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Assessment of municipal potential prosperity, carrying capacity and trade

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ABSTRACT

Understanding the potential prosperity of municipal economies, the welfare and the role of trade of these economies is an important issue in a world in which more than 50% of the population lives in urban centers. ABC Paulista groups three cities which act as production centers combining the abundance of labor and knowledge with the proximity to big consumer centers. The emergy approach recognizes the existence of deterministic principles in economic systems but emphasizes the role of resources, energy and environment. This approach was applied to ABC Paulista to evaluate municipal potential prosperity in the context of the energy resource constraints and showed that ABC municipalities are not autonomous and depend almost entirely on external resources. Indices for assess the human carrying capacity and the standards of living showed that only 2% of the population could be sustained indefinitely by the local emergy. The results lead to the idea that ABC can be seen as an "industry", which holds the know-how and assets transforming raw materials into vehicles and chemicals that are feedback to the surrounding system. However, the analysis of ABC trade shows that both the Brazilian and the foreign markets take advantage when buying from ABC suggesting that the search for the chances of the prolongation of this specific urban settlement may require different policies and management designs.

1. Introduction

For many centuries, society has developed based on the use of energy from non-renewable resources - those that nature is not able of replacing within the window time of the society's expansion. Urban agglomerations generate massive changes in lifestyle, land use, demand for energy and other resources as well as environmental pressure (Ascione et al., 2009). While economic growth may provide prosperity and better quality of living, much of the human impact causes irreparable consequences on environmental systems (Vaz et al., 2014).

The total population of urban areas in 2014 was estimated at nearly 3.9 billion, 54% of the world urban population, and by the year 2050, 66% of the world population is expected to be urban (UNDESA, 2014). According to the World Bank, in 2009, 75% of global economic production was concentrated in municipalities influencing the larger system within they are inserted economically, socially, politically and, especially, environmentally. This influence ranges from local to the global level (Oliveira et al., 2013). Materials, energy, and food supplies are brought to and transformed into the urban centers concentrating emergy flows and supporting economies in reduced areas. The constant increase in natural resource consumption to meet the needs of metropolitan populations and the associated generation of waste is leading to a less and less sustainable ecological footprint (Vega-Azamar et al., 2013). While the economic development is accelerated by the use of cheap fossil fuels and electricity interacting with the resources that support human life (water, air and land), from the ecosystem's perspective cities are often unsustainable. Municipalities use natural flows, and also accumulate materials that become urban assets such as buildings and infrastructure (Sevegnani et al., 2016). Thus, a fundamental point is how to evaluate the sustainable development ability of those ecological-economic systems in a quantitative manner (Agostinho et al., 2016).

The available literature regarding emergy synthesis applied to urban systems reveals a great concern in understanding, quantifying and characterizing the flows that give support to urban areas. Some papers focus this concern toward the application of results to improve public policies. Others concern on developing complementary indices to improve the information that may be used for

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decision making within specific sectors. Sahely et al. (2003) pointed out that research on urban metabolism can help solving environmental problems by highlighting the burden that the urban ecosystem causes exploiting resources and pressuring the environment. The existence and maintenance of an urban system and its internal structure depend on the flow of goods and services into, out of, and throughout that city (Huang and Chen, 2009). Consequently, there must be a steady energy flow, coming from various locations of the biosphere, in the form of materials, people and information crossing the boundaries of the municipality. A system driven by non-local resources (renewable or not) is never “sustainable”, although it can be stable for a relatively long time, depending on the availability of the support flows from outside (Ascione et al., 2009). The urban population growth generates several changes in energy demand, lifestyle and land use, and consequent environmental pressure. In this context, Perkins et al. (2009) claimed that the influence of the nature and intensity of occupation of the city's territory must be considered in regard to resource consumption and the consequent waste generation. Understanding this relationship is important for future development, planning decisions and the creation of urban regions with lower environmental impact. In 2014, Shi and Yang performed a study of the material flow between urban and natural ecosystems. The study applies a framework that combines input-output flow analysis, health assessment, and function optimization to the cities of Wuhan and Tianjin. The authors point out that this approach can diagnose the health of urban ecosystems. Geng et al. (2014) used the ecological footprint to evaluate two industrial cities from 1997 to 2009: Shenyang (China) and Kawasaki in Japan. Differently from previous studies this one compared cities from countries in different levels of development. The results show that Shenyang's ecological footprint increased, while in Kawasaki was stable. The sustainability of regional development with respect to urban agglomeration is much associated with the performance of individual cities and their interactions with each other (Cai et al., 2009). Reciprocity between subsystems with competing objectives is viewed today as a crucial determinant of system sustainability (Higgins, 2003) and for the development of new regional innovation patterns based on a careful quantitative analysis (Vaz, 2016).

Oliveira et al. (2013) suggested that some of the essential parts of a city economy are those not captured by the traditional economy concepts, such as ecosystem services, social services and knowledge-based activities (human and intellectual capital). These elements are underestimated or neglected by policymakers since they are not accounted in the cities and countries gross domestic products (GDP). This idea has been explored since the 80s when Brown (1980) used data of regional and national patterns of landscape organization to examine the energy flow control and suggested that human and nature landscapes are hierarchically structured. Thus, in these landscapes, the potential for human activity could be predicted from energy distribution or the required embodied energy. During the 90s, the embodied energy was replaced by the required emergy to assess regional systems including urban systems. Odum et al. (1995) developed a model for zonal energy simulation emphasizing that both energy and emergy for each city zone may be represented and related to the concepts and hypotheses of the model. Since the 80s, emergy synthesis has been widely applied to evaluate countries, regions and cities all over the world. In the last decade, Giannetti et al. (2006), created a graphic tool, called emergy ternary diagram, to support environmental accounting and environmental decision-making that was applied to the Taipei urban system studied by Huang and Odum, 1991 (Almeida et al., 2007). In 2010, Giannetti et al. compared the emergy indices with well-known sustainability metrics among the countries of the Southern Cone Common Market and concluded that emergy indices provide a broader vision that considers the biosphere point of view and complements the traditional indices. More recently, Hossaini and Hewage (2013) applied emergy accounting to Canada and its provinces resulting several emergy-based indicators as well as emergy maps. The maps showed clearly resource consumption, emergy per person, and emergy density across Canada. Campbell and Garmestani (2012) performed an emergy evaluation of the San Luis Basin regional system in southern Colorado, aiming to create a framework based on the Energy Systems Theory (EST) developed by Odum (1994). The region was also evaluated as a part of the larger system aiming to determine if it was moving away or towards the sustainability.

In Europe, emergy was successfully used to evaluate Italian cities and regions. Pulselli et al. (2007) used an integrated framework to the Province of Cagliari, to examine human-dominated systems. They presented an approach to urban and regional studies in which the numerous interactions between ecological and economic processes are considered as a whole. These authors observed that industrial districts and cities, with many transformation processes and high population density, function as nodes with the highest intensity of emergy flows and the highest levels of organization. They concluded that the emergy land use patterns may help planning and management of spatial allocation the arrangement of infrastructures in regard to ecosystem functions and emergy flow redistribution. In 2008, Pulselli et al. showed how to integrate diverse methods to provide an assessment of the environmental sustainability at the territorial level. The article described the SPIn-Eco Project (2001–2004) that assessed the environmental state and the sustainability of the Province of Siena. Ascione et al. (2009) estimated the resource base of Rome using emergy concepts to understand the direct and indirect environmental work supporting the city. They calculated the portion of municipal assets, population and activities that could rely solely on locally available renewable resources, and showed how to use their results for policy making. Ulgiati et al. (2011) used the data of Rome (Ascione et al., 2009) and of the agricultural sector of the Campania Region (Zucaro et al., 2010) to propose and apply a complexity indicator based on the energy and resource used by a system called diversity ratio. Pulselli (2010) used a geographic information system combined with the emergy accounting for monitoring the resource use in the Abruzzo region in Italy representing the spatial distribution of the emergy flows with a cartographic visualization. Morandi (2012) developed and applied a model to real cases considering nested territorial systems with three levels of organization, i.e. European Union, Italy and Tuscany.

In spite of the number of studies developed in America and in Europe, it is in Asia that emergy is widely applied to evaluate urban systems and to propose management models and public policies. Lei at al. (2008) provided a holistic view of the complex urban system of Macao and introduced the net emergy ratio and net emergy to assess the real wealth of Macao. Lei and Wang (2008) investigated and characterized the urban evolution of Macao from 1983 to 2003 highlighting the contribution of the tourism emergy flow. Later, Lei et al. (2015) studied the metabolism of Macao using mass, energy and emergy analysis to quantify the metabolic processes that occurred in the city. The study showed that how the anabolic and catabolic densities increased due to the high influx of visitors. Zhang et al. (2009a, b) developed indicators for evaluating the city's metabolic processes and verified its use in a case study of Beijing. The emergy-based indicator (non-renewable emergy/money ratio) considered fluxes, stocks, and the efficiency, and showed that three cities exhibited similar overall trends of increasing total emergy. Later, Zhang et al. (2011) analyzed Beijing's system to evaluate its environmental resources, economy, and environmental and economic relations with the regions outside the city during 14 years of development. The authors compared Beijing's emergy indices with those of five other Chinese cities and of China as a whole to assess Beijing's relative development status.

Su et al. (2009) proposed a framework to assess the urban ecosystem health with respect to the energy and materials metabolism. These authors combined emergy-based indicators with the critical components of the urban ecosystem health and assessed the health of 20 typical Chinese cities in view of environmental impact, vigor, resilience, structure, and ecosystem service function maintenance. Also using emergy concepts, Liu et al. (2009) assessed the urban ecosystem health of Baotou confronting the results of the traditional ecosystem health assessment. Chen et al. (2011) presented a conceptual model to quantify ecological and economic interactions between two cities, which include raw material flows, transportation, tourism, water flow, labor transfer, goods flow, mineral flow, etc. In 2013, Liu et al. evaluated economic and ecological losses, and proposed a sustainability policy-making framework for 31 Chinese cities. Yang et al. (2013) used emergy and carbon footprint accounting to investigate the environmental pressure generated by household consumption in Xiamen, a coastal city in south-east China.

Wang et al. (2015) applied emergy theory to measure regional sustainability in the Yellow River Delta region of China that has Dongying as its main city, in a holistic way. The study used data from 2009 and the authors used GIS technology, making possible to assess not only the natural resources but also the Net Primary Production of the ecosystem. The authors calculated an Emergy Sustainable Index (ESI) of 0.79, which was observed as higher when compared to other cities in other studies, but the fraction of nonrenewable resources was still the highest among all. Sun et al. (2015) applied the urban metabolism tool to study a typical industrial city in China. These authors pointed out that most of existing urban metabolism studies focused on metabolic flux analysis, the amount of substances and energy metabolism. In this study, the key factors of the urban metabolism were studied by combining emergy (to analyze the sustainable development level) and the Logarithmic Mean Divisia Index (to identify the driving forces of emergy use). Policy recommendations involve the use of renewable and cleaner energy sources to reach a regenerative and preventative eco-industrial development. Dong et al. (2015) studied the industrial and urban symbiosis in Guiyang and described the process in which municipal solid wastes recycling and waste energy utilization were incorporated to the city metabolism. Recently, Lou and Ulgiati (2013) performed an emergy evaluation of the Chinese economy aiming to compare the findings with the previously published results and standardizing the previous calculation procedures.

Most of the literature references related to cities sustainability and their interaction with the environment have no more than 10 years, and there is still a vast space for contributions and developments. In this work, emergy accounting is applied to evaluate, through an approach capable to gather economic and environmental aspects, the potential prosperity, carrying capacity and trade of ABC Paulista (ABC), which is composed of three municipalities: Santo André (A), São Bernardo do Campo (C) and São Caetano do Sul (C).

2. Methods

Emergy measures both the work of nature and that of humans in generating products and services. The methodology was developed by Odum (1996) and accounts for the resources provided by the environment or the economy to obtain a product, process or service. The potential prosperity, the carrying capacity and the trade of ABC are assessed with the emergy indices proposed by Sweeney et al. (2007) for the evaluation of countries, which were combined with the shift-share analysis to estimate the flows from the Brazilian internal economy.

The emergy method states that the resources that support any system are divided into renewable (R), non-renewable (N), and purchased resources (F) that come from outside the system. The total emergy (U) is the sum of renewable (R), non-renewable (N), and purchased resources (F), and accounts for all inputs of energy needed directly or indirectly to make any product or service. Each flow is multiplied by a Unit Emergy Value (UEV) to obtain the amount of emergy. UEVs follow the concept of transformity, defined by Odum (1996), as the quotient between the emergy of a product and its energy, translating the solar emergy required to obtain 1 J of a product or service (sej/J). The use of a common basis (solar equivalent joules, sej) permits to account all the sources that contribute to a system, and the emergy indices provide information on the relationship system/environment (Table 1).

In the study of countries, states, counties, cities, frequently some data, being them economic, environmental or social, become more and more scarce the smaller the system is. Due to the lack of regional data regarding each municipality of ABC, the Shift-Share analysis was used to estimate the exchanges between ABC and Brazil.

The Shift-Share analysis quantifies the labor used in a given sector or industry and compares it to a larger scale scenario where the sector is inserted. The Shift-Share analysis was applied to A, B, C and ABC placed in the larger scenario, Brazil. The method and the detailed calculations for the Shift-share analysis can be found in the Supplementary Material (Part A).

The emergy accounting was performed based on the tables from National Environmental Accounting Database (NEAD, 2000), as described by Sweeney et al. (2007). The energy of renewable resources and the flow of imported and exported resources were obtained from governmental institutions websites and from the city council (IBGE, 2013; CRESESB, 2010; SECEX, 2012; SEADE, 2012; City council, 2011a, b, c). The UEVs were based on information obtained by bibliographic research using the approximate planetary baseline of 15.83×10^{24} sej/year (Odum et al., 2000). Services that come from inside Brazil were calculated using the Shift-Share analysis. The method and the detailed calculations for the Shift-share analysis can be found in the Supplementary Material (Part A). Direct labor that comes from other municipalities of the state of São Paulo was calculated combining data of Census 2010 published by IBGE (2013).

2.1. System's description

ABC is an urban agglomerate composed by three cities: Santo André (A), São Bernardo do Campo (B) and São Caetano do Sul (C) located in the state of São Paulo, Brazil, and belongs to the Greater São Paulo along with other 39 municipalities. These cities are important industrial, technological and housing centers, and their major industrial activities are related to automotive and chemical sectors. The 2009 GDP of ABC contributed with 4.8% of the GDP of the state of São Paulo, and with almost 3% of the GDP of Brazil. In Brazil's GDP rank, São Bernardo do Campo occupied the 13th position and Santo André 29th (IBGE, 2013) (Table 2). The region is also an important supplier of natural resources, as the Billings dam, partially located in Santo André and São Bernardo do Campo is one of the main water reservoirs of Greater São Paulo (Fig. 1).

Both A and B count with rural areas, whilst C is surrounded and limited by the neighbors' urban growth and has no place for expansion other than vertical growth (Sevegnani et al., 2013). Fig. 1 shows a satellite image of the urban cluster and Table 2 shows main figures about the ABC and its municipalities. In regard to the

Table 1
Description of the emergy indices for general use and to evaluate national/regional/urban systems.

	Description
ELR = F + N/R	The environmental loading ratio estimates the stress of the local environment due to its activity. It is the ratio of the economic inputs (F) and local nonrenewable emergy (N) to free environmental emergy (R). The lower the portion of renewable emergy used, the higher the pressure on the environment.
EYR = R + N + F/U	The emergy yield ratio is the ratio of the emergy of the output to the emergy of economics inputs and represents the emergy return on economic investment. This indicator computes the process ability to profit from local resources. The lower the portion of the economic input (F) the higher is this ability. However, this index does not differentiate local and imported resources.
EIR = F/N + R	The emergy investment ratio shows the relation between the emergy of the economic inputs with those provided by the local environment, renewable or not. It evaluates if a system is an efficient user of emergy that comes from outside its boundaries.
ESI = EYR/ELR	The emergy sustainability index arises from the ratio of EYR to ELR. The fact that it is preferable to have a higher emergy yield per unit of environmental loading defines this index that evidences if a process offers a profitable contribution to the user with a low environmental pressure.
U/population	Emergy per capita (sej/person): the ratio of total emergy used in the economy of a region or nation to the total population. Emergy per capita can be used as a measure of potential, average standard of living of the population.
(R/U) × population	Renewable carrying capacity at present living (persons): represents the environment's ability to support economic development based solely on its renewable emergy sources. The result is the population capable to "sequester" the equivalent emergy that comes only from renewable sources (Brown and Ulgiati, 2001).
8 × (R/U) × population	Developed carrying (persons): is the population capable to "sequester" the equivalent emergy that comes only from renewable sources if the quantity of these resources was multiplied by eight. The use of this value (eight) assumes that developed countries use eight times more emergy than their renewable base supply (Odum, 1996).
Emergy of electricity/U	Electricity fraction (%): the fraction of emergy of electricity compared to the total emergy.
Fuel/population	Fuel use per capita (sej/person): the fraction of emergy of fuel compared to the total emergy.
EMR = U/GDP	The emergy money ratio is calculated by the sum of all emergy of the system (U = R + N + F) divided by the GDP of the region under study (sej/USD). This indicator makes possible to evaluate and quantify each emergy flow in monetary units. EMR not only indicates the effort to generate a dollar (or how much emergy is required to generate one currency unit), but also the buying power of one dollar in a given area (or how much emergy can be bought by one currency unit).
Emergy benefit ratio	The emergy benefit to the purchaser or seller is inferred by the ratio of the emergy in the product (exports) to the emergy in the money received (money received from exports x EMR).

Where: R: the sum of all renewable emergy that flows into the system; N: the local non-renewable resources of the system; F: the flow of imported emergy is the sum of all purchased resources from outside the system's boundaries, including goods and electricity imports; and U: the total emergy.

Table 2
Main information about the municipalities of ABC Paulista.

	Municipality			ABC
	A	B	C	
Area[a] (km^2)	175	406	15	596
Population[a] (inhabit.)	673,396	810,979	152,093	1,636,468
GDP (10^3 USD)	7,354,801	14,467,883	4,460,101	26,282,785
GDP[(*)] per capita[a] (USD)	10,921	17,840	29,324	16,060
Human development index [a,b]	0.835	0.834	0.919	–
Percentage of green area[c]	35.8	47.0	0.1	42.5
Total in green area (km^2) [c]	62.62	190.70	0.02	253.33
Latitude[a]	−23° 39′ 50″	−23° 41′ 38″	−23° 37′ 23″	–
Longitude[a]	−46° 32′ 18″	−46° 33′ 54″	−46° 33′ 04″	–
Height (m)[a]	755	762	744	–

Where: Santo **A**ndré (A), São **B**ernardo do Campo (B) and São **C**aetano do Sul (C).
[a] IBGE (2013).
[b] UNPD (2000).
[c] Secretary of Environment (2009).

industry activity profile, A is mainly focused on the chemical sector while B and C activities are more focused in the automotive industry. The ABC cities compete for market and local resources. However, from the standpoint of regional development, they share the relative benefits of clustering industrial activities, similar climate conditions, and infrastructure facilities. Further information can be found in Sevegnani et al., 2016.

3. Results and discussion

For conducting a critical inventory of the relevant processes, storages and flows that contribute to ABC the energy system diagram (Fig. 2) helps to understand the dynamics of this urban ecosystem. With the aid of the diagram, it is possible to identify the renewable natural resources (rain, wind and sun) that feed the ABC (urban areas, agricultural areas, industrial activities), and its storages (water reservoirs, biomass, built environment). The water reservoir, partially located at A and B, provides water to various municipalities in the region of Greater São Paulo including C. Resources purchased from outside ABC borders are shown in the upper part of the diagram (water, fuel, electricity, machinery, products and services). On the right side of the diagram, the financial transactions among municipalities and foreign markets are illustrated. The industrial activities make use of the built environment yielding manufactured goods that are exported to other locations. All these activities produce a stock of capital that is represented within the studied system.

ABC accounts for 0.5% of the national total emergy (Giannetti et al., 2013). Table 3 makes clear that ABC depends principally on resources that come from Brazil and other countries. The contribution of the renewable and non-renewable resources to ABC is negligible, and imports from foreign countries contribute in a similar share to the total emergy of ABC (48.6%) of those imported from Brazil (51.2%). It is also remarkable that 37.5% of the total emergy of ABC is associated with the services embedded in the imported goods. This result indicates that the industrial activities performed within ABC mainly support labor in foreign countries since only 3.2% of the total emergy is associated to services inside Brazil and 13.2% to direct labor. The main imported inputs are electricity (approximately 19% in A, 12% in B and 16% in C) and fuels (11% in A, 7% in B and 9% in C).

The analysis of individual flows, *per se*, provides valuable information to describe and to understand national/regional/urban systems. However, emergy indices allow assessing the systems in regard to their contribution to the larger system in which they are inserted (Table 4).

The emergy indices (Odum, 1996) confirm ABC's dependence on external resources, with special emphasis on C. The values of EYR, close to one, indicate that these urban agglomerates do not appropriate local resources to increase the emergy output or the emergy returned to the larger system after processing (Table 4).

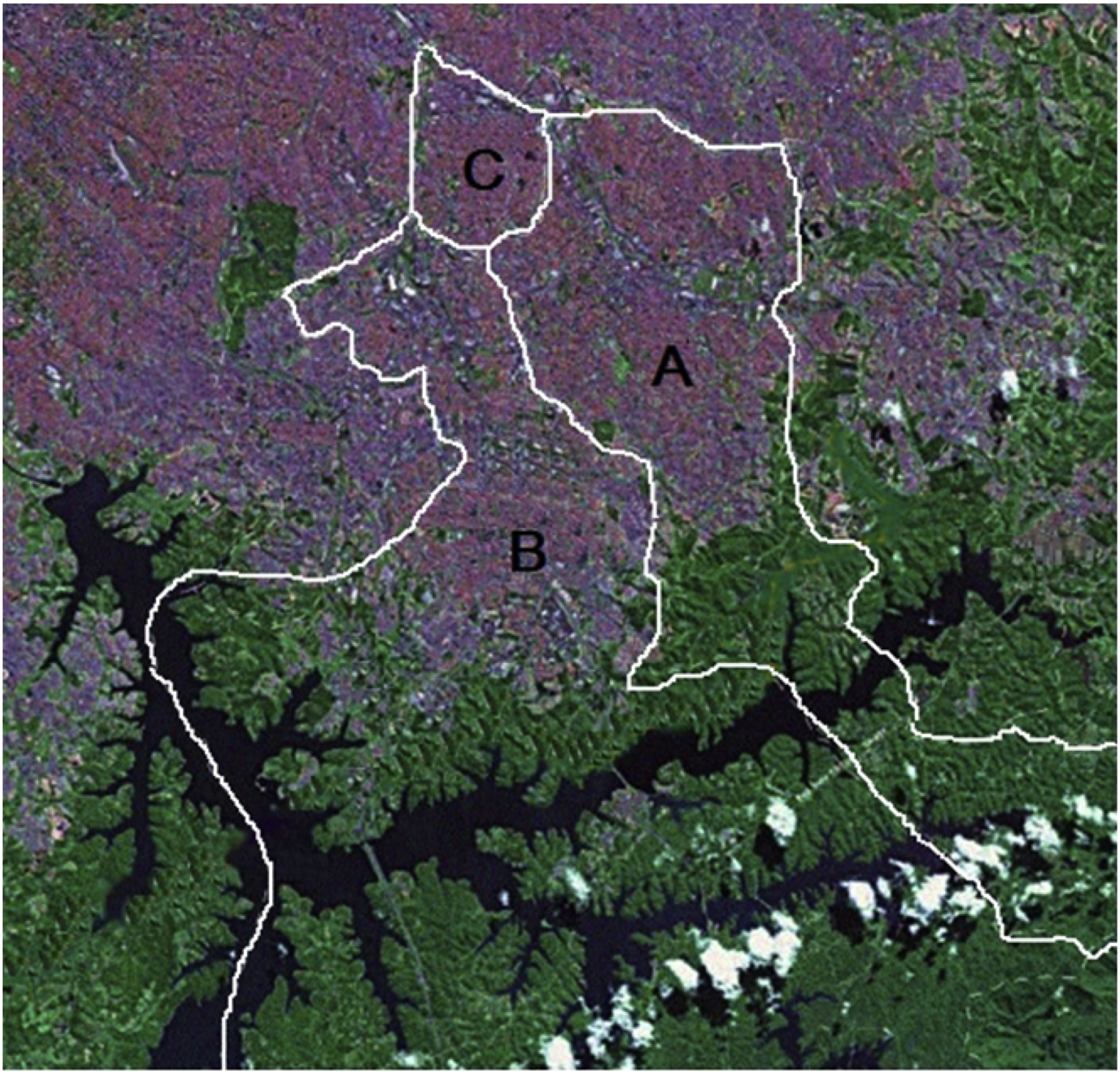

Fig. 1. Satellite image of ABC Paulista and the Billings dam. Where: Where: Santo **A**ndré (A), São **B**ernardo do Campo (B) along with their green areas and the water reservoir (Billings dam); and São **C**aetano do Sul (C) located in the middle of the urban area.

However, the transformations occurring in ABC cause high environmental stress revealed by the values of ELR. When a high value of purchased resources contributes to EYR, ELR increases, evidencing the environmental stress on the surrounding environment. This urban system can be classified as non-sustainable, in the sense that it presents low environmental yield and high environmental loading (Brown and Ulgiati, 2001).

The results shown in Tables 3 and 4 lead to the idea that ABC can be seen as an "industry", which transforms raw materials into vehicles and chemicals that are feedback to the surrounding system. This "industry" holds the know-how (information) and the infrastructure but depends almost totally on imports of external emergy. ABC municipalities are not autonomous, as they do not use local sources in their main economy. This result is reflected by the low ESI values (Table 4) that evidence the pressure on the environment derived from the intense economy dependent on external resources, added to the relatively low contribution of local resources to the growth of the gross domestic product.

3.1. Evaluation of the ABC potential prosperity

Since historically urban growth is centered where emergy flows spatially converge to support their economy, the emergy investment ratio, which accounts for the imbalance between free and environmental resources, can be used to estimate the potential urban prosperity. The emergy investment ratio determines the extent to which the economic system uses emergy from resources elsewhere, and was used to evaluate the resource base for ABC. Systems with lower EIR get more emergy from the environment and EIR values allow determining if an economic-environmental system is capable of enduring and prospering. For countries, an EIR = 8 was estimated by Odum (1987), based upon the

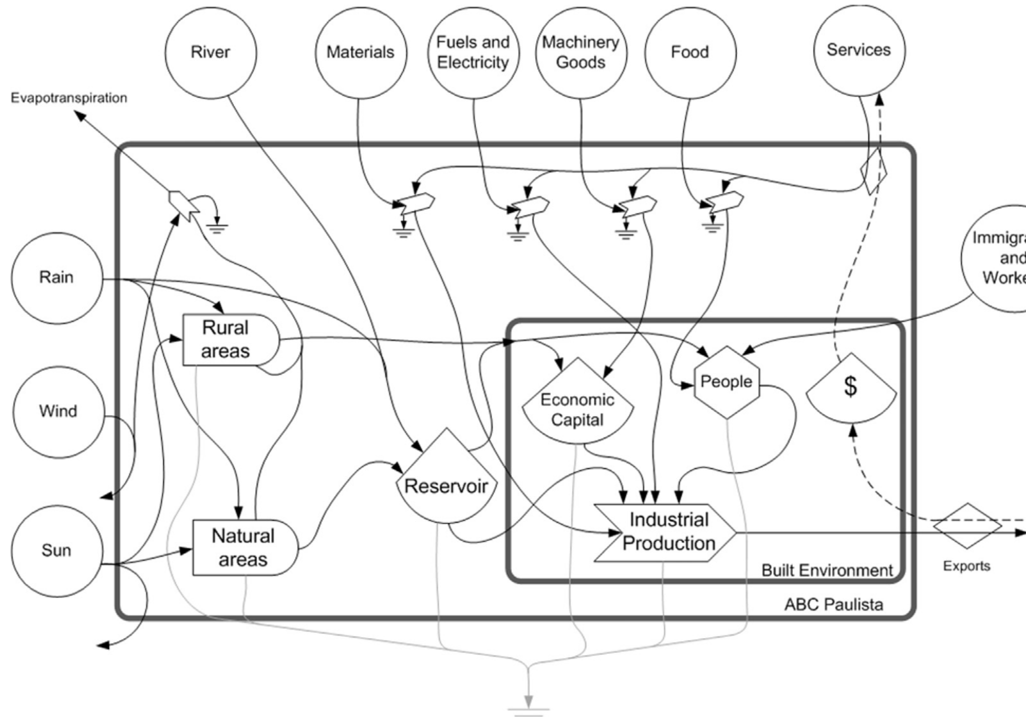

Fig. 2. System's diagram for ABC Paulista, where symbols follow the format recommended by emergy synthesis: (→) fluxes; () energy/material sources placed outside the system; () interactions between fluxes; () biomass production; () consumers, () storages; and () heat loss. The symbol represents money exchange.

relationship between imported and indigenous free resources was about 7:1 of United States in the 80s. At the urban scale, the imbalance between imported and local resource usage is substantially higher. The equation for the curve EIR versus the percentage of local resources (Fig. 3; EIR $= 98.1 \times \%\,(R + N)^{-1.01}$) allows estimating a value of about 10% for matching free and purchased resources in order to increase or optimize their environmental yield which, however, will remain around 1. Results of Rome, Taipei, Montreal, Macao and ABC are compared in Fig. 3. Rome has most of the emergy investment directed to attend the tourism activity (Ascione et al., 2009; Zucaro et al., 2014). Taipei has an industrial activity that is comparable to ABC's (DOED, Taipei City Government, 2014), and Macao is characterized by holding great gambling structure and tourism (Lei et al., 2008).

Clearly, all the cities rely on less than 5% of indigenous resources, independently of their intrinsic characteristics. However, this result indicates that the lower the percentage of local resources usage, the higher will be the investment required from external resources and the higher the dependence on external emergy. The exponential form of the curve also suggests that cities like C, which completely dismissed the contribution of local resources, are extremely fragile, and somehow artificial. Public policies should prioritize understanding, characterizing and quantifying the local flows that may give support to urban areas, by replacing the external flows and reinforcing their potential prosperity.

3.2. Evaluation of the carrying capacity and the ABC living standard

The emergy flow per person is an index of the standard of living which includes environmental and economic contributions to the quality of life. The use of emergy per person is similar for all three municipalities (Table 5), and expresses the people's standard of living. The emergy per person in ABC is half the emergy available per person in the country (4.22×10^{16} sej per person; Giannetti et al., 2013), and about one-third of the emergy available for the population of Montreal (6.25×10^{16} sej per person; Vega-Azamar et al., 2013). Societies can choose to put some of their energy resources into increasing the assets, thereby, improving the quality of life rather than allowing all the additional energy to go into supporting additional people. Considering that the quality of life may also be indicated by the fraction emergy in electricity use, since this ratio is a measure of the high transformity activities of people, and therefore, it should be correlated with the contributions of technology to higher standards of living. The electricity use is more pronounced in A contributing with 21.4% of its total emergy, from which almost 68% is used by the industrial sector. In B the electricity contributes 12.6% to the total emergy (61% of which due to the industrial sector). In C the contribution of the electricity is 19.6%, and the industrial sector corresponds to almost 50% of this value. Thus, the comparison between the values of emergy per person in ABC with those of Brazil and Montreal, and the figures relative to fuel and electricity usage indicate that these municipalities support the societal choice of working as production centers since the total emergy inflow is mainly directed to the industrial system.

A better understanding of human carrying capacity can be gained by separating the energy resources for society into renewable and nonrenewable components. The renewable carrying capacity at present living standard shows that the ABC environment's ability to support economic development based solely on its renewable emergy sources would carry only 4500 persons. C would support only 0.0005% of its actual population on a renewable basis. If purchased emergy inflows relative to ABC's renewable emergy increase to the average ratio for a developed country, the population living in ABC standards could increase to 36,000 persons. These values contrast with the actual ABC population of more than 1,600,000 persons and indicate that only 2% of the population could be sustained indefinitely at the standard of living as defined by

Table 3
Matter, energy and emergy flows supporting ABC. Detailed calculations are available in the Supplementary Material, Part B.

	Item	Units	Quantity	UEV (sej/unit)	Emergy × 10^{19} (sej/year)	% (sej/sej)
Local renewable resources						
1	Solar radiation	J/yr	2.63×10^{18}	1	0.26	<0.1
2	Rain (Chem. energy in green areas)[a]	J/yr	3.10×10^{15}	3.10×10^{04}	9.63	0.2
3	Rain (Chem. energy of run-off)[a]	J/yr	1.06×10^{13}	3.10×10^{04}	0.03	<0.1
4	Rain (Geopotential energy)[a]	J/yr	4.35×10^{14}	4.70×10^{04}	2.04	<0.1
5	Kinetic wind energy	J/yr	1.14×10^{15}	2.45×10^{03}	0.28	<0.1
6	Geothermal heat	J/yr	1.01×10^{15}	5.80×10^{04}	5.89	0.1
7	Water use from Billings dam	m^3/yr	9.66×10^{07}	3.81×10^{11}	3.69	0.1
8	Evaporation	m^3/yr	1.45×10^{07}	2.44×10^{11}	0.35	<0.1
	Total of renewable resources[b]				**21**	**0.5**
Local non-renewable resources						
9	Topsoil loss	J/yr	6.62×10^{07}	1.24×10^{05}	0.00	<0.1
	Total of non-renewable resources				**0.00**	**<0.1**
Imports from inside Brazil						
10	Fuels (Total)	J/yr	–	–	349.84	8.5
11	Electricity (Total)	J/yr	2.18×10^{16}	2.77×10^{05}	603.35	14.7
12	Treated water	L/yr	9.81×10^{10}	1.55×10^{09}	15.21	0.4
13	Food	J/yr	7.50×10^{15}	1.43×10^{05}	107.11	2.6
14	Services from inside Brazil	USD/yr	2.79×10^{08}	4.78×10^{12}	133.15	3.2
15	Agriculture goods from inside Brazil	USD/yr	6.94×10^{08}	4.78×10^{12}	331.30	8.1
16	Labor (commuter workers)	people/yr	2.77×10^{05}	2.04×10^{16}	564.56	13.7
	Total of Imports from inside Brazil, (F_{int})				**2104**	**51.2**
Imports from outside Brazil						
17	Main food items (Total)	kg/yr	–	–	92.09	2.2
18	Metals (Total)	kg/yr	–	–	51.66	1.3
19	Chemicals	kg/yr	2.43×10^{08}	6.38×10^{11}	15.54	0.4
20	Cement	kg/yr	1.26×10^{06}	2.20×10^{12}	0.28	<0.1
21	Rocks	kg/yr	2.40×10^{06}	1.64×10^{09}	0.00	<0.1
22	Paper and derivatives	kg/yr	1.84×10^{07}	6.55×10^{12}	12.07	0.3
23	Plastic	kg/yr	8.73×10^{07}	9.68×10^{12}	84.46	2.1
24	Textiles	kg/yr	4.66×10^{06}	1.34×10^{14}	62.46	1.5
25	Glass	kg/yr	3.49×10^{06}	3.50×10^{12}	1.22	<0.1
26	Machinery	kg/yr	1.20×10^{08}	1.12×10^{13}	133.95	3.3
27	Wood	kg/yr	9.10×10^{05}	6.79×10^{11}	0.06	<0.1
28	Cotton	kg/yr	1.68×10^{05}	2.10×10^{13}	0.35	<0.1
29	Services of imports from outside Brazil	USD/yr	2.84×10^{09}	Diverse	1542.85	37.5
	Total of imports from outside Brazil				**1997**	**48.6**
	Total of imports (internal + external)				**4101**	**99.7**
	Total emergy				**4113**	

[a] Rain was calculated as the sum of items 2 and the greatest value between items 3 or 4.
[b] The total of renewable resources was calculated as the sum of the emergy value accounted for rain (explained above), plus items 6 and 7.

Table 4
Emergy indices of ABC and the three municipalities.

Indicator[a]		ABC	A	B	C
Environmental Loading Ratio	ELR	362	466	260	2078
Emergy Yield Ratio	EYR	1.003	1.002	1.004	1.000
Emergy Sustainability Index	ESI	0.003	0.002	0.004	<0.001

Where: Santo André (A), São **B**ernardo do Campo (B) and São **C**aetano do Sul (C).
[a] See detailed description in Table 1.

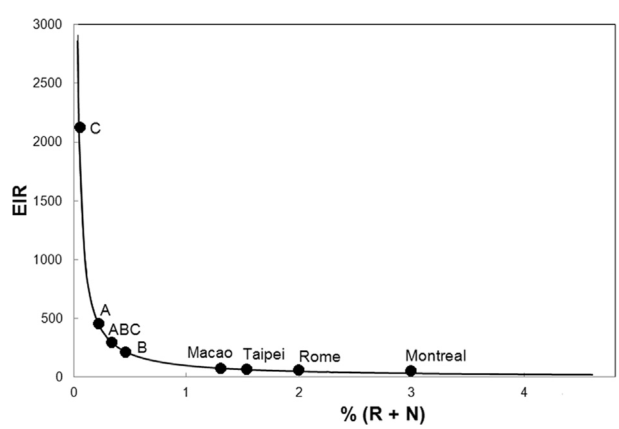

Fig. 3. Comparison of EIR results of ABC and Rome (EIR = 49, Ascione et al., 2009), Taipei (EIR = 73, Huang and Chen, 2009), Macao (EIR = 63, Lei et al., 2008) and Montreal (EIR = 29, Vega-Azamar et al., 2013). Where: Santo André (A), São Bernardo do Campo (B) and São Caetano do Sul (C).

emergy use.

3.3. Evaluation of ABC's trade

A strategy for improving the economy and to support societal organization is directing the internal production of goods and services to the foreign market. This strategy brought welfare to ABC that is partially reflected by the relatively high HDI (Table 2). The main products exported by ABC are related to the chemicals industry (plastic and textiles) and the automotive sector (machinery and metals). The detailed description of the flows exported to other regions of Brazil and for other countries is available in the Supplementary Materials, Part C, Table C1.

Based on imports and exports, ABC's economy functions as a subsidiary economy within the state, or as an "industry", concentrating industrial production activities and service delivery in a small area (Fig. 4). The emergy leaving ABC is higher than that used

Table 5
Emergy indices of ABC and the three municipalities.

Indicator[a]	Unit	ABC	SA	SBC	SCS
Emergy per person	10^{16}sej/capita	2.6	1.9	2.6	2.1
Renewable carrying capacity at present living standard	10^{3} persons	4.5	1.4	3.1	0.1
Developed carrying capacity at same living standard	10^{4} persons	3.6	1.2	2.5	0.1
Fraction of electricity to use	%	14.2	21.4	12.6	19.6
Fuel use per person	10^{15}sej/person	2.1	2.4	1.9	2.3

Where: Santo **A**ndré (A), São **B**ernardo do Campo (B) and São **C**aetano do Sul (C).
[a] See detailed description in Table 1.

for its maintenance and operation (Fig. 4). Although the EYR value indicates a contribution to the larger system of only 0.3% (Table 4), with practically no contribution of the indigenous resources, all three municipalities show the ability to transform resources from other regions and return them to the larger system with higher value. The economic balance is also positive (Fig. 4). B is responsible for about half of the ABC's exported emergy. The value of imports minus exports is positive for all municipalities confirming the increase in quality generated by the internal transformations, and the ratio exports to imports shows that A is the leading exporter of the group, followed by C and B.

The great share of the emergy accounted to support the ABC is associated with the imported goods from outside Brazil and services associated with them, and this development model depends on the use of international trade to supply goods and services for the national economy. However, this development model is disconnected from the environmental local flows and the national economy and may result in resilience loss.

The greater the emergy to money ratio the more competitive will be the area in attracting economic inflows because a dollar spent in this area can buy more free environmental resources than in areas with a lower EMR. The EMR value also informs about the effort an area must do to generate a dollar. The emergy to money ratio of ABC is similar to those of B and A, and a lower than C's, which has a higher GDP (Table 6). These results show that less emergy is required to generate a dollar in C, and that to generate the same dollar in A, two times more emergy will be required. In this context, C takes advantage in trading with B and A (Odum, 1996) and profits by importing goods and services from its neighbors.

The EMR can be used as an indirect measure of the system's contribution to the larger system (Table 6). If the EMR of a city is lower than that of the country (Brazil 5.2×10^{12} sej/USD, Giannetti et al., 2013), the city has a higher capacity to generate GDP than the country.

The emergy benefit ratio (to the seller or the purchaser) was calculated to analyze the emergy benefits that accrue to ABC as a result of exportation (Table 6). The ratio for ABC (2.0) indicates that the urban aggregate exports two times more emergy in goods and services than it receives from the money paid for them. The city that shows the smallest disadvantage is B. For improving economic and ecological sustainability, ABC (especially A and C) should consider alternatives to their current export profile including the development of industrial products that could deliver highest emergy benefit.

The emergy benefit ratio of ABC for internal trading (1.7) indicates that Brazil takes advantage when buying from ABC (to each sej delivered, ABC receives approximately 0.6 sej in currency). When ABC exports to foreign countries, the emergy benefit (2.3) points to a higher disadvantage (1 sej exported to 0.47 sej received). Observing the emergy benefit ratio considering only external exports and comparing it to the emergy benefit ratio considering only internal exports it is noted that ABC has less disadvantage when

Table 6
The emergy to money ratio and emergy benefit ratios of A, B, c and ABC.

	A	B	C	ABC
Emergy to money ratio/(sej/USD) (x 10^{11})	17.6	14.4	7.2	16.2
Emergy benefit ratio (considering total exports)	2.3	1.7	2.5	2.0
Emergy benefit ratio (considering internal exports)	1.7	1.7	1.7	1.7
Emergy benefit ratio (considering external exports)	3.5	1.7	3.4	2.3

Where: Santo **A**ndré (A), São **B**ernardo do Campo (B) and São **C**aetano do Sul (C).

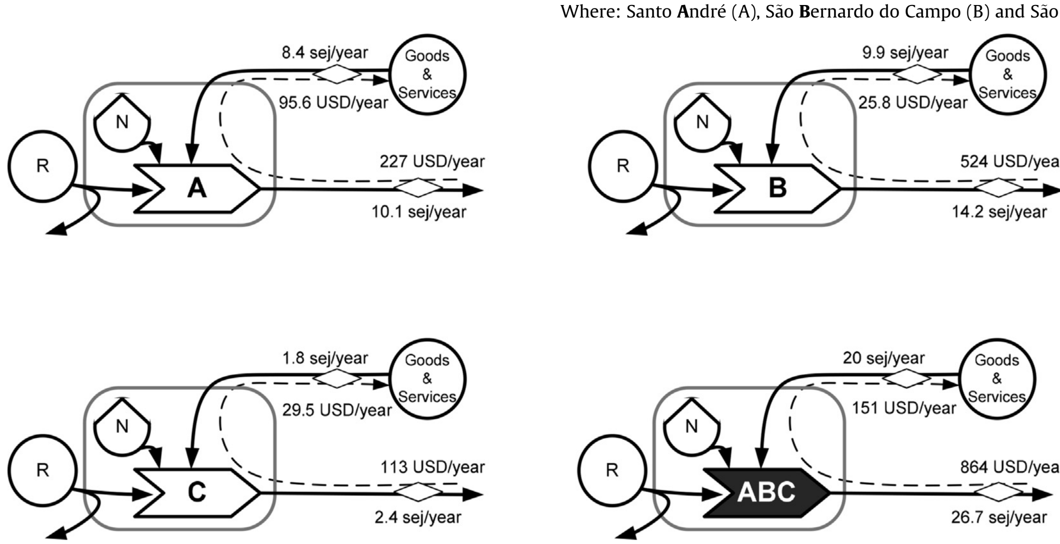

Fig. 4. Balance of trade of ABC discriminating currency payments and emergy. Values of currency are divided by 10^{7} and values of emergy by 10^{21}. Where: Santo **A**ndré (A), São **B**ernardo do Campo (B) and São **C**aetano do Sul (C).

trading with the internal Brazilian market, than when trading with the rest of the world (Table 6).

4. Concluding remarks

An assessment of the urban system of ABC was performed in order to investigate the system's potential prosperity, carrying capacity and trade. Potential prosperity was considered through the analysis of the imbalance of imported and exported resources; the assessment carrying capacity took into account the environmental and economic contributions to the quality of life, and the ABC trade was evaluated through the exchange of emergy flows with Brazil and for other countries. Results point to the vulnerability of the ABC urban system and its economic performance, and identified that the actual resource consumption at local scale is supported by resources that come from outside of the urban system. ABC transfers its environmental loading to the regions, and the pressure, in terms of nonrenewable stocks depletion or exploitation, is transferred to the larger system, which supplies ABC demands. The trade with Brazil and foreign countries was found disadvantageous for all municipalities. This result contradicts the predominant monetary approach showing that ABC exports, despite promoting economic growth, provides much more emergy to the buyers than that received back in currency units. The idea that ABC works primarily as an “industry” and not as a municipality allows to infer that, in the short term, reducing exports to foreign countries and increasing trade with Brazil should attenuate the losses in emergy terms. It is also possible to conclude that the maintenance of kind of urban structure calls for public policies different than those traditionally applied. The analysis of the human carrying capacity documented the patterns of resources usage, making possible to estimate the total amount of renewable and nonrenewable resources to be provided by the country to support the municipal's economic activities. As a consequence, checking if these resources are available is a crucial step that should precede the development of public policies for the maintenance of these urban centers for processing of materials and energy for export.

Reorganize municipal's economic activities in order to contribute to sustainable development may consider the evaluation of the potential prosperity, human carrying capacity and trade. The understanding municipal's structures and functions, through the exchange of materials and energy flows, may help to establish public policies that contribute not only to improve the quality of life of the inhabitants but also for the sustainability of the region in which these municipalities are located.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2016.11.018.

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