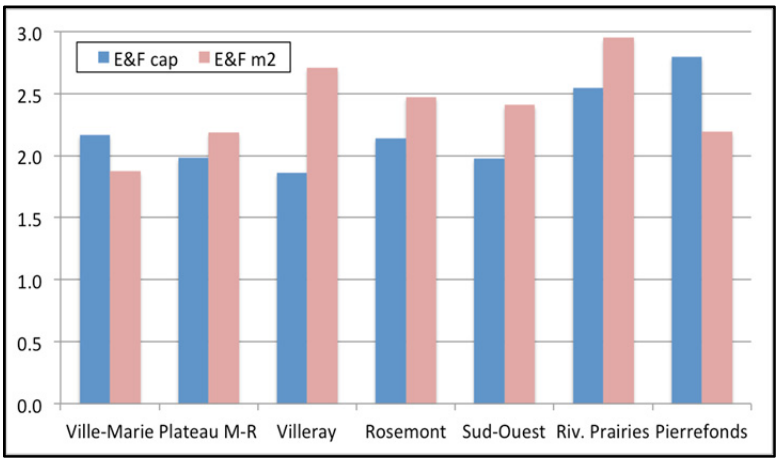

Figure 4.5 Per capita emergy (x10^{15} seJ/person·year) and per unit floor area emergy (x10^{13} seJ/m^2·year) of total electricity and fuels consumption in the seven boroughs

The decrease in gross residential density appears to coincide with a general escalation of per capita emergy from total *E&F* and, to a lesser extent, with an increase of emergy from total *E&F* in the inhabited space, with Villeray and Pierrefonds breaking the trend somewhat. This behavior seems to be more closely related to the distance to downtown than to density, without ignoring these two variables have a significant correlation (in general, the latter decreases as the former increases, see Table 4.3), or to energy consumed for housing (Figure 4.6), even though emergy from *E&F* for the operation of dwellings represents from 59 to 83% of total emergy from *E&F*.

From Figure 4.6, it can be seen that emergy from fuels and electricity for the transport of residents was highly influenced by the distance to downtown, similarly to other studies suggesting that distance to central districts is more important than variables such as housing typology and density and road layout (CMCH, 2000).

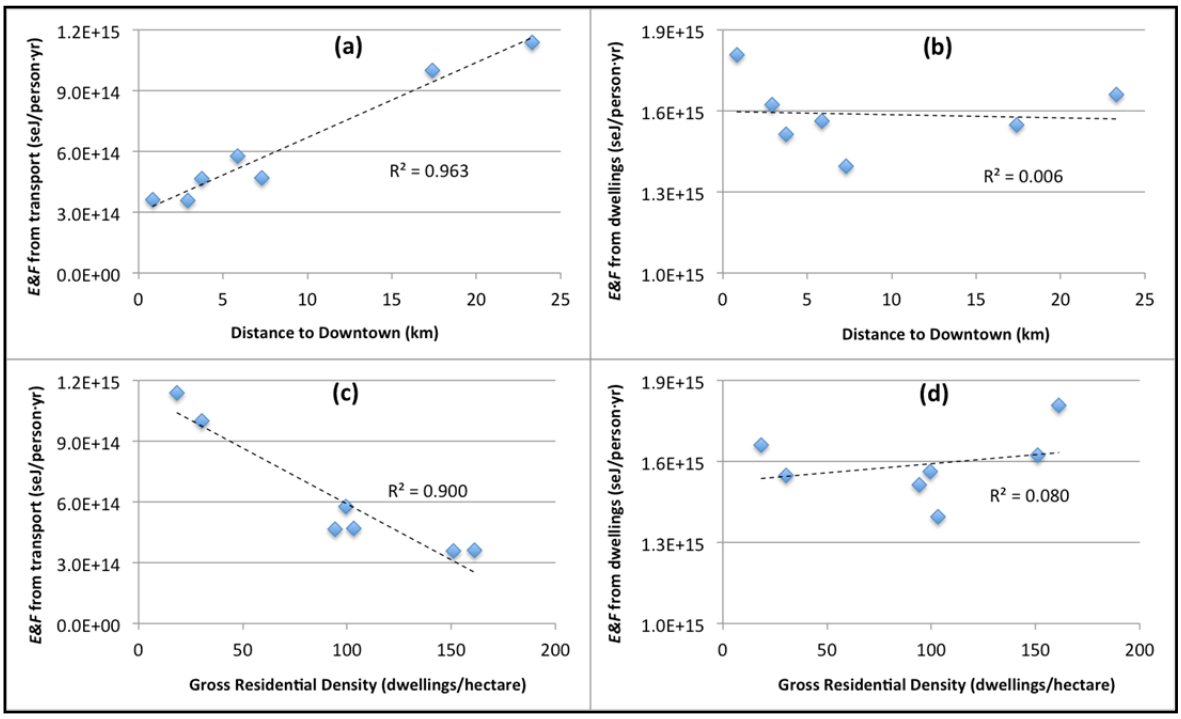

Figure 4.6 Per capita emergy from electricity and fuels: (a) transport of residents and distance to downtown, (b) operation of dwellings and distance to downtown, (c) transport of residents and gross residential density, (d) operation of dwellings and gross residential density

Distance to downtown and gross residential density were strongly correlated to per capita emergy from *E&F* for the transport of residents (Figures 4.6a and 4.6c), while correlation between these two variables and per capita emergy from *E&F* for the operation of dwellings was virtually nil (Figure 4.6b and 4.6d). For its part, geometric mean of distance to downtown and to major employment areas was also correlated to per capita emergy from *E&F* for the transport of residents, but to a lesser extent (R^2=0.693). The boroughs of Pierrefonds and Rivière Prairies exhibited the highest values of emergy from total *E&F* on a per capita basis (Figure 4.5); both are the furthest away from downtown and have the highest percentage of car use, 76.3 and 68.9% respectively (AMT, 2010).

With regard to the emergy required for the operation of dwellings, the outcomes on a per capita basis contrast with findings of life cycle energy consumption studies in which energy utilization for buildings operations in low-density areas are approximately from 1.5 to 2 times of that of high-density areas (Norman et al., 2006; Perkins et al., 2009), while here, virtually, no differences were observed (Figure 4.6d). This may be attributed to the particular characteristics of the present study (mainly, the level of aggregation of data, the selected densities and the house types).

4.5.3 Ecological economic efficiency, emergy-based ecological footprint and environmental sustainability

As mentioned in Table 4.2, *EMR* is the ratio of total emergy used to total income in boroughs which, besides indicating the capacity of money to buy emergy (Zhang et al., 2011), may be an indicator of ecological economic efficiency when regions are compared, with lower values of *EMR* corresponding to higher levels of emergy use efficiency (Cai et al., 2009). For its part, carrying capacity may be estimated by means of the support area of land (*SA*) required to obtain enough inputs to fulfill the emergy requirements of a given population (here, that of the dwellers in the studied boroughs), within a local economic and environmental system (in this case the Island of Montreal), based on the intensity of development of the region (Brown and Ulgiati, 2001), see Table 4.2.

With respect to these two indicators, in addition to their individual values, the combined performance may be observed by considering the accumulated area of the two bars for the boroughs (Figure 4.7), given that lower values correspond to better performances for each indicator. Ville-Marie presented the lowest *EMR*, which seems to happen because its level of income results in a high emergy use rate, which in turn translates into the highest SA_{cap} needed. The low per capita and the medium per household emergy consumption of Villeray are reflected in the smallest need of support land per resident, but its lowest per household income brings along the highest *EMR*. The best-combined performance corresponded to Plateau M-R. A general trend was observed; higher per capita support land areas corresponded to lower emergy to money ratios.

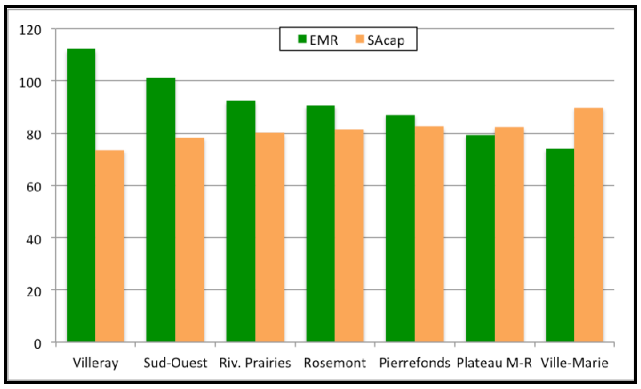

Figure 4.7 Emergy to money ratio (x10^{10} seJ/USD) and per capita support area (m^2/person·year) for the seven boroughs

Figure 4.8 presents a ternary diagram of sustainability in which the curved lines designate constant values of the *ESI*, these lines divide the triangle into sustainability areas, which are helpful to classify products or processes; the resource flow lines (dotted) represent the relative proportions of *R*, *N* and *F* (in this case, the average of the seven boroughs), given by the lengths of the perpendiculars from the vertex to the opposite side of the triangle (Almeida et al., 2007). *ESI* can inform about the possible degree of contribution of the boroughs to the regional system (the Island of Montreal) with respect to the environmental burden inflicted (Ascione et al., 2009). *ESI* gives an appraisal of long-term sustainability, in general, the higher its value the higher the dependence on renewable resources and the lower the environmental burden (Brown and Ulgiati, 1997). By the nature of the present analysis, the estimated values of *ESI* for the boroughs were well below 1, however, they would not fail to provide insights about the performance of the boroughs. The best performances corresponded to Rivière Prairies and Pierrefonds (Table 4.2), which may be explained, among other things, by the important coverage of green area, the low residential land use area to total area rate and the low habitable area to lot area ratio. The worst performance corresponded to Plateau M-R with its high residential land use area to total area rate and its relatively high per capita emergy consumption.

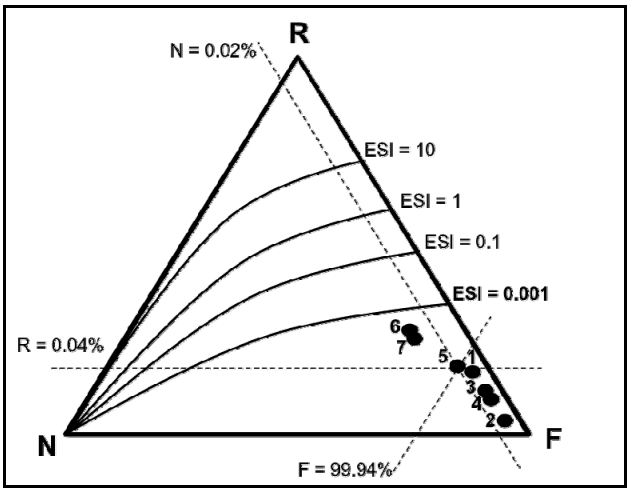

Figure 4.8 Ternary diagram of sustainability lines for 7 boroughs [1: Ville-Marie; 2: Plateau M-R; 3: Villeray; 4: Rosemont; 5: Sud-Ouest; 6: Rivière Prairies; 7: Pierrefonds] Adapted from Almeida et al. (2007, p. 71)

4.5.4 Emergy from wastes

As mentioned above, per household empower may inform on living quality. For its part, emergy from wastes, in the present study both municipal solid wastes and wastewater, divided by the total number of households in each borough is an indicator of environmental load. In the first case, high values correspond to higher availability/utilization of resources, whereas in the latter, high values indicate greater impacts. In Figure 4.9, the *EH* to *WH* ratios are plotted. These ratios may assist for assigning a ranking of sustainability; in the graphic, a higher slope denotes a larger proportion of acquired commodities and services to generated pollutants (Li and Wang, 2009). In the studied boroughs, three levels of performance were observed: Ville-Marie, Plateau M-R and Pierrefonds showed higher efficiencies; Rosemont, Rivière Prairies and Villeray presented medium efficiencies; and Sud-Ouest exhibited the poorest performance. To all appearances, this performance levels are mainly due to the fact that higher incomes give a greater capability to purchase resources (emergy), but a the same time they do not seem to have a marked influence on the amount of per household wastes generated.

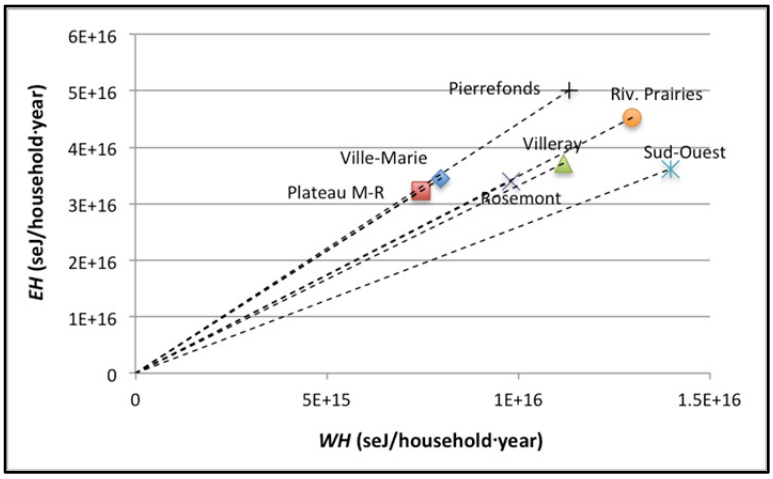

Figure 4.9 Empower per household and emergy from wastes per household

4.6 Conclusions

As expected, total emergy used varied principally according to number of dwellers, household sizes, level of income, distance to downtown and mixing of house types; imported emergy was by far the dominant flow sustaining each borough's activities. The most centrally located borough, with an atypical green area coverage of more than 30%, was the only one in which renewable emergy accounted for the evapotranspiration of rain, while, in the rest, such emergy corresponded to the kinetic energy from wind.

The highest proportions of emergy from food and water, from electricity and fuels and from acquired goods and services, with respect to total emergy used, were obtained for the borough with the lowest per household income, for the borough the furthest away from downtown and for the most centrally located borough, respectively. The contribution of these flows to total emergy use, in descending order, was: food and water, goods and services, and electricity and fuels. Also, with respect to emergy consumption per unit floor area, the lowest rate corresponded to the borough with the largest available space per person, for the cases of food and water and of goods and services, and to the borough with the second largest available space per person, for the case of electricity and fuels.

With regard to emergy from wastes, the borough with the highest income, and the largest available space per person, exhibited the smallest amounts generated both on a per capita basis and per unit floor area. The analysis of the per household emergy from wastes to empower per household ratio brought about three levels of performance; in general, the high-income boroughs showed the best efficiencies, with the exception of the one with the second highest per household income, which presented a medium efficiency.

A nonlinear fluctuation of empower per household with respect to per household income was observed, with the minimum *EH* for the borough with the second lowest household size and the median level of income level. Also, a strong positive linear correlation between household size and empower per household was confirmed; the highest per household emergy utilisations corresponded to the boroughs with the highest incomes and the largest household sizes.

The range of variation of per capita emergy was not broad, however, a gradual increment was detected when income increased, with a maximum for the borough with the highest per resident utilization rate of emergy from goods and services (the most centrally located one). In addition, some influence of per resident habitable space on per capita emergy was noted; in general, a greater amount of the former corresponded to a higher value of the latter.

As expected, emergy from fuels and electricity for the transport of dwellers was highly influenced by distance to downtown. Gross residential density and distance to the city center did not appear to be correlated neither to per capita emergy from total energy consumption nor to per capita emergy from electricity and fuels used for the operation of dwellings.

With respect to the emergy-based ecological footprint and the emergy to money ratio, a general trend was observed: higher per capita land areas needed to support the activities in the boroughs corresponded to lower ecological economic efficiencies; while in the assessment of long-term sustainability through the emergy sustainability index, the best performances corresponded to the two boroughs the furthest away from downtown (both also

with the highest incomes), which may be explained by their coverage of green areas, the low residential land use area to total area rate and the low habitable area to lot area ratio.

Finally, it will be very important to examine more cases to confirm or discard the results obtained in this work. From a wider perspective, future work should consider emergy modeling at the scale of urban planning unities based on the variables that were found to affect more significantly the intensity of emergy utilization.

4.7 References

Agence métropolitaine de transport (AMT), 2010. *Mobilité des personnes dans la région de Montréal Enquête Origine-Destination 2008, version 08.2a (Mobility of people in the Montreal area Origin-Destination Survey 2008, version 08.2a)*. (Data processing: Ricardo Vega.) http://www.enquete-od.qc.ca/docs/EnqOD08_Mobilite.pdf [in French]. Accessed March 21, 2012.

Almeida, C.M.V.B., Barrella, F.A., Giannetti, B.F., 2007. *Emergetic ternary diagrams: five examples for application in environmental accounting for decision-making*. Journal of Cleaner Production 15 (1), p. 63-74.

Ascione, M., Bargigli, S., Campanella, L., Ulgiati, S., 2011. *Exploring an urban system's dependence on the environment as a source and a sink: the city of Rome (Italy) across space and time scales*. ChemSusChem 4 (5), p. 613-627.

Ascione, M., Campanella, L., Cherubini, F., Ulgiati, S., 2009. *Environmental driving forces of urban growth and development. An emergy-based assessment of the city of Rome, Italy*. Landscape and Urban Planning 93 (3-4), p. 238-249.

Bastianoni, S., Campbell, D.E., Ridolfi, R., Pulselli, F.M., 2009. *The solar transformity of petroleum fuels*. Ecological Modelling 220(1), p. 40-50.

Bastianoni, S., Marchettini, N., Niccolucci, V., Pulselli, F.M., 2005. *Environmental accounting for the lagoon of Venice and the case of fishing*. Annali di Chimica 95 (3-4), p. 143-152.

Bramley, G., Power, S., 2009. *Urban form and social sustainability: the role of density and housing type*. Environment and Planning B: Planning and Design 36(1), p. 30-48.

Brandt-Williams, S.L., 2001. *Handbook of Emergy Evaluation. Folio #4. Emergy of Florida Agriculture*. http://www.emergysystems.org/downloads/Folios/Folio_4.pdf. Accessed September 14, 2010.

Brown, M.T., 2011. *Sample system diagrams of ecosystems and regional systems*. http://www.emergysystems.org/downloads/System_DIAGRAM.zip. Accessed Sept. 22, 2011.

Brown, M.T., Buranakarn, V., 2003. *Emergy indices and ratios for sustainable material cycles and recycle options*. Resources, Conservation and Recycling 38 (1), p. 1-22.

Brown, M.T., Ulgiati, S., 2004a. *Energy quality, emergy and transformity: H. T. Odum's contributions to quantifying and understanding systems*. Ecological Engineering 178 (1-2), p. 201-213.

Brown, M.T., Ulgiati, S., 2004b. *Emergy analysis and environmental accounting* in: Cleveland, C. J. (Eds.), Encyclopedia of Energy, Elsevier Academic, Oxford, p. 329-354.

Brown, M.T., Ulgiati, S., 2002. *Emergy evaluations and environmental loading of electricity production systems*. Journal of Cleaner Production 10 (4), p. 321-334.

Brown, M.T., Ulgiati, S., 2001. *Emergy measures of carrying capacity to evaluate economic investments*. Population and Environment 22 (5), p. 471-501.

Brown, M.T., Ulgiati, S., 1997. *Emergy-based indices and ratios to evaluate sustainability: monitoring economies and technology towards environmentally sound innovation*. Ecological Engineering 9 (1-2), p. 51-69.

Cai, Z.F., Zhang, L.X., Zhang, B., Chen, Z.M., 2009. *Emergy-based analysis of Beijing-Tianjin-Tangshan region in China*. Communications in Nonlinear Science and Numerical Simulation 14 (12), p. 4319-4331.

Campbell, D.E., Brandt-Williams, S.L., Meisch, M.E.A., 2005. *Environmental accounting using emergy: Evaluation of the State of West Virginia*. http://www.epa.gov/nheerl/publications/files/wvevaluationposted.pdf. Accessed September 29, 2010.

Campbell, S., 1996. Green cities, growing cities, just cities? Urban planning and the contradictions of sustainable development. Journal of the American Planning Association 62(3), p. 296-312.

Canada Mortgage and Housing Corporation (CMHC), 2001. *Analysis of the annual energy and water consumption of apartment buildings in the CMHC HiSTAR Database*. Research Highlight, p. 4.

Canada Mortgage and Housing Corporation (CMHC), 2000. *Greenhouse gas emissions from urban travel: tool for evaluating neighbourhood sustainability*. Research Report, p. 60.

Chen, S., Chen, B., 2012. *Network environ perspective for urban metabolism and carbon emissions: A case study of Vienna, Austria*. Environmental Science and Technology 46(8), p. 4498-4506.

City of Montreal, 2012. *Profils économiques des arrondissements. Montréal en statistiques. Par territoire. Arrondissements de Montréal. (Economic profiles of boroughs. Montreal in statisics. By territory. Montreal's boroughs)*. http://ville.montreal.qc.ca/portal/page?_pageid=6897,67845597&_dad=portal&_schema=PORTAL. Accessed May 04, 2012.

City of Montreal, 2011a. *The Montreal Economy*. http://www.montreal2025.com/decouvrir_economie.php?lang=en. Accessed October 27, 2011.

City of Montreal, 2011c. *Portrait 2010 des matières résiduelles de l'agglomération de Montréal (2010 Portrait of municipal solid wastes of the Montreal Agglomeration)*, p. 52.

City of Montreal, 2009. *Profils sociodémographiques des arrondissements. Édition 2009. Montréal en statistiques. Par territoire. Arrondissements de Montréal (Socio-demographic profiles of boroughs. 2009 Edition. Montreal in statisics. By territory. Montreal's boroughs)*. http://ville.montreal.qc.ca/portal/page?_pageid=6897,67845597&_dad=portal&_schema=PORTAL. Accessed July 28, 2012.

City of Montreal, 2004. *Montreal's Master Plan*. http://ville.montreal.qc.ca/portal/page?_pageid=2762,3099656&_dad=portal&_schema=PORTAL. Accessed March 14, 2013.

Codoban, N., Kennedy, C. A., 2008. *Metabolism of neighborhoods*. Journal of Urban Planning and Development 134(1), p. 21-31.

Communauté Métropolitaine de Montréal (CMM), 2011. *Les forms d'habitat et la planification des densités résidentielles (Housing types and planning of residential densities)*, p. 24.

Davies, J. H., Davies, D. R., 2010. *Earth's surface heat flux*. Solid Earth, vol. 1, p. 15-24.

Decker, E.H., Elliott, S., Smith, F.A., Blake, D.R., Rowland, F.S., 2000. *Energy and material flow through the urban ecosystem*. Annual Review of Energy and the Environment 25, p. 685-740.

Environment Canada, 2011. *Canadian Climate Normals or Averages 1971-2000. Montreal Pierre Elliot Trudeau International Airport Station*. http://climate.weatheroffice.gc.ca/climate_normals/results_e.html?stnID=5415&lang=e&dCode=1&StationName

=MONTREAL&SearchType=Contains&province=ALL&provBut=&month1=0&month2=12. Accessed November 22, 2011.

Hendriks, C., Obernosterer, R., Müller, D., Kytzia, S., Baccini, P., Brunner, P.H., 2000. *Material Flow Analysis: A tool to support environmental policy decision making. Case studies on the city of Vienna and the Swiss lowlands*. Local Environment 5 (3), p. 311-328.

Huang, S.-L., Chen, C.-W., 2005. Huang, S.-L., Chen, C.-W., 2005. *Theory of urban energetics and mechanisms of urban development*. Ecological Modelling 189 (1-2), p. 49-71.

Institute of Statistics of Quebec (ISQ), 2012. *Bulletin statistique régional Montréal, Édition 2012 (Montreal Regional Statistical Bulletin, 2012 Edition)*, p. 27.

Kennedy, C., Pincetl, S., Bunje, P., 2011. *The study of urban metabolism and its applications to urban planning and design*. Environmental Pollution 159 (8-9), p. 1965-1973.

LEAD International, 2008. *Megacities and climate change. Sustainable urban living in a changing world*. First ed. LEAD International, London, p. 56.

Li, D., Wang, R., 2009. *Hybrid Emergy-LCA (HEML) based metabolic evaluation of urban residential areas: the case of Beijing, China*. Ecological Complexity 6(4), p. 484-493.

Muñiz, I., Galindo, A., 2005. Urban form and the ecological footprint of commuting. The case of Barcelona. Ecological Economics 55(4), p. 499-514.

National Aeronautic and Space Administration (NASA), 2000. Insolation Levels. Surface meteorology and Solar Energy Data Set (taken from: Whitlock, Charles H., D. E. Brown, W. S. Chandler, R. C. DiPasquale, N. Meloche, G. J. Leng, S. K. Gupta, A. C. Wilber, N. A. Ritchey, A. B. Carlson, D. P. Kratz, et P. W. Stackhouse. 2000. Release 3 NASA Surface Meteorology and Solar Energy Data Set For Renewable Energy Industry Use. Proceedings of Rise and Shine 2000, the 26th Annual Conference of the Solar Energy Society of Canada Inc. and Solar, Oct. 21-24, 2000, Halifax, Nova Scotia, Canada).

Natural Resources Canada. Office of Energy Efficiency (NRC-OEE). *2007. Fuel Consumption Guide 2008*, p. 65.

Norman, J., MacLean, H. L., Kennedy, C. A., 2006. *Comparing high and low residential density: life-cycle analysis of energy use and greenhouse gas emissions*. Journal of Urban Planning and Development 132(1), p. 10-21.

Odum, H.T., 1996. *Environmental accounting: Emergy and environmental decision making*. First ed., John Wiley, New York, p. 370.

Odum, H.T., 2000. *Handbook of Emergy Evaluation. Folio #2. Emergy of Global Processes*. http://www.emergysystems.org/downloads/Folios/Folio_2.pdf. Accessed September 14, 2010.

Paez, A., Mercado, R. G., Farber, S., Morency, C., Roorda, M. 2010. *Accessibility to health care facilities in Montreal Island: an application of relative accessibility indicators from the perspective of senior and non-senior residents*. International Journal of Health Geographics, 2010, 9:52. DOI: 10.1186/1476-072X-9-52.

Pauleit, S., Duhme, F., 2000. *Assessing the environmental performance of land cover types for urban planning*. Landscape and Urban Planning 52(1), p. 1-20.

Perkins, A., Hamnett, S., Pullen, S., Zito, R., Trebilcock, D., 2009. *Transport, Housing and Urban Form: The Life Cycle Energy Consumption and Emissions of City Centre Apartments Compared with Suburban Dwellings*. Urban Policy and Research 27(4), p. 377-396.

Pulselli, R.M., 2010. *Integrating emergy evaluation and geographic information systems for monitoring resource use in the Abruzzo region (Italy)*. Journal of Environmental Management 91(11), p. 2349-2357.

Pulselli, R. M., Simoncini, E., Pulselli, F. M., Bastianoni, S., 2007. *Emergy analysis of building manufacturing, maintenance and use: Em-building indices to evaluate housing sustainability*. Energy and Buildings 39(5), p. 620-628.

Rees, W., Wackernagel, M., 1996. *Urban ecological footprints: why cities cannot be sustainable - and why they are a key to sustainability*. Environmental Impact Assessment Review 16(4-6), p. 223-248.

Rickwood, P., Glazebrook, G., Searle, G., 2008. *Urban Structure and Energy - A Review*. Urban Policy and Research 26(1), p. 57-81.

Sciubba, E., Ulgiati, S., 2005. *Emergy and exergy analyses: Complementary methods or irreducible ideological opinions?* Energy 30(10), p. 1953-1988.

Statistics Canada, 2013. *Households and the Environment 2011*, p. 181.

Statistics Canada, 2012. *Consumer Price Indexes, historical summary*. http://www.statcan.gc .ca/tables-tableaux/sum-som/l01/cst01/econ46a-eng.htm. Accessed July 12, 2012.

Statistics Canada, 2010. *Households and the Environment: Energy Use 2007*, p. 39.

Statistics Canada, 2009. *Food Statistics 2008*, p. 42.

Steemers, K., 2003. *Energy and the city: density, buildings and transport*. Energy and Buildings 35(1), p. 3-14.

Treolar, G.J., Love, P.E.D., Holt, G.D., 2001. *Using national input-output data for embodied energy analysis of individual residential buildings*. Construction Management and Economics 19(1), p. 49-61.

Troy, P., Holloway, D., Randolph, B. 2005. *Water Use and the Built Environment: Patterns of Water Consumption in Sidney*. City Futures. Research Paper, p. 82.

Tukker, A., Cohen, M.J., Hubacek, K., Mont, O., 2010. *The impacts of household consumption and options for change*. Journal of Industrial Ecology 14(1), p. 13-30.

United Nations Human Settlements Programme (UN-HABITAT), *2011.Cities and Climate Change: Global Report on Human Settlements 2011*. 1st ed. United Kingdom; United States of America: Earthscan Publications Ltd, p. 279.

United Nations Human Settlements Programme (UN-HABITAT), 2008. *State of World Cities 2008/2009, Harmonious cities*. 1st ed. United Kingdom; United States of America: Earthscan Publications Ltd., p. 259.

Vega-Azamar, R.E., Glaus, M., Hausler, R., Oropeza-García. N.A., Romero-López, R., 2013. *An emergy analysis for urban environmental sustainability assessment, the Island of Montreal, Canada*. Landscape and Urban Planning 118, p. 18-28.

Zhang, Y., Yang, Z., Liu, G., Yu, X., 2011. *Emergy analysis of the urban metabolism of Beijing*. Ecological Modelling 222(14), p. 2377-2384.

CHAPTER 5

DISCUSSION

This section presents theoretical and operational implications arising from the results and findings obtained during the development of the three articles (Chapters 2, 3 and 4) that shape the core of the thesis, as well as the main considerations for future research avenues. During the development of the work, three geographical scales of analysis were considered: the urban agglomeration, the residential unit and the borough, which gave macro-level, micro-level and meso-level views of the urban environment, respectively.

The paper applies the principles of the systems approach to the analysis of the urban environment, particularly from the perspective of the 'solar energy footprint through time' generated by the primary function of accommodating people (residential land use), to weigh alternatives of development in an urban planning context, that is, giving the highest priority to the understanding of the entire system behaviour from the exploration of the structural relationships of its main elements: the housing, food, transportation, spending, natural resources and generated wastes subsystems.

5.1 Key findings from the case studies

5.1.1 Scales of analysis

The work scales implied the management of data with three different levels of aggregation. For the macro-level view, the city level aggregated data prevailed, but also some and provincial level data were scaled down due to unavailability issues (Chapter 2). For the micro-level view, building and housing aggregated data predominated, and electoral district aggregated data were scaled down when needed (Chapter 3), whereas for the meso-level view, borough and sub-municipalities aggregated data dominated (Chapter 4). This led to differences in the values estimated for the indicators in each scale of analysis.

As in other studies related to urban environments, it was confirmed that support for the activities in urban centers comes predominantly from the import of resources (*F*). At the city level, *F* accounted for 96.73% of total emergy used (*U*), while at borough and residential unit levels, *F* was 99.94 and 99.99%, respectively. This is due to the system under analysis boundaries; for example, while at the city level elements of regional importance, such as the St. Lawrence River, were included, at the housing unit level, the analysis is restricted to the property (lot). If the river were not included for the first case, *F* would be 99.88% of *U*.

As for the two main resource use intensity indicators, emergy consumption per person (U_{cap}) estimated for the Island of Montreal was more than three times the value estimated for the units and boroughs, which is mainly because at the macro-level analysis besides the St. Lawrence River, industrial supplies (including the payment of services for their acquisition), were included, which increased the value of *U*. In the case of emergy utilization per unit area, total empower density (*ED*) for the five housing units was more than 5 times higher than the that for the Island of Montreal and for the seven selected boroughs, which may be explained, at least partially, by the particularities of the analyzed housing units (lot coverage ratio and dwelling occupancy rate or household size), apart from the aforementioned differences in the boundaries selection.

With respect to the ecological economic efficiency, the emergy-to-money ratio (*EMR*) for Montreal was 1.7 times that for the borough and housing unit level, which is partly because at the city level, the gross domestic product (GDP) is used for the estimation of this ratio, while at the district and dwelling level, per household income was used. If household income instead of GDP is considered for the Island of Montreal, St. Lawrence River is not included and the consumption of the residential sector is only considered, the *EMR* of Montreal would be around 0.9 times the average *EMR* for the borough and housing unit level; however, this estimate has a certain degree of imprecision because the micro- and meso-level include the purchase of goods and services, a significant component of *U*, as it will be seen later.

In certain urban planning contexts, analyses tend more and more towards the neighbourhood as the unit of intervention (Codoban and Kennedy, 2008), among other things, due to the high potential for the implementation of policies with real impacts and tangible results at that scale of action and to zoning size configuration issues. Results suggest that this level of disaggregation may be reached by 'building' neighbourhoods from bottom up, that is, as the sum of housing units with the appropriate housing typology shaping the neighbourhood form or by scaling down borough level data, where statistical data allows it. At the moment, for the Island of Montreal, the highest level of disaggregation that can be obtained from the available statistical data is the electoral district.

5.1.2 Key variables: income and available space

The selected cities comparison (Chapter 2) showed a positive correlation between per capita GDP values and U_{cap} utilizations. Likewise, for the housing units (Chapter 3) and boroughs (Chapter 4), it was found that higher income levels are positively correlated to higher emergy consumptions, also on a per capita basis. However, the interpretation should be slightly different for both cases. In the reviewed urban centers, the industrial sector was included in the analysis, so it could be assumed that the largest generation of wealth may be due to an efficient use of the increased emergy availability to transform it into new products. For the units and boroughs, since the residential sector was the only one considered, a higher level of family income translates into a greater ability to acquire resources, especially in the form of goods and services.

In the analysis of the seven selected boroughs, results suggest that income is the most determinant variable when choosing the housing type and location: for single persons or couples without children with substantial income, the choice favoured medium- to high-rise downtown apartments, while for families with children and high incomes the option was inclined to detached houses in the suburbs with large living and green spaces. Moreover, at the urban agglomeration level, it was found that per inhabitant land availability (space) is strongly and non-linearly to empower density; in general, the greater the space availability

the lower the *ED*, with a marked drop for 300 m^2 or more of available land per person. Something similar occurred at the housing unit level; when availability of per resident living area increased, empower density of the habitable space (ED_{Hab}) decreased, with the difference that after a certain point (50 m^2/person) there was no decrement in ED_{Hab}, while at the borough level, per resident space availability seemed to correlate more strongly to U_{cap} rather than to *ED* or ED_{Hab}.

In the dwelling units, the greatest emergy use both on a per capita basis and per unit area was observed for the case in which the lowest per resident habitable space and the second largest income coincided, that is, where two variables identified in this study as the most significantly affecting resource utilization intensity. Also, distance to the city center was found to influence, to a lesser extent, emergy use, particularly with regard to fuel and electricity consumption for the transport of dwellers (Chapters 3 and 4), as it will be seen in more detail in the following section. In this way, at urban planning scales, emergy use may be expressed as:

$$U = f\,(\text{Income, Habitable Space, Distance to Downtown})$$

According to the findings in this study, the influence of these three variables on emergy use intensity was clearly (*i*) income, (*ii*) available space, and (*iii*) distance to the center, in that order of importance. Applying the Rank Order Centroid method (Barron and Barrett, 1996; Edwards and Barron, 1994), weight values can be assigned to these three parameters (61.1%, 27.8% and 11.1%, respectively) to obtain preliminary values of resource utilization potential (U_{Pot}) that may be used when comparing two or more districts or housing units, through:

$$U_{Pot} = [(0.611)(\text{Income}) + (0.278)(\text{Hab. Space}) + (0.111)(\text{Dist. DT})] \qquad (5.1)$$

Where, income is expressed in \$/household·year, habitable space in m^2/person and distance to downtown in kilometers. With these U_{Pot} values, screenings can be made when comparing zoning proposals in the early stages of urban planning processes to know, in a preliminary

way, the potential intensity of resource consumption, which would help in decision-making efforts to focus more thoroughly key aspects for later stages of such processes.

One distinctive feature of emergy synthesis, with respect to other methodological approaches used for estimating flows such as electricity and fuels for housing operation and residents transport, and their associated efficiency, or for calculating the amount of materials used for the construction of buildings and related infrastructure, is the ability to also include monetary flows in the analysis from an environmental perspective, which allowed the quantitative identification of income as one of the most influential variables on resource utilization intensity in the present work. Table 5.1 presents a summary of the key parameters and indicators arisen from the research work and their potential use in urban planning.

Table 5.1 Key parameters and emergy-based indicators

Parameter	Indicator	Potential use
Urban region scale		
Per capita available space	Empower density (*ED*)	Strategic land use development schemes: general guidelines for land use
Per capita GDP	Per capita emergy (U_{cap})	
Borough scale		
Per capita available living space	Per capita emergy (U_{cap})	Urban master plans: criteria for distribution and intensity allocation for the land use mix (zoning by-laws)
Household income and size	Per household emergy (*EH*), emergy-to-money ratio (*EMR*)	
Distance to downtown	Emergy used for transport ($E\&F_{Transp}$)	
Green area coverage (%)	Emergy sustainability index (*ESI*)	Urban master plans: guidelines for green area coverage
Housing unit scale		
Household income	Per capita emergy (U_{cap})	Specific urban planning programs: criteria for zoning distribution
Per capita available living space	Empower density of the habitable area (ED_{Hab})	Building regulations: guidelines for dwelling sizes by housing type

5.1.3 Influence of residential density and housing types

Given the historical relevance of residential density in urban studies as one of the most important aspects of urban form, besides the fact that this parameter is one of the most widely used by urban planners, this variable was always considered throughout the

development of the work: in the analyzed housing units (Chapter 3) net densities ranged from 85 to 325 dwellings per hectare (dw/ha), while the selected boroughs (Chapter 4) were grouped around gross densities of more than 150, about 100 and less than 35 dw/ha.

The results suggest that density by itself does not appear to affect significantly the behaviour of U_{cap}, although it was correlated to *ED* and ED_{Hab}, to per capita emergy from the use of fuels and electricity ($F\&E_{cap}$) and, to a lesser extent, to *EMR*. In the seven boroughs, it was observed that gross residential density appears to have an influence on $F\&E_{cap}$ to some extent. However, this has to do more with issues indirectly related to density: longer distances to the city center correspond to low-density boroughs, which houses are sought after by larger families with important incomes (Figure 5.1) that frequently use cars, which can give low density the appearance of causing greater fuel consumptions. Similarly, shorter distances to the center correspond to high-density boroughs with apartment buildings preferred by childless couples or singles with high income (Figure 5.1), which can give high density the appearance of producing high ecological economic efficiencies (low *EMR*).

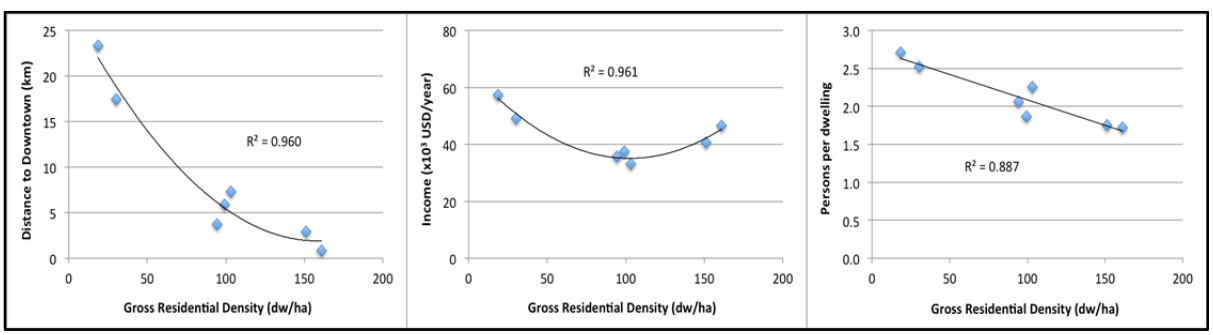

Figure 5.1 Density, distance to downtown, household income and number of residents per dwelling in the analyzed boroughs

For its part, the house types proportions do relate more directly to empower density. When controlling for certain factors in the analysis of the boroughs, the influence of the type of housing could be seen, for example, for the cases of Ville-Marie (VM) and Plateau Mont-Royal (PMR). VM and PMR are boroughs with similar gross residential densities and incomes, they are the closest to the city center and have virtually the same number of

occupants per dwelling; the main differences are the per dweller living space and the percentage of green areas and parks. In both boroughs, the proportion of detached and semidetached houses is almost the same. However, VM has about 28% more apartment buildings of 5 and more stories with higher per resident space availability than PMR, while in PMR the vast majority of the population (76%) is housed in buildings of four or less stories, with lots occupying larger land areas. This, coupled with VM's wider green area coverage, results in a lower intensity of occupation of VM's territory, measured as *ED* (2.5 times smaller than the estimated for PMR). Also, the smaller per dweller available living space in PMR causes an ED_{Hab} 1.2 greater than that the calculated for VM.

Residential density and house typology are rather related to house size, which in turn has influence on the price and on the rent of dwellings (Bengochea, 2003; CMHC, 2011). This was confirmed in the evaluation of the housing units; during the analysis, it was laterally observed that rises in net residential density are associated both to a decrease in the dwelling habitable space and to a reduction in the cost dwellings (Figure 5.2). Also, housing prices and rent costs are affected by location (Bourassa et al., 2003; CMHC, 2011), which was already mentioned as indirectly related to residential density (Figure 5.1).

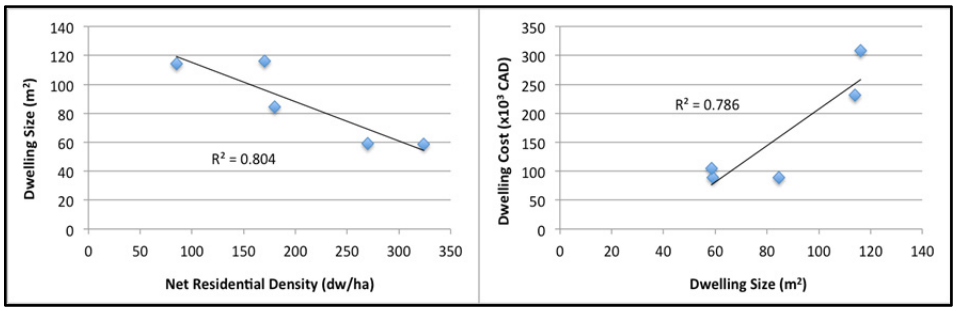

Figure 5.2 Residential density, dwelling size and dwelling cost

5.1.4 Land use intensity: empower densities

In Chapters 2, 3 and 4, the relatively strong correlation between population density and emergy use per unit area was confirmed. However, at the geographic scale of the boroughs

(Chapter 4), the most interesting trends with respect to this emergy-based indicator were found.

As a matter of fact, at the borough level, when the empower density variation in function of the distance to city center was reviewed, it was confirmed that empower density decreases as the borough 'moves' away from the center, which is similar to that reported by some authors for other equivalent geographical scales (Huang et al., 2007), although in a less marked way, in part, probably because of the unusual characteristic of the most central borough analyzed of having a significant amount of green areas (Figure 5.3).

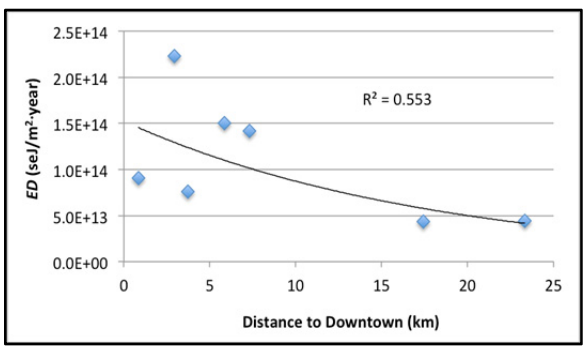

Figure 5.3 Empower density and distance to the city center

When the area covered by the residential land use is the only one considered, the variation becomes more pronounced, which has its origin in the correlation between residential density and empower density of the residential area (Figure 5.4).

The correlation holds, with slightly less strength, when mixed land use (multiple uses) is included, that is, if areas from stores, office buildings, light industrial and/or institutional and community facilities are added to the residential area. In this case, the coefficient of determination value (R^2) would be 0.830 in the distance to center-residential plus mixed land use's empower density graph and 0.747 in the residential density-residential plus mixed land use's empower density graph, which confirmes the primary significance of the accommodation function of urban centers.

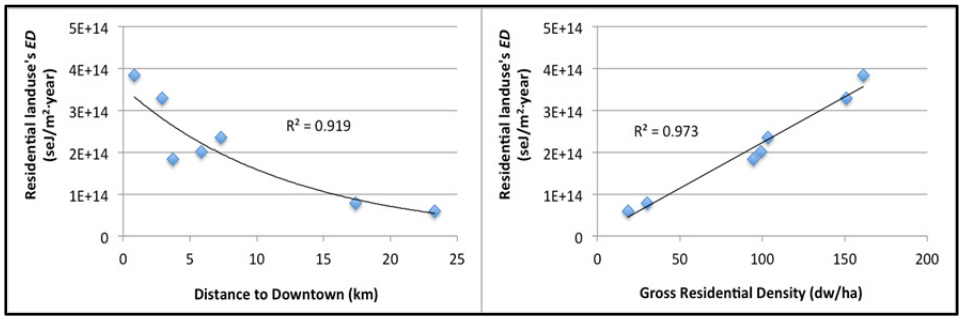

Figure 5.4 Empower density of the residential land use, density and distance to the city center

The area occupied by parks and other green areas do not necessarily have a direct relationship with the residential density (one of the main parameters for allocating intensities of occupation in urban planning).

On the other hand, if the area occupied by parks and other green areas is subtracted from the borough total area, its influence on empower density can be observed (Figure 5.5). Boroughs like Ville-Marie and Sud-Ouest, with a significant percentage of green areas, present an empower density closer to those of suburban boroughs. Thus, green area coverage can be an important parameter to take into account to reduce or control land use intensity (for the estimation of the empower densities in this section, data from Montreal's Master Plan were used; City of Montreal, 2004).

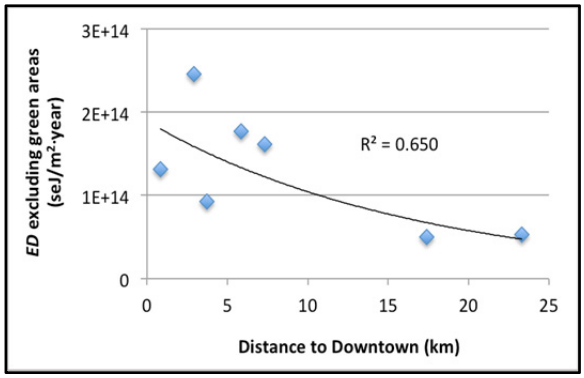

Figure 5.5 Empower density, excluding green area surface,
and distance to the city center

5.1.5 Limitations and uncertainty of the results

In addition to the limitations generally attributed to the emergy analysis methodology (shared by other tools such as life-cycle analysis), like combination of disparate time scales, representation of flows of different nature in solar equivalents and problems related to the allocation of splits and byproducts (Hau and Bakshi, 2004), the present study has limitations inherent to an exploratory research based on case studies.

One of the limitations of using case studies in research is the level of validity (internal and external) of the obtained results; however, exploratory research, by its very nature, has to rely often on case studies, although with some sacrifice in the degree of control (Leedy and Ormrod, 2010). For the cities comparison (Chapter 2), certain sources of uncertainty were discussed in section 2.3.2, while for the residential units (Chapter 3) and the boroughs (Chapter 4), the amount and particularities of the analyzed cases may seem an obvious limitation (especially for the case of the units). For the three cases, a way to increment results robustness is, of course, the consideration of a greater and more representative sample size, but special care has to be taken regarding the data quality and desaggregation as the base of the calculation.

Particularly, for the housing units, another way to provide a more robust data set for the analysis would be the application of a survey based on a standardized questionnaire, similar to those carried out in transport studies, but with far fewer questions and interviewees, for the general characterization of neighbourhoods to quantify more precisely the emergy consumption patterns at the appropriate level of geographical disaggregation (scale). For the case of the boroughs, the sample size is not so limited as it may appear, given that data for each one of them have formal statistical validity and correspond to the whole set of dwellings and dwellers, thus when analyzing seven boroughs (out of 19 for the Island of Montreal) and controlling for some parameters (density, income, household size, distance to downtown), there is much more internal validity than that of the residential units and a certain degree of

external validity (see the similarities with the reported behaviour for Taipei's empower density zin function of the distance to the city center).

On the other hand, one important source of uncertainty in emergy evaluations comes from unit emergy values. Some authors report that emergy researchers frequently assume an error range of one order of magnitude when they use unit emergy values that come from other studies calculations, but this may vary less or more (Ingwersen, 2010). Other authors recognize that there are different degrees of uncertainty depending on the level of knowledge of the process under analysis; however, they claim that the generalized transformities (often obtained from averages of those published in the litrature) do not differ significantly from the ones calculated for specific case studies (Hau and Bakshi, 2004). In turn, a variation of around 5% in the calculation of the total emergy used on the Island of Montreal in 2005 was estimated in this work, when the criteria for the money flows conversion shifted from exchange rates to purchasing power parities (section 2.3.3).

5.2 Operational implications

5.2.1 Tool for emergy calculation

Regardless of the findings and results obtained, the methodology used in the present work can become a tool to support decision-making at different geographical scales of urban environments.

At the local scale, resource utilization intensity may be used as an alternative or as a complement to green certifications for housing or neighbourhoods, such as "Leadership in Energy and Environmental Design" (LEED) and "Building Research Establishment Environmental Assessment Method" (BREEAM). At the district or zoning level, hypothetical residential intensities may be weighted, which would be useful as a basis for the comparison of alternatives in urban physical planning. At the curban region scale, the tool could be useful for the evaluation of environmental sustainability.

With the elements and procedures used for calculating the emergy consumptions of the case studies, it is possible to generate a tool based on dynamic spreadsheets for the estimation of hypothetical residential zonings' main emergy-based indicators, so that, future scenarios of urban development, and their associated consequences, can be compared.

The tool estimates the emergy utilization considering population, number of dwellings and projected surface, based on combinations of house types, number of occupants per dwelling (household size), income, average daily distance to travel by residents and modal split (Figure 5.6). The tool will estimate the total emergy used and, from it, it will calculate the main indicators of resource use intensity (waste generation can also be included). Planners can use the tool at early stages of urban planning processes.

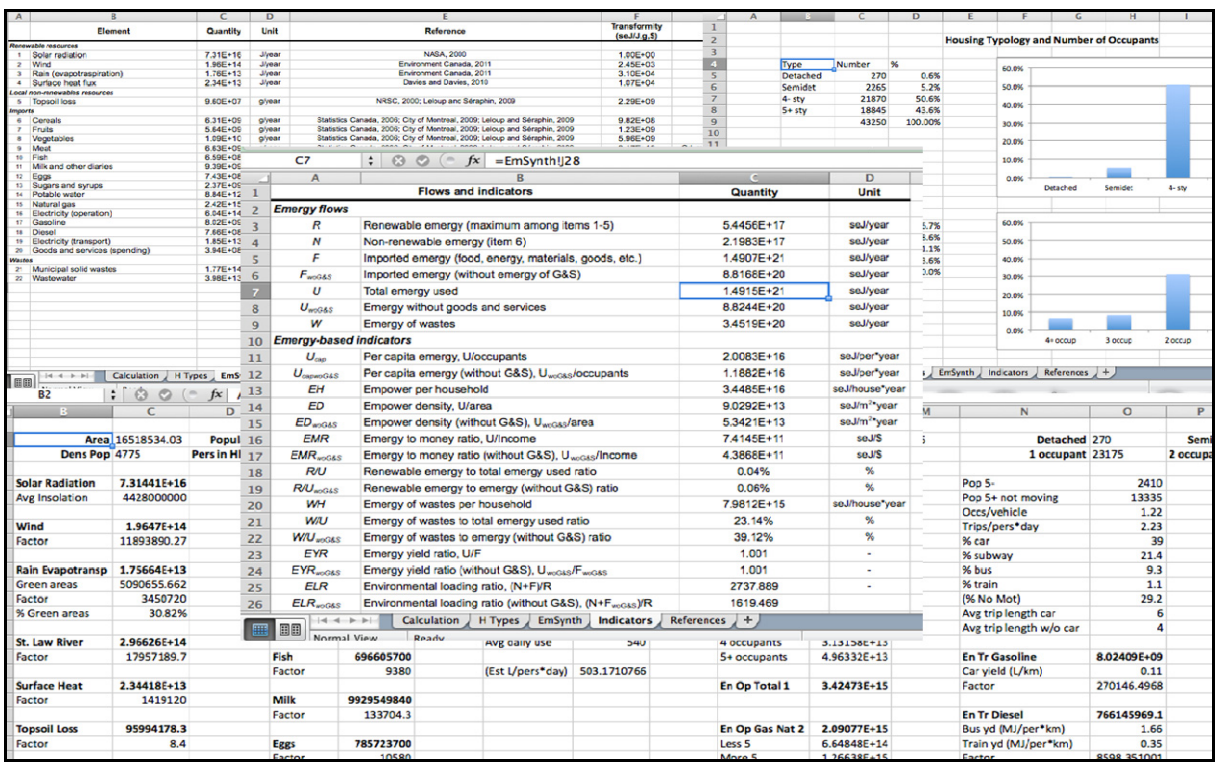

Figure 5.6 Emergy calculator

The calculation tool does not consider the emergy embodied in building materials because in the present work it was found that the contribution of the structure, the buildings bulk

component, averaged 1.2% of total emergy use (Chapter 3); however, it can be included. Also, as key data currently used comes from the City of Montreal socio-demographic profiles of boroughs, economic profiles of boroughs, and statistical profiles of electoral districts (Chapters 3 and 4), for the moment, the more disaggregated level of analysis is the electoral district, but more detailed levels of disaggregation may be set from census data or other valid surveys.

Once the main emergy-based indicators estimation is completed, the results from the dynamic spreadsheet can be exported and mapped with the help of a geographic information system (GIS) tool to explore possible suitable locations, according to U_{cap}, ED, ED_{Hab}, EMR and EH. Figure 5.7 and Annex II illustrate the residential ED for the island of Montreal at the electoral district level, but it is also possible to map U_{cap}, ED, ED_{Hab}, EMR and EH from the results estimated by the calculation tool, as mentioned above.

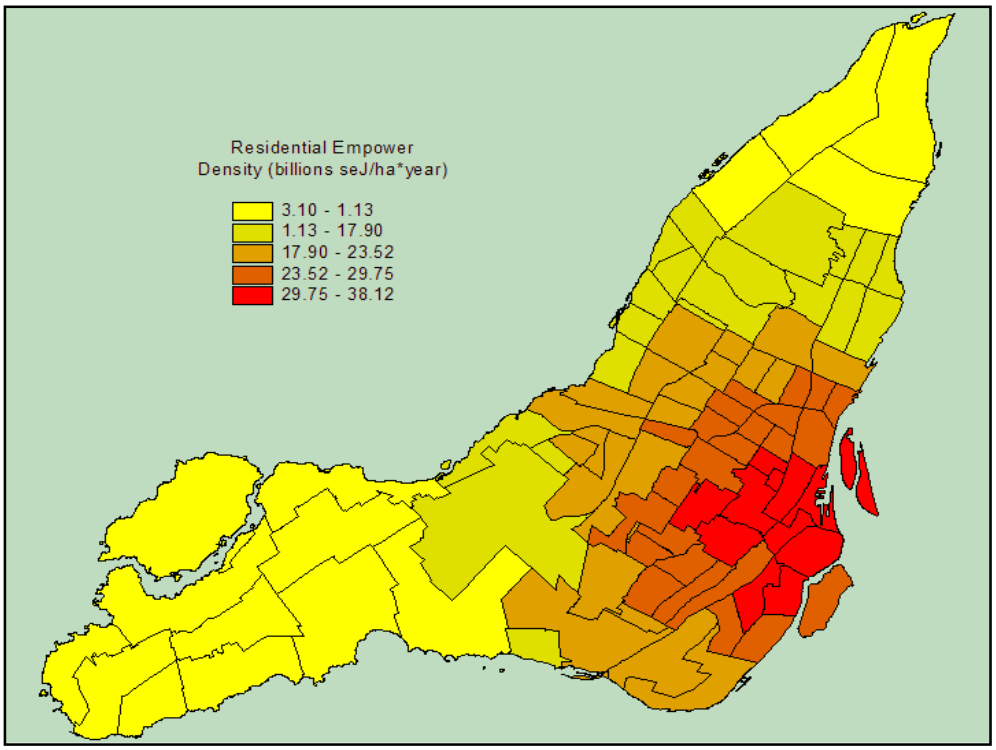

Figure 5.7 Empower density of the residential land use for the City of Montreal's electoral districts and adjacent municipalities

The cartographical representation of the emergy-based indicators provides the spectrum for optimizing the possibilities for assigning locations for zoning proposals. The procedure may also be performed in reverse order, that is, if the possible locations available for real-state development (or re-development) projects are known, from such locations occupation intensities intervals can be determined (U_{cap}, ED, etc.) for defining the appropriate characteristics for the projects. Thus, the use of a GIS tool would help to set potential scenarios of development for better planning urban interventions.

5.2.2 Local remediation emergy ratio

As mentioned above, green spaces can be a significant factor in controlling land use intensity. However, if their potential for accommodating local systems of waste treatment is considered in addition to their inherent renewable flow contribution, their environmental relevance may be increased. One way to assess such potential would be the local remediation emergy ratio (*LRER*) proposed for the boroughs.

$$\boldsymbol{LRER} = \frac{\boldsymbol{F} + \boldsymbol{N} + \boldsymbol{W_{ET}}}{\boldsymbol{R_{GA}} + \boldsymbol{W_{LR}}} \tag{5.2}$$

Where, F: imported emergy, N: locally non-renewable emergy; R_{GA}: renewable emergy from green spaces; W_{ET}: emergy from waste treatment in facilities outside the borough; W_{LR}: emergy recovered by the local waste treatment. Clearly, lower values correspond to better environmental performances. The ratio can be extended to include the emergy used for the transport of the remaining wastes to the external treatment site, if appropriate data are available.

To illustrate the proposed indicator, the Sud-Ouest borough is considered (Chapter 4). *LRER* is estimated for two scenarios: (*i*) all wastes (municipal solid wastes and wastewater) are treated externally, and (*ii*) local composting of the organic fraction of municipal solid wastes, which is about 5.3% (City of Montreal, 2011) and treatment of 25% of wastewater in a

constructed wetland in the green areas of the borough. Table 1 shows the details for the calculation of *LRER*. The values of recovery rates and treatment transformities for solid waste and wastewater were collected from Marchettini et al. (2007) and Zhou et al. (2009), respectively. For the Sud-Ouest borough, F = 1.19x10^{21} seJ, N = 2.48x10^{17} seJ, R_{GA} = 2.97x10^{17} seJ, total solid wastes = 5.80x10^{10} g and total wastewater = 6.26x10^{12} g for the year of the study.

Table 5.2 Estimation of the local remediation emergy ratio for the Sud-Ouest borough

Scenario 1: Without local treatment. LRER = 4516					
	Quantity (g)	Treatment transformity (seJ/g)	Recovery rate (seJ/g)	Treatment emergy (seJ)	Recovered emergy (seJ)
External landfill	5.80x10^{10}	5.22x10^{8}	-	3.03x10^{19}	-
External activated sludge treatment plant	6.26x10^{12}	1.94x10^{7}	-	1.21x10^{20}	-
			Total	1.51x10^{20}	-
Scenario 2: With local treatment. LRER = 229					
	Quantity (g)	Treatment transformity (seJ/g)	Recovery rate (seJ/g)	Treatment emergy (seJ)	Recovered emergy (seJ)
Compost	3.07x10^{9}	-	4.82x10^{8}	-	1.48x10^{18}
External landfill	5.49x10^{10}	5.22x10^{8}	-	2.87x10^{19}	-
Constructed wetland	1.57x10^{12}	-	2.51x10^{6}	-	3.94x10^{18}
External activated sludge treatment plant	4.69x10^{12}	1.94x10^{7}	-	9.10x10^{19}	-
			Total	1.20x10^{20}	5.42x10^{18}

5.3 Future Research

It should be noted that the case studies were carried out with cross-sectional data and, as a result, they provide a snapshot with of the variables that resulted the most significant for the specific period of study, so that one of the next logical steps should be the review of the evolution over time of these variables to try to confirm or discard their relevance for longer time intervals.

A first approach to address this is the analysis of data from censuses and national surveys and counts, which typically have a five-year frequency in a great number of countries. In Canada,

such data present a dissemination blocks disaggregation level, which are areas equivalent to a city block bounded by intersecting streets (Statistics Canada, 2012), for which statistics of occupied houses, number of residents, block areas, etc. (that may be easily generalized or aggregated by scaling up the data to the neighbourhood or urban zoning scales with a high level of detail) are reported. For the manufacturing sector and other economic sectors, CANSIM, the socioeconomic database of Statistics Canada, may be used, and for energy consumption, official statistical yearbooks are widely available, among other data sources.

A second approach, and a direct repercussion from this work, is the development of a dynamic model for the estimation of the main resource use intensity indicators throughout time (Figure 5.8), which may be adopted by urban and environmental planners to obtain complementary criteria in their decision making processes.

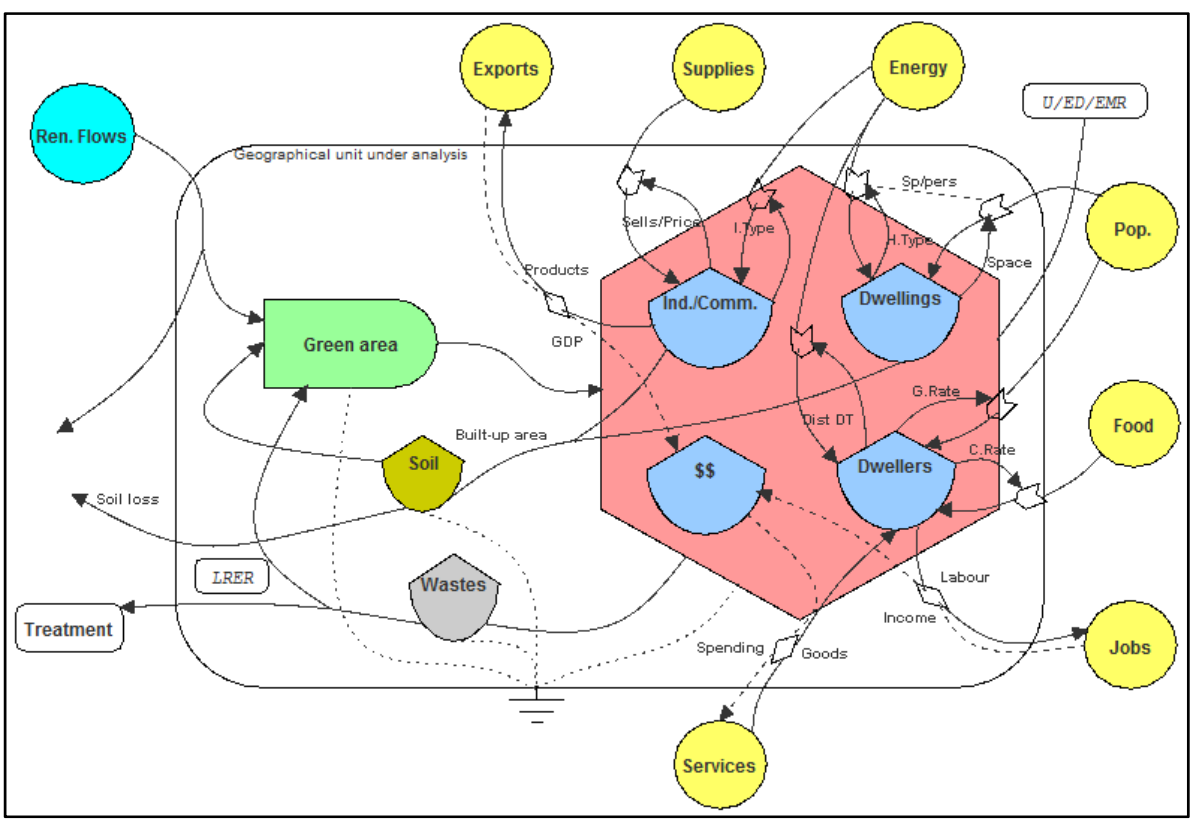

Figure 5.8 Dynamic model for the estimation of the emergy-based indicators

The dynamic model will include, on the one hand, the above-mentioned scaled data from censuses and other sources and, on the other hand, estimations from: (*i*) integrated land use and transportation models that simulate the consequences of the change in the location of activities (fuel and electricity use and greenhouse gases from the derived transportation patterns), (*ii*) energy consumption simulation tools for the operation of dwellings and buildings according to housing type and floor area (and the associated generation of GHG), and (*iii*) tools for the quantification of civil works supplies that may lead to the estimation of the emergy embodied in building materials (and the associated generation of GHG), if considered relevant for new real-state developments.

However, this is not enough to feed the emergy dynamic model; it would be necessary to explore, at least, the following research lines:

- fast methodology for calculating greenhouse gases and other air emissions emergy, as a complement for the solid waste and wastewater emergy;

- estimation of emergy utilization intensities for industrial (light and heavy industry), commercial, institutional and services land uses for specific case studies at urban zoning scales;

- development of a system dynamics model to understand and explain the interactions between specific areas with different socioeconomic characteristics and locations of urban centers (for instance, those belonging to downtown, inner suburbs, outer suburbs, etc.) at urban zoning scales;

- exploration of the effects on resource use intensity, both at local (districts) and at regional level (urban center) for urban forms praised by polycentrism, which proposes networks of centralities for spatial planning and territory management rather than a single central business district associated to the downtown.

The proposed model's results could be easily exported to GIS platforms, which functionalities would allow spatial analyses at different work scales. Using such analyses, policies and development scenarios could be simulated, and their implications and consequences would be represented cartographically to facilitate understanding and bring better support for decision-makers, not only urban or environmental planners, but other ones with different professional backgrounds.

Primarily, the kind of questions that this set of research avenues would seek to answer would be, for example, what might be the expected migration rate from one or more zones of a city to another zone in which an industrial complex will be installed and what consequences this would bring to the energy footprints through time of the involved zones and to the whole urban region emergy use intensity map?

This kind of dynamic tool could contribute with complementary elements to those provided by tools traditionally used in urban planning, especially, for the urban life-cycle analysis upstream part, that is, in the evaluation of resource utilization, which may be coupled with other environmental approaches that focus on the impacts, providing, in this manner, more complete environmental criteria for urban sustainable development planning.

CONCLUSION

Constant increase in resource consumption in urban regions, and the associated waste generation, is leading to a less and less bearable ecological footprint. A major contributor is the residential sector and, in many cases, this is related to deficient planning. One key point to better inform urban planning processes is the influence of the nature and intensity of occupation of the city's territory (urban form) on resource consumption. For the residential sector, this involves housing density, spatial distribution of dwellings, housing typology, and other aspects like the distance to the city center.

The main objective of the work was to explore the appropriateness of the emergy synthesis method to assist decision-making in physical urban planning, with an emphasis on the human settlements' primary function of accommodating people (residential land use). The method allows the incorporation of environmental and socioeconomic flows in solar energy equivalents accounting for the work that the environment carries out to make a given product or service. It was expected that urban form would affect resource use intensity, even if it only were to a certain extent.

In general, and above all, it was observed that the use of this methodological tool with a different approach, more focused on resource use and its related 'solar energy footprint through time', has a promising potential in urban planning decision-making efforts at the zoning level of urban master plans.

The analyses from the three scales explored in the work have identified income as the variable most significantly influencing resource utilization intensity, measured as emergy, followed by available space per person (this variable is rarely addressed in urban environmental assessments). Distance to the city center also influences emergy use, similarly to other studies reported in the literature.

At the city scale, when comparing ten urban regions selected from published studies, it was noted that the empower density, an emergy-based indicator for the territory use intensity, fell markedly when each inhabitant had about 300 m^2 or more of available land. At the housing unit scale, it was observed that a higher per household income increased per capita emergy consumption in all the analyzed cases and that increasing the availability of living space per resident did not result in a diminution of the habitable space's empower density after 50 m^2/person. At the borough scale, it was observed that income, household size and, to a lesser extent, distance to downtown were the variables affecting more markedly the intensity of emergy utilization.

The results suggest that density by itself does not appear to affect significantly the behaviour of per capita emergy consumption, but it is correlated to empower density and to per capita emergy from fuels and electricity. For its part, income seems to largely determine the choice of a dwelling (and its location), thus indirectly influencing the emergy use intensity in function of the distance to the city center and the correlation between residential density and ecological economic efficiency (emergy-to-money ratio). For single persons or childless couples with high incomes, housing choice leans toward downtown apartments with important floor areas while for families with children and high income the suburbs with more space and availability of green areas are preferred. Ecological economic efficiencies are poorer in districts where incomes are lower, while the best performances correspond to the most central district (highest per capita emergy consumption) and the farthest districts from the center (highest per household emergy consumptions).

This efficiency and the emergy from purchased goods and services are probably the most interesting original points found in the present work. While it was confirmed that land use intensity varies with distance from the city center and it was found that at the more disaggregated level of analysis revised per capita emergy consumption did not vary significantly, the level of income was determining for the emergy-to-money ratios, giving the impression that the wealthiest citizens are more 'efficient'. However, at the same time, higher income levels corresponded to higher emergy consumptions, related importantly to emergy

from purchased goods and services. Since in urban centers, emergy inflows come from non-renewable sources in their overwhelming majority, then, such efficiency may not be considered sustainable, at least from a 'deep environmental perspective'.

Beyond the above-mentioned, one distinctive feature of emergy synthesis, with respect to other methodological approaches used for the estimation of flows interacting in urban regions, more focused on energy use and its efficiency, both for dwelling operation and for dwellers transport, or on the life-cycles of construction materials used in buildings and other infrastructure, is the possibility of further perform an environmental assessment of the monetary flows used as remuneration for the work done by the residents, for the acquisition of goods and services, and as payment for imports and exports.

Within the larger framework of urban decision-making (social, economic and environmental aspects), the contribution of the work lies of course in the sustainability's environmental dimension, more specifically to the 'left side' of the urban life-cycle analysis, that is, in the assessment of resource utilization in planning contexts, which can be used to couple other approaches that focus more on the urban activities' impacts; thus emergy-based indicators may complement traditional indicators of urban sustainable development. The systemic approach used in this work tried to grasp the relationships of the urban structure's main elements, even with the risks and limitations involved, to try to contribute to the sustainable city utopia (and to the hypothetical existence of an optimum size or form) to which, eventually, we will come closer only by adding up the local sustainability of every human settlement in the global network of cities with the participation of each particular field of action and knowledge.

ANNEX I

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Research paper

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

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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

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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 × 1023 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

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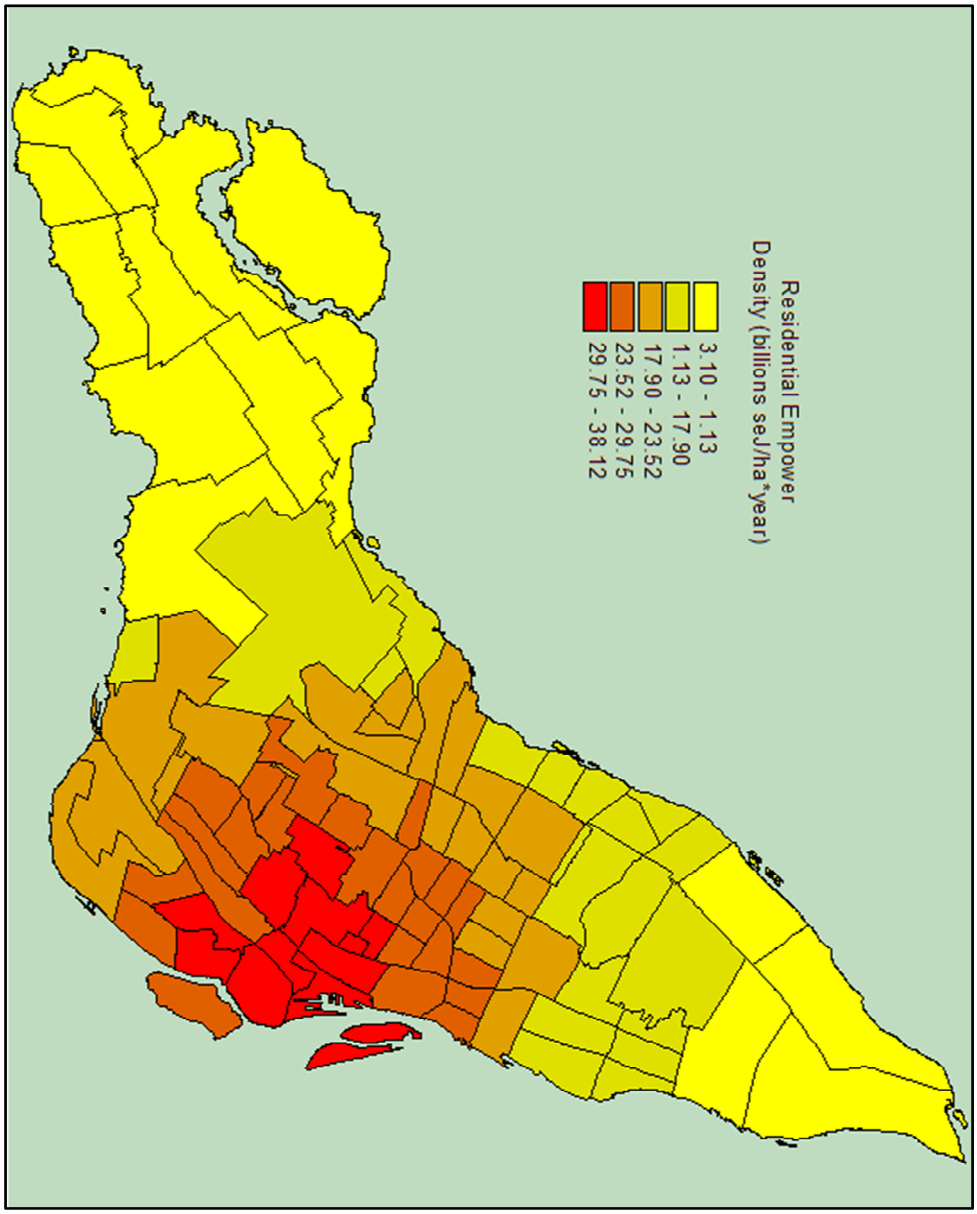
ANNEX II

Empower density of the residential land use for the City of Montreal's electoral districts and adjacent municipalities



BIBLIOGRAPHY

Agence métropolitaine de transport (AMT), 2010. *Mobilité des personnes dans la région de Montréal Enquête Origine-Destination 2008, version 08.2a (Mobility of people in the Montreal area Origin-Destination Survey 2008, version 08.2a)*. (Data processing: Ricardo Vega.) http://www.enquete-od.qc.ca/docs/EnqOD08_Mobilite.pdf [in French]. Accessed March 21, 2012.

Almeida, C.M.V.B., Barrella, F.A., Giannetti, B.F., 2007. *Emergetic ternary diagrams: five examples for application in environmental accounting for decision-making*. Journal of Cleaner Production 15 (1), p. 63-74.

Andrianoff, T., 2010. *Does denser mean richer?* http://timandrianoff.com/mapping/mapping_PRD.pdf. Accessed November 14, 2011.

Ascione, M., Bargigli, S., Campanella, L., Ulgiati, S., 2011. *Exploring an urban system's dependence on the environment as a source and a sink: the city of Rome (Italy) across space and time scales*. ChemSusChem 4 (5), p. 613-627.

Ascione, M., Campanella, L., Cherubini, F., Ulgiati, S., 2009. *Environmental driving forces of urban growth and development. An emergy-based assessment of the city of Rome, Italy*. Landscape and Urban Planning 93 (3-4), p. 238-249.

Baouendi, R., Zmeureanu, R., Bradley, B., 2005. *Energy and emission estimator: A prototype tool for designing canadian houses*. Journal of Architectural Engineering 11 (2), p. 50-59.

Barron, F. Hutton, Barrett, Bruce E., 1996. *Decision quality using ranked attribute weights*. Management Science 42 (11), p. 1515-1523.

Bastianoni, S., Campbell, D.E., Ridolfi, R., Pulselli, F.M., 2009. *The solar transformity of petroleum fuels*. Ecological Modelling 220(1), p. 40-50.

Bastianoni, S., Marchettini, N., Niccolucci, V., Pulselli, F.M., 2005. *Environmental accounting for the lagoon of Venice and the case of fishing*. Annali di Chimica 95 (3-4), p. 143-152.

Bengochea Morancho, Aurelia, 2003. *A hedonic valuation of urban green areas*. Landscape and Urban Planning 66 (1), p. 35-41.

Boarini, R., Johansson A., Mira d'Ercole, M., 2006. *Alternative measures of well-being*. Statistics Brief OECD, No. 11, May 2006, p. 8.

Bonenfant, R.R. Jr. 2009. *How to estimate the cost of structural steel*. American Society of Professional Estimators' Technical Paper. Estimating Today, January 2009, p. 15-22.

Bourassa, Steven C., Hoesli, Martin, Peng, Vincent S., 2003. *Do housing submarkets really matter?* Journal of Housing Economics 12 (1), p. 12-28.

Bramley, G., Power, S., 2009. *Urban form and social sustainability: the role of density and housing type*. Environment and Planning B: Planning and Design 36 (1), p. 30-48.

Brandt-Williams, S.L., 2001. *Handbook of Emergy Evaluation. Folio #4. Emergy of Florida Agriculture*. http://www.emergysystems.org/downloads/Folios/Folio_4.pdf. Accessed September 14, 2010.

Brown, M.T., 2011. *Sample system diagrams of ecosystems and regional systems*. http://www.emergysystems.org/downloads/System_DIAGRAM.zip. Accessed Sept. 22, 2011.

Brown, M.T., Bardi, E., 2001. *Handbook of Emergy Evaluation. Folio #3. Emergy of Ecosystems*. http://www.emergysystems.org/downloads/Folios/Folio_3.pdf. Accessed September 14, 2010.

Brown, M.T., Buranakarn, V., 2003. *Emergy indices and ratios for sustainable material cycles and recycle options*. Resources, Conservation and Recycling 38 (1), p. 1-22.

Brown, M.T., Ulgiati, S., 2004a. *Energy quality, emergy and transformity: H. T. Odum's contributions to quantifying and understanding systems*. Ecological Engineering 178 (1-2), p. 201-213.

Brown, M.T., Ulgiati, S., 2004b. *Emergy analysis and environmental accounting* in: Cleveland, C. J. (Eds.), Encyclopedia of Energy, Elsevier Academic, Oxford, p. 329-354.

Brown, M.T., Ulgiati, S., 2002. *Emergy evaluations and environmental loading of electricity production systems*. Journal of Cleaner Production 10 (4), p. 321-334.

Brown, M.T., Ulgiati, S., 2001. *Emergy measures of carrying capacity to evaluate economic investments*. Population and Environment 22 (5), p. 471-501.

Brown, M.T., Ulgiati, S., 1997. *Emergy-based indices and ratios to evaluate sustainability: monitoring economies and technology towards environmentally sound innovation*. Ecological Engineering 9 (1-2), p. 51-69.

Browne, David, O'Regan, Bernadette, Moles, Richard, 2011. *Material flow accounting in an Irish city-region 1992-2002*. Journal of Cleaner Production 19 (9-10), p. 967-976.

Burgess, E.W., 1925. *The growth of the city: An introduction to a research project*, in: Marzluff, J. M., Shulenberger, E., Endlicher, W., Alberti, M., Bradley, G., Ryan, C., ZumBrunnen, C., Simon, U. (Eds.), Urban Ecology. An International Perspective on the Interaction Between Humans and Nature. Springer Science+Bussiness Media, LLC., New York, 2008, p. 71-78.

Cabrera, S., Jaffé, K., 1998. *On the energetic cost of human societies: Energy consumption as an econometric index*. Interciencia 23 (6), p. 350-354.

Cai, Z.F., Zhang, L.X., Zhang, B., Chen, Z.M., 2009. *Emergy-based analysis of Beijing-Tianjin-Tangshan region in China*. Communications in Nonlinear Science and Numerical Simulation 14 (12), p. 4319-4331.

Campbell, S., 1996. *Green cities, growing cities, just cities?* Urban planning and the contradictions of sustainable development. Journal of the American Planning Association 62 (3), p. 296-312.

Campbell, D.E., Brandt-Williams, S.L., Meisch, M.E.A., 2005. *Environmental accounting using emergy: Evaluation of the State of West Virginia*. http://www.epa.gov/nheerl/publications/files/wvevaluationposted.pdf. Accessed September 29, 2010.

Canada Mortgage and Housing Corporation (CMHC), 2011. *Rental market report Montreal census metropolitan area*, p. 46.

Canada Mortgage and Housing Corporation (CMHC), 2001. *Analysis of the annual energy and water consumption of apartment buildings in the CMHC HiSTAR*. Research Highlight, p. 4.

Canada Mortgage and Housing Corporation (CMHC), 2000. *Greenhouse gas emissions from urban travel: tool for evaluating neighbourhood sustainability*. Research Report, p. 60.

Canadian Institute of Planners (CIP), 2013. *What is planning?* http://www.cip-icu.ca/web/la/en/pa/3FC2AFA9F72245C4B8D2E709990D58C3/template.asp. Accessed September 03, 2013.

Canadian Wood Council (CWC), 2004. *Energy and the Environment in Residential Construction*. Sustainable Building Series No. 1, p. 15.

Cao, T.T., Dornhaus, A., 2008. *Ants under crowded conditions consume more energy*. Biology Letters 4 (6), p. 613-615.

Castellini, C., Bastianoni, S., Granai, C., Dal Bosco, A., Brunetti, M., 2006. *Sustainability of poultry production using the emergy approach: comparison of conventional and*

organic rearing systems. Agriculture, Ecosystems and Environment 114 (2-4), p. 343-350.

Chen, S., Chen, B., 2012. *Network environ perspective for urban metabolism and carbon emissions: A case study of Vienna, Austria*. Environmental Science and Technology 46 (8), p. 4498-4506.

City of Montreal, 2013. *Open data portal. Polygons delimiting Montreal's neighborhoods and living environments (Portail données ouvertes. Polygons qui délimitent les quartiers et les milieu de vie de Montréal)*. Accessed April 12, 2013

City of Montreal, 2012. *Profils économiques des arrondissements. Montréal en statistiques. Par territoire. Arrondissements de Montréal. (Economic profiles of boroughs. Montreal in statisics. By territory. Montreal's boroughs)*. http://ville.montreal.qc.ca/portal/page?_pageid=6897,67845597&_dad=portal&_schema=PORTAL. Accessed May 04, 2012.

City of Montreal, 2011a. *The Montreal Economy*. http://www.montreal2025.com/decouvrir_economie.php?lang=en. Accessed October 27, 2011.

City of Montreal, 2011b. Eau potable traitée, agglomération de Montréal, moyenne annuelle (Treated drinking water, Agglomeration of Montreal, annual average). http://ville.montreal.qc.ca/portal/page?_pageid=6897,67889708&_dad=portal&_schema=PORTAL [in French]. Accessed March 29, 2011.

City of Montreal, 2011c. *Portrait 2010 des matières résiduelles de l'agglomération de Montréal (2010 Portrait of municipal solid wastes of the Montreal Agglomeration)*, p. 52.

City of Montreal, 2010a. *Établissements exportateurs et valeur des exportations, agglomération de Montréal (Exporting establishments and value of exports, agglomeration of Montreal)*. http://ville.montreal.qc.ca/portal/page?_pageid=6897,67885697&_dad=portal&_schema=PORTAL [in French]. Accessed April, 12, 2011.

City of Montreal, 2010b. *Volume et dépenses des touristes, agglomération de Montréal (Volume and expending by tourists, agglomeration of Montreal)*. http://ville.montreal.qc.ca/portal/page?_pageid=6897,67889573&_dad=portal&_schema=PORTAL [in French]. Accessed April, 12, 2011.

City of Montreal, 2009a. *Profils des 58 districts électoraux de la ville de Montréal. Édition 2009 (City of Montreal's 58 Electoral Districts Profiles. 2009 Edition)*, p. 136.

City of Montreal, 2009b. *Profil sociodémographique. Agglomération de Montréal. Édition 2009 (Socio-demographic profile. Montreal Agglomeration. 2009 Edition)*, p. 27.

City of Montreal, 2009c. *Profils sociodémographiques des arrondissements. Édition 2009. Montréal en statistiques. Par territoire. Arrondissements de Montréal (Socio-demographic profiles of boroughs. 2009 Edition. Montreal in statisics. By territory. Montreal's boroughs)*. http://ville.montreal.qc.ca/portal/page?_pageid=6897,67845597&_dad=portal&_schema=PORTAL. Accessed July 28, 2012.

City of Montreal, 2006. *Politique de protection et de mise en valeur des milieux naturels de Montréal. Bilan et orientations (Protection and enhancement policy for the natural environment of Montreal. Assessment and directions)*, p. 24.

City of Montreal, 2005. *Plan de transport de Montréal. Portrait et diagnostic. Note technique 9: Transport des marchandises (Montreal Transportation Plan. Portrait and Diagnostics. Technical Note 9: Transport of Goods)*, p. 21.

City of Montreal, 2004. *Montreal's Master Plan*. http://ville.montreal.qc.ca/portal/page?_pageid=2762,3099656&_dad=portal&_schema=PORTAL. Accessed March 14, 2013.

Codoban, N., Kennedy, C. A., 2008. *Metabolism of neighborhoods*. Journal of Urban Planning and Development 134(1), p. 21-31.

Communauté Métropolitaine de Montréal (CMM), 2011a. *Quantités gérées par les municipalités de l'agglomération de Montréal. Tableau de borde du Plan métropolitaine de gestion des matières résiduelles (Quantities handled by the municipalities of the agglomeration of Montreal. Dashboard of the waste management metropolitan plan)*. http://tbpmgmr.cmm.qc.ca/swf/MesureIndicateurs.php [in French]. Accessed April 6, 2011.

Communauté Métropolitaine de Montréal (CMM), 2011b. *Les forms d'habitat et la planification des densités résidentielles (Housing types and planning of residential densities)*, p. 24.

Davies, J. H., Davies, D. R., 2010. *Earth's surface heat flux*. Solid Earth, vol. 1, p. 15-24.

Decker, E.H., Elliott, S., Smith, F.A., Blake, D.R., Rowland, F.S., 2000. *Energy and material flow through the urban ecosystem*. Annual Review of Energy and the Environment 25, p. 685-740.

Economic Research Service of the United States Department of Agriculture (ERS-USDA), 2011. *International macroeconomic data set. Real GDP (2005 dollars) Historical*. http://www.ers.usda.gov/Data/Macroeconomics/Data/HistoricalRealGDPValues.xls. Accessed October, 20, 2011.

Edwards, Ward, Barron, F. Hutton, 1994. *SMARTS and SMARTER: Improved simple methods for multiattribute utility measurement*. Organizational, Behaviour and Human Decision Processes 60 (3), p. 306-325.

Engel-Yan, J., C. Kennedy, S. Saiz, K. Pressnail, 2005. *Toward sustainable neighbourhoods: the need to consider infrastructure interactions*. Canadian Journal of Civil Engineering 32 (1), p. 45-57.

Environment Canada, 2011. *Canadian Climate Normals or Averages 1971-2000. Montreal Pierre Elliot Trudeau International Airport Station*. http://climate.weatheroffice.gc.ca/climate_normals/results_e.html?stnID=5415&lang=e&dCode=1&StationName=MONTREAL&SearchType=Contains&province=ALL&provBut=&month1=0&month2=12. Accessed November 22, 2011.

Environment Canada, 2012. *Withdrawal water uses*. http://www.ec.gc.ca/eau-water/default.asp?lang=En&n=851B096C-1. Accessed, April 19, 2013.

Environment Canada, 2010. *Flows of the St. Lawrence River and its Main Tributaries*. http://www.ec.gc.ca/stl/default.asp?lang=En&n=B82B3625-1. Accessed December 9, 2010.

European Communities (EC), 2001. *Economy-wide material flow accounts and derived indicators. A methodological guide*. Office for Official Publications of the European Communities, Luxembourg, p. 92.

Farnsworth, E. 2010. *How to estimate the cost of a timber framed structure*. American Society of Professional Estimators, p. 6.

Fay, Roger, Treloar Graham, Iyer-Raniga, Usha, 2000. *Life-cycle energy analysis of buildings: a case study*. Building Research and Information 28 (1), p. 31-41.

Folke, C., Jansson, A., Larsson, J., Constanza, R., 1997. *Ecosystem appropriation by cities*. Ambio 26 (3), p. 167-172.

Fonck, C., Jaffé, K., 1996. *On the energetic cost of sociality*. Physiology and Behavior 59 (4-5), p. 713-719.

Forkes, J., 2007. *Nitrogen balance for the urban food metabolism of Toronto, Canada*. Resources, Conservation and Recycling 52 (1), p. 74-94.

Hau, J.L. and Bakshi, B.R., 2004. *Promise and problems of emergy analysis*. Ecological Modelling 178 (1-2), p 215-225.

Hendriks, C., Obernosterer, R., Müller, D., Kytzia, S., Baccini, P., Brunner, P.H., 2000. *Material Flow Analysis: A tool to support environmental policy decision making. Case studies on the city of Vienna and the Swiss lowlands*. Local Environment 5 (3), p. 311-328.

Hermanowicz, S.W., Asano, T., 1999. *Abel Wolman's the metabolism of cities revisited: A case for water recycling and reuse*. Water Science and Technology 40 (4-5), p. 29-36.

Hinterberger, Friedrich, Giljum, Stefan, Hammer, Mark, (2003). *Material flow accounting and analysis. A valuable tool for analyses of society-nature interrelationships*. Entry prepared for the Internet Encyclopedia of Ecological Economics, Sustainable Europe Research Institute, p. 1-19.

Hodder, D., Thiffault C., Saia, M.-A., 2001. *Atlas des bois de Montréal (Atlas of Montreal's Woods)*, p. 87.

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

Huang, S.-L., Chen, C.-W., 2005. *Theory of urban energetics and mechanisms of urban development*. Ecological Modelling 189 (1-2), p. 49-71.

Huang, S.-L., Hsu, W.-L., 2003. *Materials flow analysis and emergy evaluation of Taipei's urban construction*. Landscape and Urban Planning 63 (2), p. 61-74.

Huang, Shu-Li, Kao, Wei-Chieh, Lee, Chun-Lin, 2007. *Energetic mechanisms and development of an urban landscape system*. Ecological Modelling 201 (3-4), p. 495-506.

Hydro-Québec, 2011. *Rapport annuel 2010 (Annual report 2010)*, p. 118.

Hydro-Québec, 2009. *Profil régional des activités d'Hydro-Québec. Région de Montréal (Regional Profile of Hydro-Québec. Montreal Area)*, p. 110.

Hydro-Québec, 2005. *Comparaison des prix de l'électricité dans les grandes villes nord-americaines (Comparison of electricity prices in major North American cities)*, p. 74.

Ingwersen, W.W., 2010. *Uncertainty characterization for emergy values*. Ecological Modelling 221 (3), p. 445-452.

Institute of Statistics of Quebec (ISQ), 2012. *Bulletin statistique régional Montréal, Édition 2012 (Montreal Regional Statistics Bulletin, 2012 Edition)*, p. 27.

Institute of Statistics of Quebec (ISQ), 2011. *Produit intérieur brut aux prix de base par région administrative, Québec, 2003-2007 (Gross domestic product at basic prices by Quebec administrative region, 2003-2007)*. http://www.stat.gouv.qc.ca/donstat/econm_finnc/conjn_econm/compt_econm/pib_ra_2003-2007.htm [in French]. Accessed September 15, 2011.

Institute of Statistics of Quebec (ISQ), 2010. *Bulletin statistique régional Montréal, Édition 2010 (Montreal Regional Statistics Bulletin, 2010 Edition),* p. 32.

Institute of Statistics of Quebec (ISQ), *2009. Coûts des matières premières et de l'énergie utilisés dans le secteur de la fabrication, par région administrative et sous-secteur du SCIAN, Québec, 2005 (Cost of the raw materials and energy used in the manufacturing sector, by administrative region and NAICS subsector, Québec, 2005)*. http://www.stat.gouv.qc.ca/donstat/econm_finnc/sectr_manfc/profil_secteur/ra_2005_scian3_couts.htm [in French]. Accessed February 21, 2011.

Kennedy, C., Cuddihy, J., Engel-Yan, J., 2007. *The changing metabolism of cities*. Journal of Industrial Ecology 11 (2), p. 43-59.

Kennedy, C., Pincetl, S., Bunje, P., 2011. *The study of urban metabolism and its applications to urban planning and design*. Environmental Pollution 159 (8-9), p. 1965-1973.

LEAD International, 2008. *Megacities and climate change. Sustainable urban living in a changing world*. First ed. LEAD International, London, p. 56.

Leedy, P.D., Ormrod, J.E. , 2010. *Practical research: Planning and design*. Ninth ed., Pearson, Boston, p. 336.

Lei, K., Wang, Z., Ton, S., 2008. *Holistic emergy analysis of Macao*. Ecological Engineering 32 (1), p. 30-43.

Leloup, X., Séraphin, I., 2009. *Étude post occupation de projets résidentiels pour familles en milieu urbain dense (Post occupancy study of residential projects for families in dense urban environment)*. Institut National de la Recherche Scientifique (National Institute for Scientific Research), p. 120.

Li, D., Wang, R., 2009. *Hybrid Emergy-LCA (HEML) based metabolic evaluation of urban residential areas: the case of Beijing, China*. Ecological Complexity 6 (4), p. 484-493.

Liu, R., 2007. *Energy consumption and energy intensity in multi-unit residential buildings in Canada*. Canadian Building Energy End-Use Data and Analysis Center, p. 20.

Liu, Y., Song, Y., Arp, H.P., 2012. *Examination of the relationship between urban form and urban eco-efficiency in China*. Habitat International 36 (1), p 171-177.

Liu, G.Y., Yang, Z.F., Chen, B., Su, M.R., Zhang, Y., Zhang, L.X., Jiang, M.M., 2011a. *Extended exergy analysis of urban socioeconomic system: a case study of Beijing, 1996-2006*. International Journal of Exergy 9 (2), p. 168-191.

Liu, G.Y., Yang, Z.F., Chen, B., Zhang, Y., 2011b. *Ecological network determination of sectoral linkages, utility relations and structural characteristics on urban ecological economic system*. Ecological Modelling 222 (15), p. 2825-2834.

Marchettini, N., Ridolfi, R., Rustici, M., 2007. *An environmental analysis for comparing waste management options and strategies*. Waste Management 27 (4), p. 562-571.

Ministry of Natural Resources and Wildlife of Quebec (MNRW), 2011. *Granulats : sable et gravier (Aggregates: sand and gravel)*. http://www.mrnf.gouv.qc.ca/mines/industrie/industrie-substances-sable.jsp [in French]. Accessed January 28, 2011.

Muñiz, I., Galindo, A., 2005. *Urban form and the ecological footprint of commuting. The case of Barcelona*. Ecological Economics 55 (4), p. 499-514.

National Aeronautic and Space Administration (NASA), 2000. *Insolation Levels. Surface meteorology and Solar Energy Data Set* (taken from: Whitlock, Charles H., D. E. Brown, W. S. Chandler, R. C. DiPasquale, N. Meloche, G. J. Leng, S. K. Gupta, A. C. Wilber, N. A. Ritchey, A. B. Carlson, D. P. Kratz, et P. W. Stackhouse. 2000. Release 3 NASA Surface Meteorology and Solar Energy Data Set For Renewable Energy Industry Use. Proceedings of Rise and Shine 2000, the 26th Annual Conference of the Solar Energy Society of Canada Inc. and Solar, Oct. 21-24, 2000, Halifax, Nova Scotia, Canada).

Natural Resources Canada. Office of Energy Efficiency (NRC-OEE), 2007. *Fuel Consumption Guide 2008*, p. 65.

Newman, P.W.G., (1999). *Sustainability and cities: extending the metabolism model*. Landscape and Urban Planning 44(4), p. 219-226.

Newman, Peter W. G., Kenworthy, Jeffrey R., 1989. *Gasoline consumption and cities. A comparison of U.S. cities with a global survey*. Journal of the American Planning Association 55 (1), p. 24-37.

Nocus, S. F. 2009. *How to estimate the cost of load bearing wood framed walls*. American Society of Professional Estimators' Technical Paper. Estimating Today, April 2009, p. 11.

Norman, J., MacLean, H. L., Kennedy, C. A., 2006. *Comparing high and low residential density: life-cycle analysis of energy use and greenhouse gas emissions*. Journal of Urban Planning and Development 132(1), p. 10-21.

Organisation for Economic Co-operation and Development (OECD), 2011. *2005 Purchasing Power Parities (PPP) Benchmark Results. Table 1.12 PPP in national currencies per US dollar (United States = 1.00)*. http://stats. oecd.org/Index.aspx?DataSetCode=PPP2005. Accessed October 4, 2011.

Odum, H.T., 1996. *Environmental accounting: Emergy and environmental decision making*. First ed., John Wiley, New York, p. 370.

Odum, H.T., 2000. *Handbook of Emergy Evaluation. Folio #2. Emergy of Global Processes*. http://www.emergysystems.org/downloads/Folios/Folio_2.pdf. Accessed September 14, 2010.

Paez, A., Mercado, R. G., Farber, S., Morency, C., Roorda, M. 2010. *Accessibility to health care facilities in Montreal Island: an application of relative accessibility indicators from the perspective of senior and non-senior residents*. International Journal of Health Geographics, 2010, 9:52. DOI: 10.1186/1476-072X-9-52.

Pauleit, S., Duhme, F., 2000. *Assessing the environmental performance of land cover types for urban planning*. Landscape and Urban Planning 52(1), p. 1-20.

Perkins, A., Hamnett, S., Pullen, S., Zito, R., Trebilcock, D., 2009. *Transport, Housing and Urban Form: The Life Cycle Energy Consumption and Emissions of City Centre Apartments Compared with Suburban Dwellings*. Urban Policy and Research 27(4), p. 377-396.

Pullen, S.F., 2000. *Energy used in the construction and operation of houses*. Architectural Science Review 43 (2), p. 87-94.

Pulselli, R.M., 2010. *Integrating emergy evaluation and geographic information systems for monitoring resource use in the Abruzzo region (Italy)*. Journal of Environmental Management 91 (11), p. 2349-2357.

Pulselli, R.M., Simoncini, E., Ridolfi, R., Bastianoni, S., 2008. *Specific emergy of cement and concrete: an energy-based appraisal of building materials and their transport*. Ecological Indicators 8 (5), p. 647-656.

Pulselli, R. M., Simoncini, E., Pulselli, F. M., Bastianoni, S., 2007. *Emergy analysis of building manufacturing, maintenance and use: Em-building indices to evaluate housing sustainability*. Energy and Buildings 39 (5), p. 620-628.

Pulselli, R. M., Pulselli, F. M., Marchettini, N., Bastianoni, S. 2006. *Environmental accounting of buildings: outcomes from the emergy analysis*. WIT Transactions on Ecology and the Environment 93 (The Sustainable City IV: Urban Regeneration and Sustainability), p. 489-498.

Purenne, P., 2009. *Rapport annuel 2008. Analyse de la qualité des eaux brutes et de l'eau traitée à la Station d'épuration et évaluation du rendement des installations (Annual Report 2008. Analysis of the quality of raw and treated water at the treatment plant and evaluation of the facilities' performance)*, p. 58.

Purenne, P., 2007. Rapport annuel 2005. *Analyse de la qualité des eaux brutes et de l'eau traitée à la Station d'épuration et évaluation du rendement des installations (Annual Report 2005. Analysis of the quality of raw and treated water at the treatment plant and evaluation of the facilities' performance)*, p. 55.

Ramesh, T., Prakash, Ravi, Shukla, K.K., 2010. *Life cycle energy analysis of buildings: An overview*. Energy and Buildings 42 (10), p. 1592-1600.

Rees, W., Wackernagel, M., 1996. *Urban ecological footprints: why cities cannot be sustainable - and why they are a key to sustainability*. Environmental Impact Assessment Review 16 (4-6), p. 223-248.

Rickwood, P., Glazebrook, G., Searle, G., 2008. *Urban Structure and Energy - A Review*. Urban Policy and Research 26 (1), p. 57-81.

Safirova, E., Houde, S., Harrington, W., 2007. *Spatial development and energy consumption*. Resources For The Future. Discussion paper, p. 47.

Sahely, H.R., Dudding, S., Kennedy, C.A., 2003. *Estimating the urban metabolism of Canadian cities: Greater Toronto Area Case Study*. Canadian Journal of Civil Engineering 30 (2), p. 468-483.

Sartori, Igor, Hestnes, Anne Grete, 2007. *Energy use in the life cycle of conventional and low-energy buildings: A review article*. Energy and Buildings 39 (3), p. 249-257.

Schlesier, B. E. 2010. *How to estimate the cost of concrete construction*. American Society of Professional Estimators' Technical Paper. Estimating Today, March 2010, p. 12.

Schreyer, P., Koechlin F., 2002. *Purchasing power parities – measurement and uses*. Statistics Brief OECD, No. 3, March 2002, p. 8.

Sciubba, E., Bastianoni, S., Tiezzi, E., 2008. *Exergy and extended exergy accounting of very large complex systems with an application to the province of Siena, Italy*. Journal of Environmental Management 86 (2), p. 372-382.

Sciubba, E., Ulgiati, S., 2005. *Emergy and exergy analyses: Complementary methods or irreducible ideological opinions?* Energy 30 (10), p. 1953-1988.

Statistics Canada, 2013. *Households and the Environment 2011*, p. 181.

Statistics Canada, 2012. *Census Dictionary*, p. 166.

Statistics Canada, 2012. *Consumer Price Indexes, historical summary*. http://www.statcan .gc.ca/tables-tableaux/sum-som/l01/cst01/econ46a-eng.htm. Accessed July 12, 2012.

Statistics Canada, 2010. *Households and the Environment: Energy Use 2007*, p. 39.

Statistics Canada, 2009. *Food Statistics 2008*, p. 42.

Statistics Canada, 2006. *Food Statistics 2005*, p. 46.

Steemers, K., 2003. *Energy and the city: density, buildings and transport*. Energy and Buildings 35 (1), p. 3-14.

Treolar, G.J., Love, P.E.D., Holt, G.D., 2001. *Using national input-output data for embodied energy analysis of individual residential buildings*. Construction Management and Economics 19 (1), p. 49-61.

Troy, P., Holloway, D., Randolph, B. 2005. *Water Use and the Built Environment: Patterns of Water Consumption in Sidney*. City Futures. Research Papers, p. 82.

Tukker, A., Cohen, M.J., Hubacek, K., Mont, O., 2010. *The impacts of household consumption and options for change*. Journal of Industrial Ecology 14 (1), p. 13-30.

Ulgiati, S., Brown, M.T., Bastianoni, S., Marchettini, N., 1995. *Emergy-based indices and ratios to evaluate the sustainable use of resources*. Ecological Engineering 5 (4), p. 519-531.

Ulgiati, S., Odum, H.T., Bastianoni, S., 1994. *Emergy use, environmental loading and sustainability*. An emergy analysis of Italy. Ecological Modelling 73 (3-4), p. 215-268.

United Nations (UN), 2012. *World Urbanization Prospects, the 2011 Revision*. Department of Economic and Social Affairs, Population Division, Population Estimates and Projections Section.

United Nations Environment Programme (UNEP), 2002. *Global Environmental Outlook 3 (GEO-3)*. 1st ed. United Kingdom: Earthscan Publications Ltd., p. 446.

United Nations Human Settlements Programme (UN-HABITAT), 2011.*Cities and Climate Change: Global Report on Human Settlements 2011*. 1st ed. United Kingdom; United States of America: Earthscan Publications Ltd, p. 279.

United Nations Human Settlements Programme (UN-HABITAT), *2008. State of World Cities 2008/2009, Harmonious cities*. 1st ed. United Kingdom; United States of America: Earthscan Publications Ltd., p. 259.

United Nations Human Settlements Programme (UN-HABITAT), *2006. State of the World's Cities 2006/2007*. 1st ed. United Kingdom; United States of America: Earthscan Publications Ltd, p. 202.

Vega-Azamar, R.E., Glaus, M., Hausler, R., Oropeza-García. N.A., Romero-López, R., 2013. *An emergy analysis for urban environmental sustainability assessment, the Island of Montreal, Canada*. Landscape and Urban Planning 118, p. 18-28.

Wackernagel, Mathis, Rees, William, 1996. *Our ecological footprint: Reducing human impact on Earth*, 1st ed., New Society Publishers, Gabriola Island, B.C., Canada, p. 160.

Wolman, A.,1965. *The metabolism of cities*. Scientific American 213(3), p. 179-190.

Zhang, Y., Singh, S., Bakshi, B.R., 2010. *Accounting for Ecosystem Services in Life Cycle Assessment, Part I: A Critical Review*. Environmental Science and Technology 44 (7), p. 2232-2242.

Zhang, Y., Yang, Z., Liu, G., Yu, X., 2011. Emergy analysis of the urban metabolism of Beijing. Ecological Modelling 222(14), p. 2377-2384.

Zhang, Y., Zhao, Y.W., Yang, Z.F., Chen, B., Chen, G.Q., 2009. *Measurement and evaluation of the metabolic capacity of an urban ecosystem*. Communications in Nonlinear Science and Numerical Simulation 14 (4), p. 1758-1765.

Zhou, J. B., Jiang, M. M., Chen, B., Chen, G. Q., 2009. *Emergy evaluations for constructed wetland and conventional wastewater treatments*. Communications in Nonlinear Science and Numerical Simulation 14 (4), p. 1781-1789.