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Scaling in Urban Complex Systems: Mexico City Metabolism

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Abstract

Large cities are usually wealthier, denser in terms of population, more expensive, more congested but also more productive culturally and technologically. Mexico City is one of the most dynamic cities of the global economy but also presents the highest crime and congestion levels on the road network. The socio-metabolic approach interprets cities as a socio-metabolic system that interacts with systems in the natural environment. Although considerable progress has been made in studying cities as complex adaptive systems using such approach, many important issues such as social and innovation dimensions remain unexplored, mainly in Mexico City context. The principal purpose of this study is to analyze the metabolic scaling of socio-cultural and technological aspects in the context of Mexico City in order to predict the energy necessary to maintain the city socially connected and to estimate the impact of such social connections on the socio-economic-environmental indicators. We take into account the total population, the cultural infrastructure, the social cohesion, the traffic congestion level, the cost of fuel car, the minimum income, and the number of patents in the analysis as the agglomeration effects in Mexico City. We consider this study can support the design of public policies using the metabolic approach.

Keywords: urban complex systems, urban economy, urban population, scale

1. Introduction

Large cities are usually wealthier, denser in terms of population, more expensive, more congested but also more productive culturally and technologically. Mexico City is one of the most dynamic cities of the global economy. It is Latin America's financial center and Mexico's

political, economic, and cultural capital. Mexico City also provides the most important access to markets and clients. One of the main reasons to invest in Mexico City is the capital's enormous potential to be an active and leading competitor in the new global market. According to [1], Mexico City recorded 4.1 million workers during 2016, mainly in commerce and professional, financial, and corporate services. Following [1], in respect to the national level, the state represented 8.5% of the workers in commerce and 18.0% in professional, financial, and corporate services; the gross domestic product (GDP) of Mexico City was 2.9 trillion pesos in 2015, contributing with 16.7% of national GDP; tertiary sector, which includes trade and real estate services, contributed with 89% of the state's GDP in 2015. Mexico City has 281 km of railways. It also has an international airport. Out of 115,695 students with completed studies from engineering, manufacturing, and construction in Mexico, 13,796 are from Mexico City. Mexico recorded 27,186 researchers at January 2017; 31.6% of them were in Mexico City. Most of the researchers in the state focused on the areas of humanities, as well as medicine and health sciences [1].

In contrast, Mexico City presents the highest congestion level on the road network at global level, causing more than 90% extra travel time for citizens during busy hours [2]. The traffic congestion affects directly on the quality of life. But citizens prefer to use private transportation instead of the public transport network because it offers a poor coverage and a lack of modal transfer centers. Additionally, the general crime rate in Mexico City is above the U.S. national average, and crime varies widely. Armed robberies, kidnappings, car thefts, credit card fraud, and various forms of residential/street crime are daily concerns. Thefts of the vehicle's operating computer and sound systems are also common crimes.

Due to their inherent complexity, Mexico City problematic cannot be studied using traditional approaches of science based on the Physics reductionism perspective because this approach breaks down the problems in their parts, analyzes them taking into account only the most relevant variables and then extrapolates the results to understand their overall behavior. Certainly in the past, in very specific contexts, the Physics reductionist approach was very successful and allowed for great achievements and the scientific and technological advance that we know today. However, the reductionist approach is no longer enough to face the challenges of the 21st century. The decision-making of Mexico City government every day face unpredictable situations that change over time, formed by complex systems of problems. Therefore, it is necessary to use modern science tools based on complex systems paradigm whose methodological framework is complexity science. The complex systems perspective considers open subsystems interacting with their environment, non-reversible energy, and information processes, dynamic states of entities and subsystems far from equilibrium as well as teleological analysis, in the case of human and social subsystems [3]. This approach indicates that phenomena are not the result of a cause-effect chain in which the result can be proportional and predictable only with the knowledge of the parts, but rather, that the systems behave in a non-linear way [4]. Thus, the complex systems approach supports the development of our skills needed to deal with problematic and complex situations so that we are able to change them holistically. In the application of the complex systems approach, the most important feature of study is the emergent properties of complex systems [5] due to a process of self-organization. Such emerging

properties cannot be determined by analytical methods or models [6], but rather by using simulation, an experimental tool essential in modern science.

Although it is true that a large number of definitions of a complex system have been proposed from different fields of science such as Biology, Physics, Sociology, and Economics, there is no precise formal definition accepted by the scientific community. Broadly speaking, such proposals co-exist in defining a complex system as a system composed by interrelated elements that generate information and whose operations are based on simple rules. From the interrelations of its elements, new properties or collective behaviors are generated at different scales. To the above, we add that a complex system is increasingly complex as human actions are explicitly considered.

On the other hand, it is observed that the majority of urban science has not treated cities as complex systems [7]; however, methods and models from the complexity science are likely to yield insight into urban structure and dynamics. From the complexity perspective, cities are complex adaptive systems characterized by heterogeneity, interconnectivity, scaling, circular—causality, and development as follows [8]:

- Heterogeneity: diversity of people and organizations.
- Interconnectivity: everything is connected in networks.
- Scaling: cities of different sizes have different problems.
- Circular—causality: cause and effect are mixed.
- Development: cities change in open-ended ways.

As discussed by [9], cities are the first large social networks. It means cities are not just large collections of people instead they are agglomerations of social links. Following [9], space, time, and infrastructure play a fundamental role in enabling social interactions in allowing them to become open-ended in terms of increased connectivity, and sustainable from the point of view of energy use, such interactions imply cost of people, material, energy, and information flows through decentralized networks of infrastructure that are built gradually as the city grows. In this direction, cities, to realize the full socioeconomic potential, need to expand connectivity per person and of social inclusions [9]. Rapport [10] states that the bio-physical approach of studying and quantifying urban material and energy flows, which draws on approaches in the field of industrial ecology, is the predominant interpretation of urban metabolism that has strong connections to the field of industrial ecology which look for ways to optimize the metabolism of industrial systems through industrial symbiosis. Following [10], studies of urban material and energy flow are often used to identify ways to improve the environmental and economic performance of an urban area. The socio-metabolic approach interprets the society as a socio-metabolic system that interacts with systems in the natural environment. Although considerable progress has been made in studying cities as complex adaptive systems using the metabolic approach, many important issues such as social and innovation dimensions remain unexplored, mainly in Mexico City context. The principal purpose of this study is to analyze the metabolic scaling of socio-cultural and technological aspects in the context of Mexico City

in order to predict the energy necessary to maintain the city socially connected and to estimate the impact of such social connections on the socio-economic-environmental indicators.

The book chapter is divided into five main sections. In Section 2, the socio-metabolic approach applied to the study of urban complex systems is reviewed. In Section 3, the analysis of the metabolic scaling of cultural and technological issues in the context of Mexico City is presented. The energy necessary to maintain the Mexico City connected and its impact on the socio-economic-environmental indicators is evaluated in Section 4. The concluding remarks are drawn in Section 5.

2. The socio-metabolic approach

Human society has been maintained culturally and biophysically. In the first case by a flow of self-referential communication, organized in subsystems of society each with its own codes, while in the second case by a continuous flow of energy and materials from/to natural environment (social metabolism), and by deliberate interventions into the environment [11]. Geddes [12] explained that from the biology perspective, a city can be conceptualized as an organism, opposed to a mechanical system, made of complex and intricate processes that keep it alive, in a regional balance where the relation between the city and the surrounding agricultural economy is symbiotic [13].

The social metabolism is a concept from biology and transferred to the world of relations between society and nature [14]. The concept of social metabolism has not only proven a useful metaphor to stress the biophysical foundation of social systems and their economy, but it has emerged as a key analytical concept in sustainability science [15]. Associated with the concept of social metabolism, we find the notion of socio-metabolic transition to describe fundamental changes in socio-economic energy and material use that occur in the course of human history; in some cases, such transitions have implied the multiplication of metabolic rates, for instance, the transition from agrarian toward industrial society, and in other cases, such transitions have implied the emancipation of the energy systems from land use, for example, the transition from a solar energy system tapping into renewable flows of biomass toward a fossil fuel powered energy systems based on the exploitation of large stocks of energy resources [15]. One interesting study about the potential of the social metabolism approach to study the industrialization of the agriculture is presented in [14]. It provides information about how the socio-ecological transition took place in agriculture. In this context, Bringezu et al. [16] make the point that in industrial ecology and ecological economics interdisciplinary fields, sophisticated methods and tools have been developed to study material and energy flows in socio-economic systems in order to contribute to the design and implementation of more sustainable types of industrial metabolism.

The concept of urban metabolism was first introduced by Abel Wolman in the middle sixties to compare an organism and a city. In his seminal study, Wolman used national data on water, food, and fuel use, along with production rates of sewage, waste, and air pollutants to determine per capita inflow and outflow rates for a hypothetical American city. Actually,

urban metabolism is fundamental to developing sustainable cities and communities. In this direction, cities, like organisms, need energy and resources as inputs to sustain life, which are processes and ultimately released to the environment as wastes.

Urban metabolism may be defined as the sum total of the technical and socio-economic processes that occur in cities, resulting in growth, production of energy, and elimination of waste [17]. In [18], an extended concept of urban metabolism is presented where the metabolic inflows and outflows are its central dimension, but urban quality the biophysical processes determining the environmental impacts associated with environmental sources and sinks as well as urban drivers, patterns, and lifestyles are conceptually interlinked in a holistic approach while economic and social inflows and outflows such as information, cultural goods, and employment are also covered. In this context, urban metabolism framework is the process of material exchanges between the city and its natural environment, whose use involves focusing on material flows within the city as a potential way to uncover environmental, social, economic, and political aspects of resource distribution in a holistic way [19].

According to Hyman [20], material flows are the key intervention point to achieve urban sustainability. Castán Broto et al. [21] note that there is considerable optimism about the opportunities that urban metabolic analysis opens for more sustainable and more just cities.

3. Analysis of the metabolic scaling of cultural and technological issues

In this section, we present the analysis of the metabolic scaling of socio-cultural and technological aspects in the context of Mexico City. We use per capita indicators, which on one hand, conflate general effects of urbanization [22], and on the other hand, are ubiquitous in official statistics and policy documents compiled by Mexican governmental agencies and international bodies worldwide. Mexico City's society has been maintained culturally and biophysically along many hundreds of years. In the first case by a flow of self-referential social communication (information) organized in subsystems of society each with its own codes; while, in the second case by a continuous flow of energy and matters from/to natural environment, and by deliberate interventions into the environment to uncover environmental, social, economic, and political aspects of resource distribution (see **Figure 1**).

According to the INEGI [23], based on the surveys conducted from 1900 to 2010 as well as on the Intercensal Survey in 2015, **Table 1** and **Figure 2** show the population growth in Mexico City from 1900 to 2015. It is important to note that the exponential population growth started in 1950 and continues in 1970.

Mexico City has a 1000-year-old cultural richness in which various expressions give it its own cultural identity. In this direction, the Mexican city is an intercultural mosaic of ethnic varieties in which indigenous communities, indigenous peoples, and communities from different origin interact all together every day. These groups and their worldview through different cultural practices conform the identity of citizens [24]. The cultural heritage of Mexico City

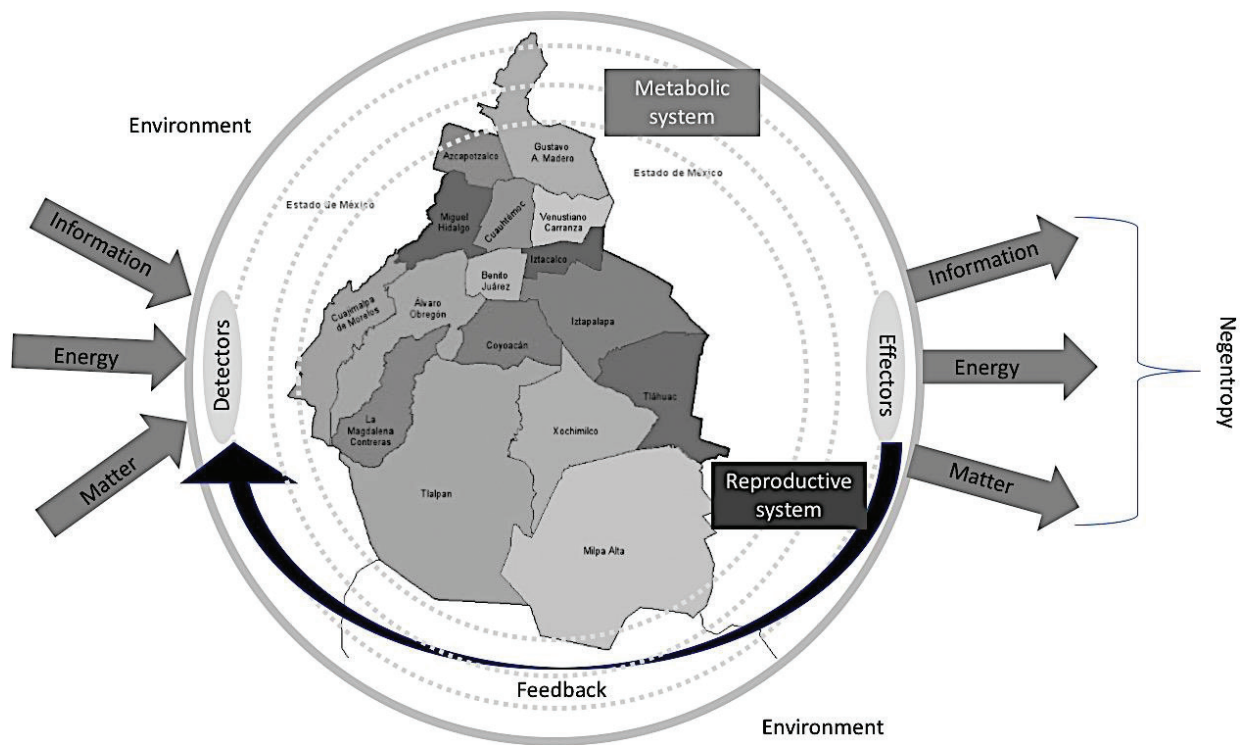


Figure 1. Conceptual model of Mexico City as a complex adaptive system with metabolic and reproductive subsystems.

Millions of inhabitants	Year
0.7	1900
1.2	1930
3.1	1950
6.9	1970
8.2	1990
8.6	2000
8.8	2010
8.9	2015

Table 1. Total population in Mexico City from 1900 to 2015.

is reflected in the diversity of archeological, historical and artistic monuments, expressions of popular culture, gastronomy, festivities, traditions, and normative systems that coexist in the same geographical space [24]. According to the Atlas of Mexico’s cultural infrastructure 2010 [25], in this year, there were 310 archeological sites in this city, 5 of them open to the public, and an estimated universe of 7000 historical monuments from the 16th to the 19th centuries, and 11,071 which were characterized by the National Institute of Fine Arts as artistic monuments of the 20th and 21st centuries. As for the natural heritage, in Mexico City there are geographically located 23 natural areas protected by local and national laws and 33 gullies declared as areas of environmental value [24]. **Table 2** shows the cultural infrastructure per capita in Mexico City in 2010.

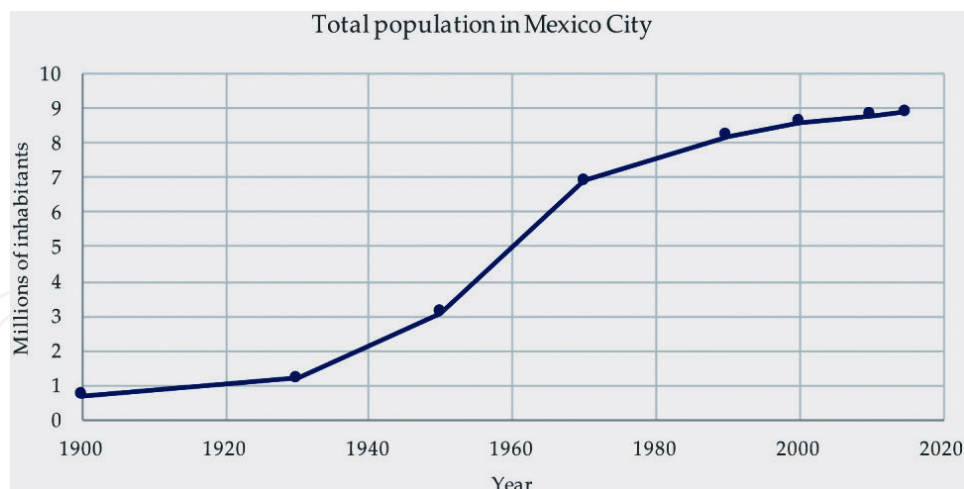


Figure 2. Total population in Mexico City between 1900 and 2015.

Cultural infrastructure	Per capita in 2010
Archeological sites	0.0000352
Historical monuments from the 16th to the 19th centuries	0.0008
Historical monuments from the 20th to the 21st centuries	0.0013

Table 2. Cultural infrastructure per capita in Mexico City, 2010.

On the other hand, the measurement of social cohesion estimated by the CONEVAL [26] incorporates indicators that help to know the level of economic and social inequality of the population at national, state, and municipal levels, as well as indicators of support networks and social exchange at the state level. This allows us to approach the level of equity and solidarity that exists in a society. To measure the degree of social cohesion, CONEVAL uses Gini coefficient that measures the economic inequality of a society, by exploring the level of concentration that exists in the distribution of income among the population. The Gini coefficient takes values between 0 and 1; a value that tends to 1 reflects greater inequality in the distribution of income. On the contrary, if the value tends to zero, there are greater conditions of equity in the distribution of income. **Table 3** shows the Mexico City social cohesion values estimated by CONEVAL for three years: 1990, 2000, and 2010. We observe that the social cohesion in Mexico City has decreased from the last 27 years, with the consequences associated.

Agglomeration effects in Mexico City are manifested, on one hand, as an increase in overall travel times when compared to a free flow situation, and on the other hand, as the increase

Social cohesion	Year
0.536	1990
0.505	2000
0.439	2010

Table 3. Social cohesion in Mexico City [26].

in the cost of public transportation. For the first case, **Figure 3** shows the evolution of the congestion level in Mexico City considering the TomTom Traffic Index [27]. For example, a congestion level of 57% in 2010 corresponds to 57% extra travel time for any trip, anywhere in the Mexico City, at any time compared to what it would be in a free flow situation. The TomTom Traffic Index is based on speed measurements from TomTom’s historical traffic database. These speed measurements are used to calculate the travel times on individual road segments and entire networks. By weighting based on the number of measurements, busier, and more important roads in the network have more influence than quieter, less important roads. **Figure 4** shows the evolution of the congestion level versus the population growth in Mexico City. In this case, the congestion level suddenly rises as well as population along time.

Analyzing the cost of public transportation relative to the minimum income, we can see in **Figure 5** that the first has suddenly risen from 2005. In consequence, citizens have not been able to stay socially connected, due to the cost of transportation, leading to expected decreases



Figure 3. Congestion level evolution in Mexico City.

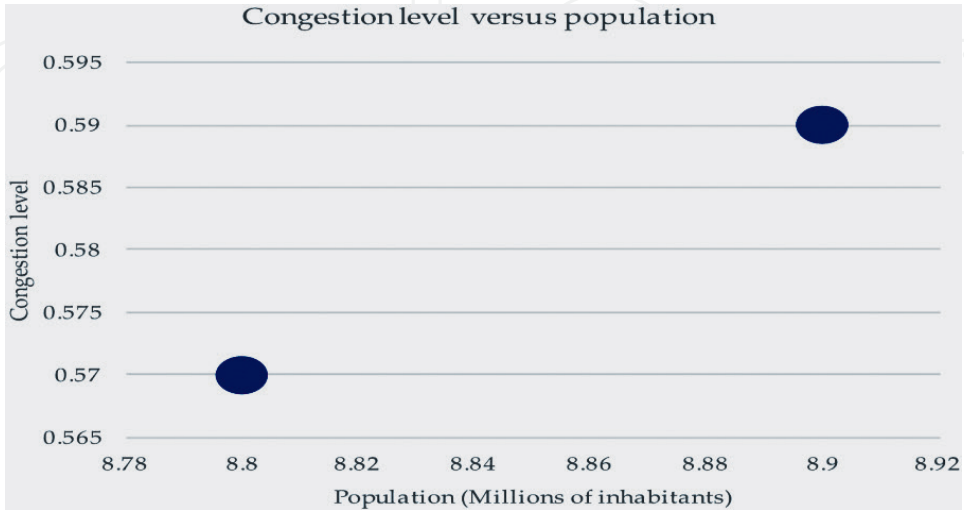


Figure 4. Congestion level versus population in Mexico City.

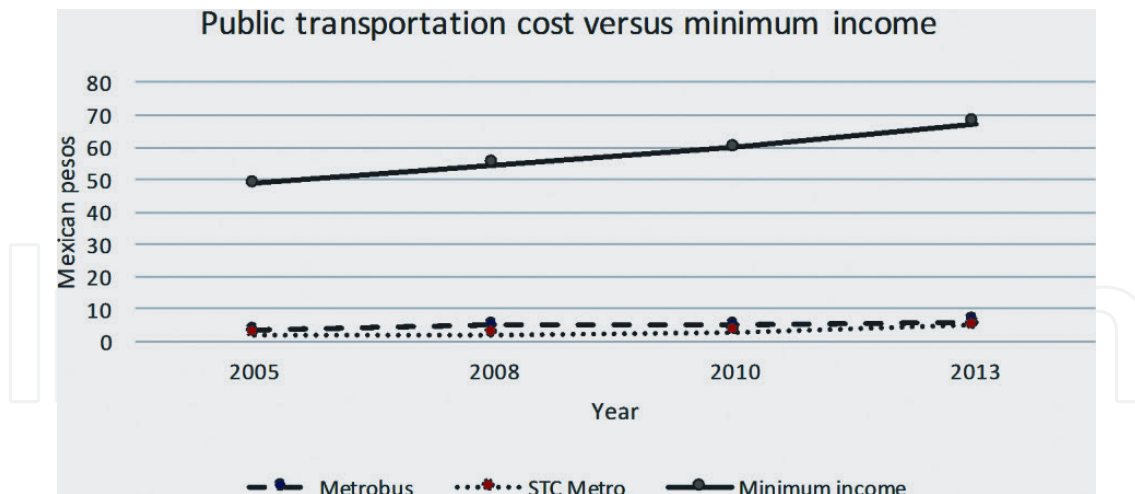


Figure 5. Evolution of public transportation cost versus minimum income in Mexico City.

in their socioeconomic production as suggested by [9]. Additionally, in 2013, the cost of public transport represented almost the 9% of the minimum income in the case of Metrobus. For the same year, the cost of Metro represented almost the 8% (see **Figure 6**).

It is important to note that citizens in Mexico City prefer to use private vehicles for mobility purposes instead of the public transport networks, such as Metro and Metrobus, because these networks offers a poor service coverage, a lack of modal transfer centers and a high vulnerability in terms of connectivity and accessibility [2]. The big problem using private vehicles is the cost of fuel associate (see **Figure 7**). In general, the sheer distance to everyday destinations means some families spend 25% of their income on transport so Mexico City's greenhouses gas (GHG) emissions by up to 70% and cost USD 2.5 billion (33 billion Mexican pesos) each year in lost economic productivity [28].

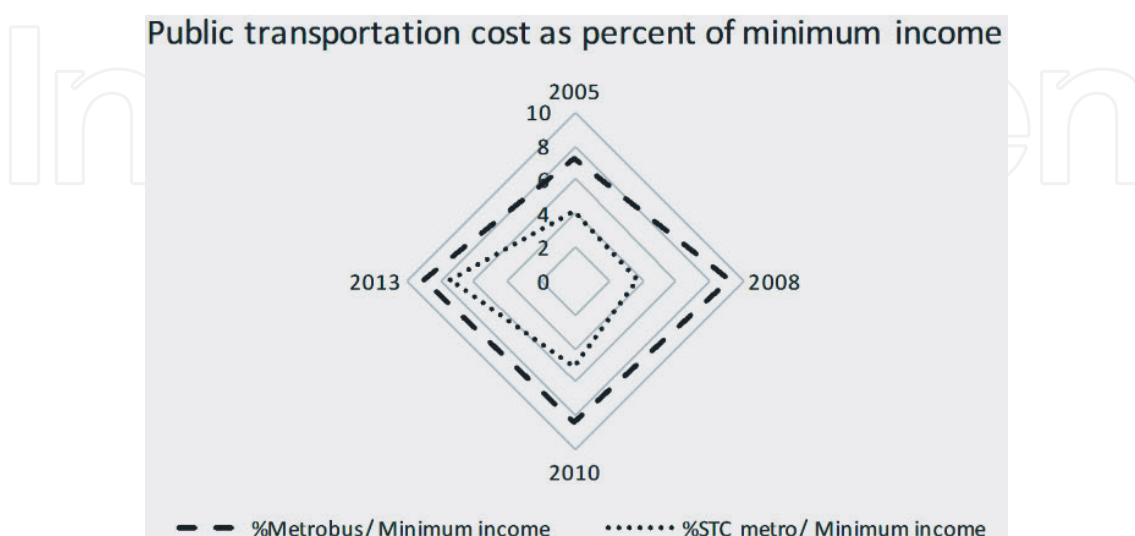


Figure 6. Public transportation cost as percent of minimum income in Mexico City.

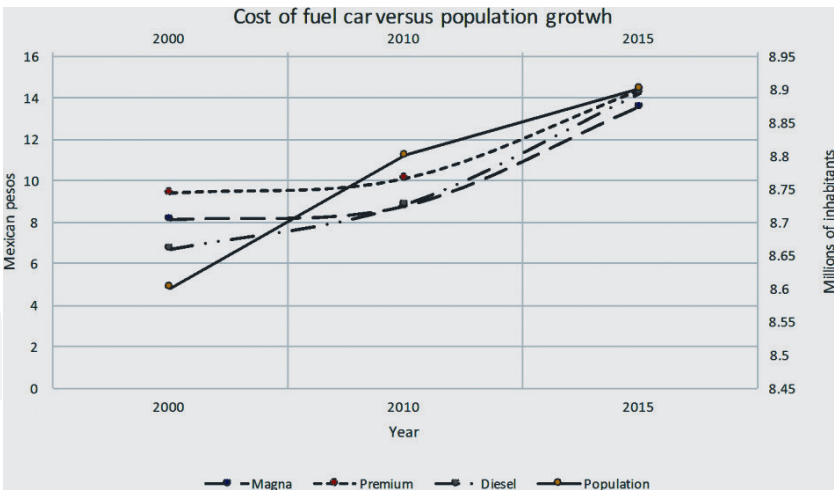


Figure 7. Evolution of cost fuel car versus population growth in Mexico City.

Patents	Year
166	2000
215	2001
206	2002
167	2003
179	2004
212	2005
181	2006
219	2007
219	2008
233	2009
321	2010
308	2011
427	2012
390	2013
337	2014
367	2015

Table 4. Patents requested by Mexico City as residence of the inventor between 2000 and 2014.

As suggested by [28], one solution for this situation is the development of mixed-use areas, where we can find housing, restaurants, services, schools, cultural facilities, parks, and more, so under this scenario if connectivity in Mexico City is increased, the need for private vehicles will be reduced, thus increasing the viability of public transport, walking, and bicycling.

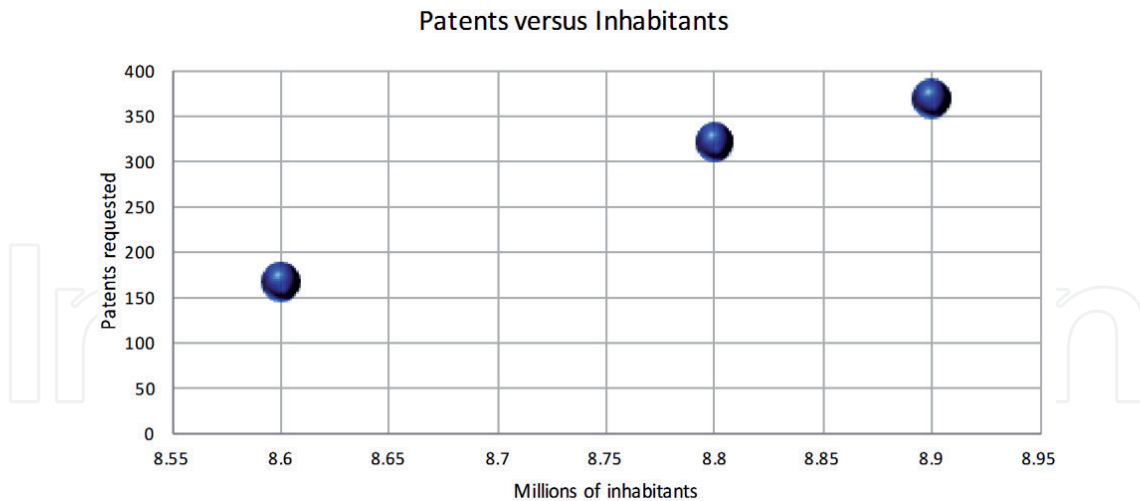


Figure 8. Patents requested versus population growth in Mexico City.

Following [28], other benefits of mixed-use areas are the shared community spaces that foster interactions among community members: interactions that would not be possible under a car-centric model, and the saving individuals money on transportation by reducing the length and number of every day trips and eliminating the need for car ownership. In short, mixed-use areas support local business.

Other agglomeration effect in Mexico City is manifested as increase in per capita temporal rates of socioeconomic activities, such as innovation [22]. One dimension of technological aspects in Mexico City is the number of patents [29]. **Table 4** shows the evolution in the number of patents requested by Mexico City as residence of the inventor from 2000 to 2014. **Figure 8** shows the relationship between the patents requested by Mexico City as residence of the inventor and the population growth for three different years, 2000, 2010, and 2015. We observe that as increase in in population size corresponds to an increase in the number of patents requested.

4. The energy necessary to maintain the Mexico City connected

In this section, we present the estimation of energy necessary to maintain the city connected as well as the impact of social connections on the socio-economic-environmental indicators. We use the data from UN-HABITAT Global Urban Observatory [30]. For the period 1999–2004, transport was the highest consumer of energy in Mexico City followed by industry and residential and commercial buildings (see **Figure 9**).

Residential buildings include all energy used for activities by households, except for transport. Industry includes a combination of all industrial sub-sectors, such as mining and quarrying, iron and steel, and construction. Energy used for transport by industry is not included, but is reported under transportation. Transport includes all fuels used in road vehicles and non-road transport. In the first case, military, as well as agricultural and

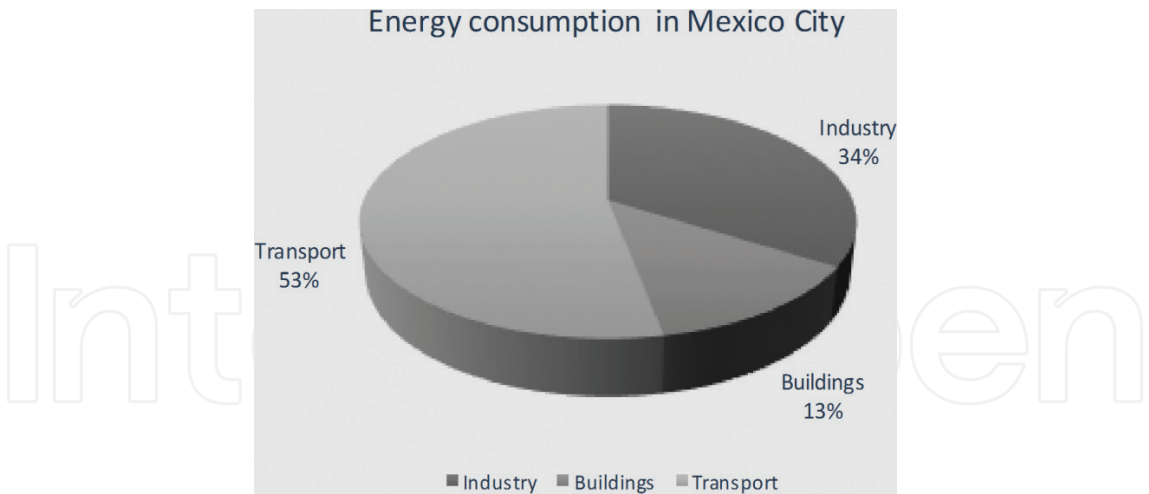


Figure 9. Energy consumption in Mexico City, data from various sources 1999–2004 [30].

industrial highway use are included. The second case includes transport in the industry sector and covers railways, air, internal navigation, fuel used for transport of minerals by pipeline and non-specified transport. In 2008, the annual per capita energy consumption tendency in Mexico City was major than 1900 kilowatt-hours (KWh) and included transport, public lighting, and water pumping (see **Figure 10**). Demand for water has doubled every 20 years, at a rate exceeding that of population growth suggesting that losses, increased connections to the water supply network and increased per capita consumption all play a part [32]. According to Valdez [33], to meet demand for water, Mexico City has to withdraw water from ever more distant sources, often over 100 km away. This situation imposes a considerable energy cost on the system: at 4.5 kWh/m³, water transported from a distance uses almost 20 times the amount of energy as the withdrawn from aquifers below the city [32].

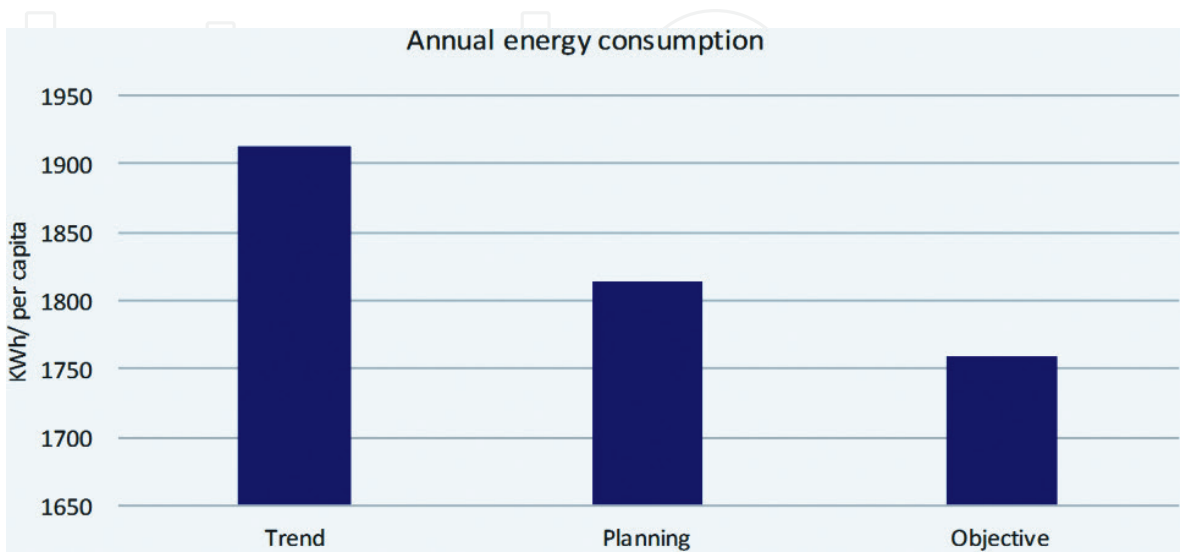


Figure 10. Energy consumption per capita in Mexico City, transport, public lighting, and water pumping [31].

5. Concluding remarks

The principal purpose of this study was to analyze the metabolic scaling of socio-cultural and technological aspects in the context of Mexico City in order to predict the energy necessary to maintain the city socially connected and to estimate the impact of such social connections on the socio-economic-environmental indicators. Agglomeration effects in Mexico City are manifested, as an increase in population, on overall travel times when compared to a free flow situation, in the cost of public transportation, in the number of patents, in the demand for water, and as a decrease in social cohesion. We observed that the exponential population growth in Mexico City started in 1950 and continues in 1970. Based on the social cohesion values estimated by CONEVAL for three years: 1990, 2000, and 2010, we observed that the social cohesion in Mexico City decreased from the last 27 years, with the consequences associated. In general, the sheer distance to everyday destinations means some families spend 25% of their income on transport. Demand for water has doubled every 20 years, at a rate exceeding that of population growth. All these socio-economic outputs of Mexico City are proportional to the number of social interactions realized per unit time. Mexico City to realize the full socioeconomic potential need to expand connectivity per person and of social inclusions but the big problem is that such connectivity is supported in many cases by transport causing high congestion levels. We consider that an initiative to expand the connectivity in Mexico City need to be based in the use of the Information and Communication Technologies (ICT's) and updating the use areas from non-mixed-use to the mixed-use approach in order to favor the social interactions.

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