Building Energy Demand Based on Urban Morphology Analysis: Case Study in Maceió, Brazil

Tathiane Martins, Luc Adolphe, Marion Bonhomme

Building Energy Demand Based on Urban Morphology Analysis:
Case Study in Maceió, Brazil

TATHIANE MARTINS[1,2], LUC ADOLPHE[1], MARION BONHOMME[1]

[1]LRA, Ecole Nationale Superieure d'Architecture, Toulouse, France
[2]FAU/PROARQ, Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brazil

ABSTRACT: This study presents a morphological study to assist in the prediction of energy demand of buildings in the context of a Brazilian city. Different parameters have been applied in the analysis of urban geometry in order to realize a cartography of morphologically homogeneous areas, each one presenting a different influence on the energy demand of buildings. As a first methodological step, the morphological parameters were automated and calculated in a Geographical Information System software, ArcMAP/ArcGIS®. The morphological results obtained for a case study in Maceió, Brazil, were analysed using Principal Components Analysis (PCA), from which it was possible to identify the significance of the parameters to the urban context. Through a Clustering Analysis, different typological configurations were grouped, classified and, then, submitted to computational simulations for energy demand analysis. Six morphological indicators were retained and five representative typological classes of the urban fabric for the Brazilian city were highlighted. A major impact of three main morphological parameters was verified: total built density, verticality, compactness and the mean aspect.
Keywords: urban form, morphological indicators, buildings energy efficiency

INTRODUCTION

The dynamic process of urbanization affects the natural and built systems in several scales, source of important changes in local climate and, consequently, in the energy demand of buildings. In Brazil, the rapid process of urbanization did not follow an effective planning. The lack of public policies that works towards the regulation and control of land use and urban construction, has led cities to reproduce low-quality environmental urban models. However, in recent times, local efforts have been employed towards the elaboration of a set of environmental criteria to regulate energy efficiency applied to buildings [1]. Nevertheless, these energy policies have been mostly devoted to the individual building scale, since the potential of action in this scale seems more feasible. The urban scale approach toward the integration of energy in the local urban planning and design has not yet been largely studied nor effectively applied. The difficulty may be found in several aspects. Among others: (a) the lack of more detailed quantitative studies about the impact of urban morphology on local climate, as well as the effects of microclimate on the energy demand of urban buildings; (b) the absence of more accurate mathematical models that address the complex physical phenomena in multiple scales in tropical climate; and (c) the lack of prospective studies on the evolution of local urban form. One possible approach for this problematic could be the development of simplified tools based on relatively complex energy studies towards the regulation of urban land. Tools based on urban indicators/parameters that could characterize appropriately each particular context towards the qualification of environmental quality of urban built spaces.

In the past two decades, significant progress has been made on an attempt to measure and analyse spatial patterns that could support characterizing the urban form. Although the implementation of several spatial metrics may present itself as one of the main potential methodologies on the characterization of urban form, only recently these indicators have been used more systematically towards the energy problematic [2, 3, 4]. Each set of metrics or indicators may vary depending on the objective(s) and the scale of study. At first, these spatial metrics system would allow allocating different existing urban fabrics and highlighting common traits between them, establishing typologies based on a particular objective. It can also perform as a set of decision support tools that may be very useful for planners, since they are often intuitive and easy-to-use [4]. In addition, empirical studies have demonstrated the use of remote sensing and spatial metrics in the urban environment as a priority in the research of cities [5, 6].

This paper presents an urban morphological study to assist in the prediction and discussion of energy demand of buildings in the context of a Brazilian city.

METHOD

Three main methodological steps were applied:

a. Analysis of urban vector GIS data of the case study city and calculation of urban morphology indicators carried out with ArcMAP/ArcGIS®;
b. Statistical data treatment through Principal Components and Clustering Analysis for identification, classification and mapping of local urban archetypal structures;
c. Building energy prediction of the classified urban structures.

GIS, urban scale and morphological indicators

For application of the proposed method a case study was conducted in the city of Maceió, Alagoas, in the tropical climate context of Brazil.

In this first methodological step, GIS urban vector data of the city of Maceió - provided by the Urban Planning Department of the State of Alagoas (SEPLANDE) – were treated through the GIS, ArcGIS® where calculation routines were also created applying many of its geoprocessing tools and techniques that allowed automating the calculation of the energy-related morphological indicators for any urban vector dataset.

In order to perform the characterization of urban homogeneous areas, two different calculation mesh resolutions were initially considered (500 m x 500 m and 250 m x 250 m). As the scaling of a mesh involves cutting urban objects (streets, buildings), this crop can be critical, depending on the characteristics of the urban fabric. The cells of the mesh should not be too small, not to represent just a reduced fragment less representative of the urban fabric, and also not way too large, comprising too many different structures. To define the most appropriate mesh resolution for the case of Maceió, statistical studies were performed to analyse the predominance of the elements inside the two spatial resolutions considered. The results obtained led us choosing the 500m meshes, which holds 694 evaluation cells. The standard deviation and the resulting averages for some of the selected parameters (for this preliminary assessment) indicated better matching for the larger spatial resolution.

For the definition of the morphological parameters, we applied the methodology developed by Adolphe [2]. The author's proposal came from a simplified spatial modelling of the urban morphology, resulting in the definition of a set of environmental performance indicators for the urban fabric, among others: roughness, porosity, compactness, contiguity, mean aspect. In addition to those, we also considered in this study the well known: Plot Ratio (PR), Floor Area Ratio (FAR) and Built Density. The absolute roughness factor is the mean height of urban canopy given by the product of the height of buildings by their area, and divided by the total (built and non built) area [2]. The porosity factor is characterised by the ratio of the useful open volume to the total volume of the urban fabric. The compactness factor is defined by the ratio of the non-contiguous building envelope by their built volume, over an urban fabric. And the contiguity of an ensemble of urban buildings is characterized by the ratio of their total vertical surface adjacent with other building envelopes by the total envelope surface that is exposed to the outside environment. The climatic and morphological hypotheses, methodological procedures of development of this system of indicators as well as their full description can be found in Adolphe et al. [7].

Statistical treatment

Initially, the wide range of morphological parameters selected was thrown in the calculation routines in order to complete a Principal Component Analysis (PCA). PCA is a statistical analysis that can be used to evaluate the interrelationships among a large number of variables, in order to compile the information that is represented by them on a smaller set of statistical variables, with minimal loss of information. The use of this technique of multivariate analysis aims to minimize redundancies that may exist, enabling greater variability of the data capture in a few components, making it easier for the mapping of information [8]. Secondly, a clustering analysis was also performed. This non-parametric statistical method aims to identify and group objects by similarity, regarding a set of particular attributes and allowing the identification of behaviour pattern. The k-means clustering algorithm, chosen as the most appropriate technique for this application, consists of choosing an initial partition of the data, and then modifying the members of classes in order to obtain a new partition which presents best the natural structure of the initial data. The mean *K* point (average of each attribute) elements are then assigned to the class whose centre is the nearest [9].

It should be noted that the typological classes used in this work are purely morphological and independent of their uses.

Urban buildings energy simulation

Dynamic simulation of the energy performance of the built urban environment was performed using the CitySim code, developed by the laboratory LESO-PB from the Federal Polytechnic School of Lausanne-Switzerland. CitySim proposes coupled models for dynamic simulation of the energy balance of buildings and optimization of urban resource flow [10]. The code comprises a simplified thermal model that consists of refined version of the model of analogy to electric circuit due to Nielsen [11], more specifically based on resistor-capacitor network [10]. For prediction of radiation balance in the urban context as well as indoor and outdoors daylight, the code integrates a Simplified

Radiosity Algorithm (SRA) of Robinson and Stone [12]. Further detailed description of the whole model can be found in Robinson [10]. CitySim input variables can be added as climatic, geometric and thermophysical specifications. To the climatic parameters, it was defined a geographic location and generated a complete local climatic year in hourly time step for Maceió. For the geometry, it was considered a set of buildings in 3D, for which it was sign up the complexity of the built form (different heights, distances and orientations of the buildings). The model also allows for the definition of far field obstructions due to the topography of the urban site. The glazing ratio, in the urban scale considered, is introduced by assigning an opening fraction by facade. For the thermophysical specifications (solar factor, windows and walls U-value, shortwave reflectance, etc.), the buildings features for each typological class of Maceió were assigned by field-based survey. The calculation performed for the energy balance of buildings is based on the demand for air conditioning and artificial lighting of the buildings indoor.

RESULTS

The results of the morphological analysis in ArcGIS® were treated with XLStat application in Excel.

Initially it was analysed the correlation matrix between the resulting morphological parameters, calculated for the 694 mesh urban cells (Table 1). It can be seen that the correlations are often quite strong between certain variables, as highlighted in the light grey colour in the table below. In order to avoid redundancy in the information obtained, it was decided to keep only one of the parameters of each pair where the correlation is significant.

Table 1: correlation matrix with the initial parameters.

Parameters	Nb. Buildings	Built Volume	Height STD	Total built area	Plot ratio	Porosity	Empty area	Total floor area	Rugosity	Built density	Contiguity	Compactness	Weighted height	Average built area
Nb. Buildings	1,00	0,68	0,04	0,63	0,91	-0,91	-0,91	0,63	0,68	-0,03	0,11	-0,09	-0,03	-0,11
Built Volume	0,68	1,00	0,52	0,98	0,89	-0,89	-0,89	0,98	0,98	0,51	0,11	-0,06	0,51	0,18
Height STD	0,04	0,52	1,00	0,55	0,22	-0,22	-0,22	0,55	0,52	0,90	0,01	0,03	0,90	0,40
Total built area	0,63	0,98	0,55	1,00	0,85	-0,85	-0,85	0,98	0,98	0,55	0,10	-0,06	0,54	0,20
Plot ratio	0,91	0,89	0,22	0,85	1,00	-1,00	-1,00	0,85	0,89	0,18	0,13	-0,09	0,18	0,02
Porosity	-0,91	-0,89	-0,22	-0,85	-1,00	1,00	0,98	-0,85	-0,89	-0,18	-0,13	0,09	-0,18	-0,02
Empty area	-0,91	-0,89	-0,22	-0,85	-1,00	1,00	1,00	-0,85	-0,89	-0,18	-0,13	0,09	-0,18	-0,02
Total floor area	0,63	0,98	0,55	0,98	0,85	-0,85	-0,85	1,00	0,98	0,55	0,10	-0,06	0,54	0,20
Rugosity	0,68	0,98	0,52	0,98	0,89	-0,89	-0,89	0,98	1,00	0,51	0,11	-0,06	0,51	0,18
Built density	-0,03	0,51	0,90	0,55	0,18	-0,18	-0,18	0,55	0,51	1,00	0,01	0,04	0,99	0,50
Contiguity	0,11	0,11	0,01	0,10	0,13	-0,13	-0,13	0,10	0,11	0,01	1,00	-0,99	0,01	0,03
Compactness	-0,09	-0,06	0,03	-0,06	-0,09	0,09	0,09	-0,06	-0,06	0,04	-0,99	1,00	0,04	0,04
Weighted height	-0,03	0,51	0,90	0,54	0,18	-0,18	-0,18	0,54	0,51	0,99	0,01	0,04	1,00	0,51
Average built area	-0,11	0,18	0,40	0,20	0,02	-0,02	-0,02	0,20	0,18	0,50	0,03	0,04	0,51	1,00

These high correlation values characterize the variables dependency between each other, such as the weighted average height and built volume (r = 0.51). Other variables are complementary such as the built area and porosity (r =-0.85).

The first PCA

The 14 initial parameters were analysed between them, demonstrating, as shown in the charts below, the number of indicators to be considered, corresponding to the first turning point found on the curve [13] and the percentage of accumulated variability, represented by the axes of the factors, respectively (Fig. 1). This percentage, to be valid in this approach, should be raised to the relationship between the first two factors. And, as it can be seen in this first PCA, due to the large number of overlapping information, this percentage is relatively low.

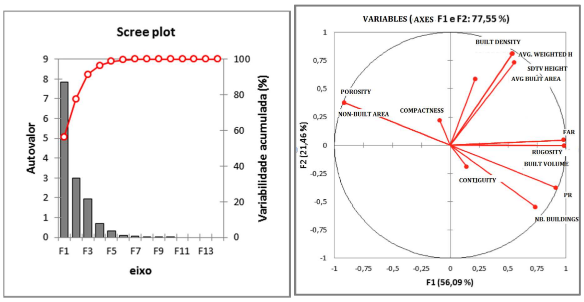

Figure 1: first PCA.

The Fig.1 above allows observing that some of the studied variables are quite close to each other, in particular: built density, average height, ratio (FAR), for example. This way, one can simplify the PCA, keeping at each time only one parameter, without significant loss of information.

The second PCA

The parameters considered in the second PCA were: porosity, roughness, average height, floor area ratio (FAR), compactness and contiguity (Fig. 3).

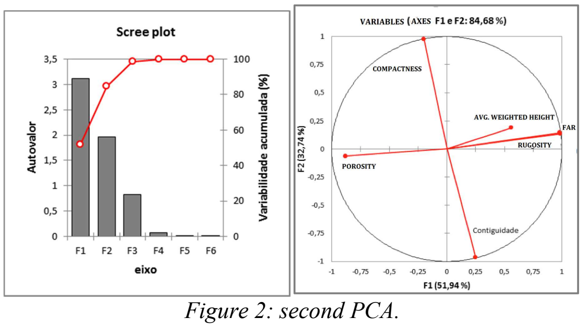

Figure 2: second PCA.

The Fig. 3 allows seeing that the parameters do not present themselves as close as before, allowing more relevant observations. In addition, some of the parameters may even vary perpendicularly and conversely, which may guarantee the relevance of these observations in the application. Analysing them by pairs, that would be the case of the relationship between contiguity and compactness and between the floor area ratio and the porosity. This analysis served two main objectives. On the one hand, it allowed understanding the relationship of morphological parameters between them and, on the other hand, making it possible to extract from a large mass of information, the most relevant data (without redundancies) for analysis and classification of the morphological typologies of the urban fabric of Maceió. For the clustering analysis of the same data, five iterations with ten repetitions were performed, converging to an intraclass and interclass variance of 20.55 and 2.13 (Determinant=0.006), respectively (Table 2).

Table 2- Summary of iteration performed clustering analysis.

Class	1	2	3	4	5
Nb. objects	260	59	223	17	135
Variance intraclasse	0,712	1,023	4,110	16,266	4,236
Min. Distance to centroid	0,097	0,168	0,327	0,678	0,342
Avg. distance to centroid	0,775	0,897	1,308	3,554	1,822
Max. distance to centroid	1,649	2,746	17,612	7,867	4,344

The method allowed highlighting five main classes, which can be easily identified by current urban morphology descriptive terms (Table 3). These classes will be briefly described and discussed in the following section.

Table 3: Five morphological urban archetypal classes according to seven principal components.

Classes	Average weighted height	Compactness	Contiguity	Roughness	Floor area ratio (FAR)	Plot ratio (PR)	Porosity
1 Sparsely built	4,22	4,75	0,07	0,10	0,08	0,08	0,97
2 Open-set mid-rise	9,11	5,18	0,02	0,25	0,88	0,22	0,96
3 Colonial compact centre	6,29	3,87	0,38	2,73	2,38	0,74	0,66
4 Modern high-rise	17,0	4,94	0,22	1,57	4,15	0,49	0,90
5 Densely built low-rise	5,15	3,66	0,03	1,71	0,75	0,56	0,70

Urban form cartography of Maceió

The map below represents the mapping of the typological urban form classes of Maceió, obtained from the analysis of the above-mentioned indicators (Fig. 10).

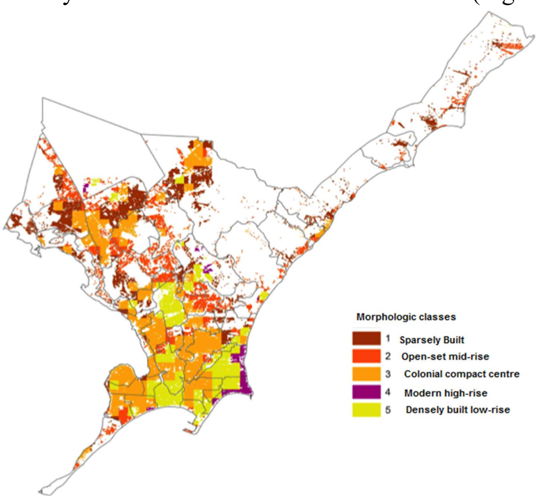

Figure 3:urban form cartography for Maceió-Brazil.

Class 1 – Sparsely built

Class 1 includes mainly the neighbourhoods on the outskirts of the city, characterized predominantly by be low-rise individual and scattered residential buildings. This class represents 37% of the urban fabric of Maceió and has a reduced floor area ratio (0.08). Its low-rise buildings have an average height of 4.22m, and high compactness (4.74).

Figure 4: Urban typology class 1 in Maceió (Author, 2012).

Class 2 – Open-set mid-rise

This morphological class covers 9% of the urban fabric of the city. It presents, among others, the vertical collective housing of up to 4 floors. This typology has increasingly expanded in urban areas of Brazilian cities, for medium and low-income population. The archetypal found in this context consists mainly of vertical buildings shaped like regular prisms, presenting mean compactness of 5.18. These buildings may find themselves trapped in the fabric and surrounded by individual dwellings (more or less compact), characterizing certain heterogeneity (Fig. 5). The buildings have their average heights of 9.11m and the distance between buildings more regular and smaller compared to the previous class.

Figure 5: Urban typology class 2 in Maceió (Author, 2012).

Class 3 – Colonial compact centre

This urban morphological class represents 32% of the urban area of Maceió and is mainly composed by commercial buildings in the colonial downtown core (Fig. 6). These areas are composed of buildings ranging from 1 to 4 stories with average height of 6.30m. It presents the smallest average of compactness (3.86) amongst the other 4 typological classes. This means they present great built volumes with very little envelope areas exposed to the exterior. This way, they present values for contiguity a lot more expressive. Most of its buildings are set on the alignment of public streets and presents its sidewalls straight on the limits of the building plot without any setbacks. Consequently the urban fabric found in this region presents low value of porosity, which may affect negatively outdoors and indoors air quality and as well as users thermal comfort. Both the plot ratio and the floor area ratio are expressively high (2.38 and 0.74, respectively).

Figure 6: Urban typology class 3 in Maceió (Author, 2012).

Class 4 – Modern high-rise

Class composed mainly by modern residential buildings situated at the coastal urban area of Maceió (Fig. 9). This is the most heterogeneous urban class from the typologies presented, particularly regarding the height heterogeneity (with a standard deviation of 9.28 m). This is due to the current intensive process of building verticalization in these areas. Despite the high total built-up density (floor area ratio of 4.15) these neighbourhoods present great porosity. This is due to the current local urban building policy that imposes progressive buildings setbacks and building height limits. Consequently, most of the buildings present high compactness values and low value of contiguity (0.036).

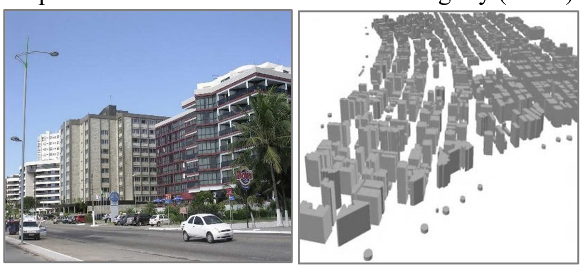

Figure 7: Urban typology class 4 in Maceió (Author, 2012).

Class 5 – Densely built low-rise

Class composed predominantly by densely individual habitat. Presents relatively homogeneity urban form, often expressed by buildings with volumes up to 2 stories (average height of 5.18 m). This urban typology covers about 19% of Maceió. Due to its low compactness (3.66) and high contiguity (0.24), it shows an important built density and buildings offering few facades and openings to the outside, which may compromise the environmental quality of the internal spaces (Fig. 8). Regarding the relation between the built and non-built areas, this urban typology presents low porosity and an expressive average roughness length (0.7 and 2.37 in average, respectively), indicators that will define aerodynamics performance of the site (change on the wind profile) and in its buildings. In tropical climate, natural ventilation associated with solar shading is the most important climatic strategy to reach thermal comfort by passive means.

Figure 8: Urban typology class 5 in Maceió (Author, 2012).

Energy demand of urban structures

In this section the energy results are presented and discussed regarding the morphological factors that defined the five archetypal classes under the climatic context of Maceió. The energy demand obtained was weighted by the floor area ratio of each typology. Their results can be depicted from the chart below showing their relative performance regarding energy demand (Fig. 9).

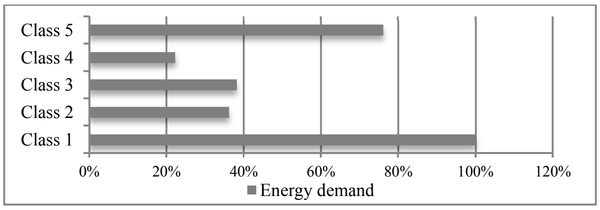

Figure 9: energy demand estimated by morphological class of Maceió-Brazil.

Analysing the results, three parameters can be named as more sensitive to the response of the energy behaviour of the typological classes of Maceió: the floor area ratio and the verticality, the compactness and the mean aspect.

The lower demand estimated by square meter corresponded to the class more densely built (class 4). The verticality factor in that area of the city raises the volume built and also the exterior built envelope area, consequently raising the compactness level. However, this demand is quite reduced regarded the floor area ratio. Although this class (class 4) is characterized as one of the most porous urban fabric, the imposed regulatory building setbacks also generates very high mean aspects (height to width ratio). This factor reduces sky view factor and increases shadows over building facades, consequently reducing heat gains by direct solar radiation. However, high levels of mean aspect may also affect the quality of interior daylight (depending on the orientation of the street).

The less efficient class corresponded to the sparsely built one, which presents higher compactness and lower mean aspect (class 1). This urban typology may present itself inconvenient not only from the point of view of energy efficiency of buildings, but also because it may produce major impact on thermal comfort of pedestrian, due to the reduction of urban shaded areas. If we compare low-rise individual habitat (presented in different urban density context such as in class 1 and 5), the continuous and/or semi-detached housings in the compact built context may require 76% less energy than the sparsely built one.

For climate contexts such as in Maceió, it can be observed the important effect induced by verticalization and densification of urban land on reducing energy demand of urban buildings. By comparing the impact between classes presenting the highest built densely areas (e.g. classes 3 and 4), we can observe a difference of 58% in energy demand between them due to the combined effect of densification and verticalization (of class 4) which led to a higher mean aspect.

It should be noted that this work presents the results of a preliminary study on an attempt to qualify and quantify the impact of urban form parameters in the energy demand of buildings in a particular context. The spatial resolution considered in this study (urban microscale) does not allow us consider aspects that may be determinant to a better or worse energy and thermal performance on the scale of the building, such as the user occupancy profile, presence of solar protection devices, consideration of internal loads, as well as all the effects on larger scale (urban mesoscale).

CONCLUSION

The study of urban land modifications and built environment development in the cities involve the pressing need for more accurate database and suitable methods for analysis and modelling characterization of the dynamics of complex urban phenomena.

The proposed method showed the ability to extract automatically from an urban vector database, the cartography of morphologically homogeneous areas of Maceió, according to a set of urban form parameters which allowed interpret the energy performance prediction of its buildings.

It should be noted that other parameters that were overlooked in the scope of this work (such as, the presence of urban vegetation, the effects of the proximity of the coastal ocean etc.), also have an important weight in the energy balance of the local climate, and are not negligible for the case of Maceió, and will be studied in future work.

The application of numerical models in urban scale requires at the same time a certain degree of accuracy, simplicity and availability of existing database. It is believed, therefore, that the simplified energy-related urban morphology indicators may provide ready for use information in decision-making process and planning of cities, allowing the consideration of the main factors that define the environmental performance of built spaces.

ACKNOWLEDGEMENTS

The authors would like to thank CAPES and CNPq for the financial support.

REFERENCES

1. Lamberts, R.; Goulart, S.; Carlo, J.; Westphal, F.; Pontes, S. O. (2007). Regulamentação de etiquetagem voluntária de nível de eficiência energética de edifícios comerciais e públicos. In: IX Encontro Nacional de Conforto em Ambientes Construídos. *Proceedings*…ENCAC, Ouro Preto, 2007.
2. Adolphe, L. (2001). A simplified model of urban morphology: application to an analysis of the environmental performance of cities. *Environment and Planning B: Planning and Design*, 28: p.183–200.
3. Huang, J.; Lub, X.; Sellers, J. M. (2007). A global comparative analysis of urban form: Applying spatial metrics and remote sensing. *Landscape and Urban Planning*, v.82. p. 184–197.
4. Salat, S. (2011). *Les villes et les formes. Sur l'urbanisme durable*. CSTB. Laboratoire des Morphologies urbaines. Paris: Hermann Editeurs.
5. Batty, M., Longley, P. (1994). Fractal Cities, a geometry of form and function. Academic Press: Londres, UK,.
6. Alberti, M.; Waddell, P. (2000). An integrated urban development and ecological simulation model. *Integrated Assessment*, v.3. p.215-227.
7. Adolphe, L.; Chatelet, A.; Ait-Ameur, K. et al. (2002). *SAGACités, Système d'Aide à la Gestion des Ambiances urbaines*, Rapport final. MENRT, Action Concertée Incitative Ville.
8. Alencar, B.J. (2009). *A análise multivariada aplicada ao tratamento da informação espacial: uma abordagem matemático-computacional em análise de agrupamentos e análise de componentes principais*. 200f. PhD Thesis – Pontifícia Universidade Católica de Minas Gerais. PUC - Tratamento da Informação Espacial.
9. Diday, E.; Lemaire, J.; Pouget, J.; Testu, F. (1982). *Eléments d'analyse de données*. Paris: Editions Dunod-Bordas.
10. Robinson, D. Computer modeling for sustainable urban design. Physical principles, methods and applications. Londres: Earthscan, 2011.
11. Nielsen, T.R. Simple tool to evaluate energy demand and indoor environment in the early stages of building design, Solar Energy, v.78, 2005. p.73–83.
12. Robinson, D.; Stone, A. (2004). A simplified radiosity algorithm for general urban radiation exchange. *Building Services Engineering Research and Technology*, v.26, n.4, p. 271-284.
13. Cattell, R.B. The screen test for the number of factors. Multivariate Behavioral Research, 1, 245-276, 1966.