# Spatial Analysis of Accessibility to Support Decision-Making in Urban Investments: a case in Amazonia - Brazil

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## ABSTRACT

City planning processes are often supported by decision-making methods that involve selection, evaluation and combination of several factors. Also, nowadays, the accessibility is one important issue for the development of cities. So, factors closely related to the accessibility are very relevant to identify and assess the location of urban facilities, which stresses the interest of evaluating accessibility methods. The main goal of the paper is to present an accessibility evaluation model applied in Santarém, in Brazil, a city located midway between the larger cities of Belem and Manaus. The paper describes the research instruments, sampling method and data analysis proposed for mapping urban accessibility. Basic activities (education, health, services, leisure and commerce) provided by the city were used to identify the main key-destinations. The model was implemented within a Geographic Information System and integrates the individual's perspective, through the definition of each key destination weight, reflecting their significance for daily activities in the urban area. The results of this model application can support city administration decision-making for new investments in order to improve urban quality of live. In addition, the model can simulate and analyze several planning proposal for the city, e.g., expansion of the transport network, the construction of new education and health services, helping to understand which will be the consequences of those actions.

*Keywords: Urban Accessibility Assessment, Geographic Information Systems, Santarém, Brazil*

## INTRODUCTION

The concept and evaluation of accessibility have been discussed for almost two hundred years. In urban context, that analysis is crucial to conduct a sustainable development process because it is linked with the opportunity of citizens to reach urban facilities and, at the same time, it can promote the reduction of urban traffic or support the improvement of urban transport systems. In one of the most interesting texts about accessibility, Hoggart (1973) sustains that accessibility is associated with the interpretation, implicit or explicit, of the easiness of reaching spatially distributed opportunities. This means that accessibility depends not only on the location of opportunities but also on the easiness of overcoming the spatial separation between individuals and specific places.

In the same line, Ingram (1971) defines accessibility of a place as its characteristic (or advantage) regarding the overcoming of any form of resistance to the movement. This author distinguishes between relative accessibility, which regards the degree of connection between two points on a surface (or network), and integral (or global) accessibility, which refers to the degree of connection between a point and all the other points on a surface (or network). The second proposal, global accessibility, is a very important issue in urban planning process because most of urban investments are capitalized as general investments and not as specific investments. In urban context, the planning processes promote strategic and integrated decision-making in order to strength connectivity and reduce trips.

The way accessibility is evaluated depends on the purpose or objective to be achieved. Morris *et al.* (1979) present an extensive classification and formulation of measures for relative and integral accessibility. In order to clearly set the domain of their study, the global or integral accessibility was defined as the focus of this work. For that reason, it is important that the model developped includes: measures of separation between all the points; measures of separation incorporating the effect of distance; measures of separation incorporating network capacity and restrictions; and complex measures of separation and supply/demand. Other contributions (Allen *et al.*, 1993; Geertman *et al.*, 1995; Love and Lindquist, 1995; Mackiewicz *et al.*, 1996; Mendes *et al.,* 2005) proposed accessibility measures that somehow can be framed in the classification of Morris *et al.* (1979).

# METHODOLOGY

The methodology is described in two steps. The first one identifies the theoretical issues of the multicriteria accessibility evaluation model focus in the domain of an accessibility index (Mendes *et al.,* 2005). The second one explains how the model can be implemented within a Geographical Information System (GIS) in order to map the spatial variation of the accessibility index. Hence, the two steps methodology illustrates a simple process for mapping spatial variation of accessibility to city basic destinations in a global point of view.

## Multicriteria accessibility model

The multicriteria accessibility evaluation model proposed in this research stands on a measure of separation incorporating the effect of distance. The principal theoretical points and assumptions in this model regarding envisioning accessibility include:

i) <u>Accessibility evaluation</u> is related to a certain objective/purpose; in this case we are concerned with accessibility evaluation for basic activities purposes in a city (education, health services, leisure and commerce).

ii) The accessibility index is a result of the combination of distances to a set of key-destinations, which can be particular points (e.g. facilities), lines (e.g. roads), or areas (e.g. neighborhoods or city blocks);
iii) Key-destinations are related to different objectives/purposes and can have different priorities (weights) in urban activities;
iv) In urban context key-destinations can be reached through streets/roads, each one can have different resistance to movement (impedance) depending on its characteristics;
v) Cost-distances to a key-destination are a result of the combination of actual distances and the impedance of network segments;
vi) Cost-distances to key-destinations can be normalized through fuzzy set functions that, after weighting, represent their contribution to the accessibility index.

The multicriteria accessibility index of a location $A_i$ assessment given by equation (1) denote the fuzzy set membership function applied to cost-distances by $f(c_{ij})$, and the weight of the key-destination $j$ by $w_j$.

$$A_i = \sum_j f(c_{ij}).w_j \qquad (1)$$

Points $i$, for which accessibility is measured, depend on the way space is modelled. The node points of a network dataset should be considered when working with geographic data stored in vector format.. Equation (1) is essentially a Weighted Linear Combination, one of the aggregation procedures available in the context of multicriteria evaluation (Voogd, 1983). In this multicriteria accessibility index, the assessment of $c_{ij}$ represents the cost-distance to a key-destination $j$ from a point $i$. Both, key-destination $j$ and point $i$ are located within urban area in evaluation.

A very important component of a multicriteria evaluation model concerns the priorities attached to the several key-destinations, i.e. the values of the weights $w_j$ in equation (1). The objective of setting weights is to quantify the importance of key-destinations relatively to one another, in terms of their contribution to an overall accessibility index. Among many methods to derive weights established and used by different authors, two are most commonly used Mendes (2000): the n-points scale (originally seven-points scale, as introduced by Osgood *et al., 1957*); and a more complex method called Pairwise Comparisons, which was developed by Saaty (1977) in the context of a decision making process known as Analytical Hierarchy Process (AHP). Both methods are valid and the adoption of one of them depends on the possibility to implement a simple or complex survey.

Cost-distances measured to each key-destination can be expressed in different scales, i.e., one can be available to travel longer distances to a key-destination than to another, giving a different meaning to identical measured values., For that reason, it is necessary to standardize them before aggregation. The process of standardization is essentially identical to that of fuzzification in fuzzy sets (Jiang and Eastman, 2000). Depending on the nature of the criterion being fuzzified, different fuzzy functions can be selected. Among the most used are: Sigmoidal (S-shaped), J-shaped, Linear and Complex (Mendes, 2000).In this model, the objective is to transform any scale to a comparable one measured according to a standardized range (e.g. 0-1). In this work, the result expresses a membership grade that ranges from 0.0 to 1.0, indicating a continuous variation from non-membership (no accessibility) to complete membership (maximum accessibility), on the basis of the cost-distance being fuzzified (figure 1).

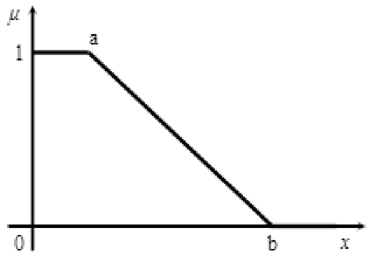


Figure 1 - Linear fuzzy set membership function

When fuzzifying distance variables, the linear monotonically decreasing function (Figure 1) is one of the most used, for which membership grade $\mu$ (i.e., standardized value) is given by equation (2). Control points *a* and *b* are critical points that should be set for each particular situation, considering their inherent meaning.

$$\mu = (x - x_b)/(x_b - x_a) \qquad (2)$$

*When* $x > x_b$ , $\mu = 0$ ;   $x < x_a$ , $\mu = 1$

When evaluating the accessibility to urban facilities, the value 0 is often adopted for the point *a*, assuming that the assessment reduces immediately from the point where the facility is located. However, a value for $x_a$ can be adopted to characterize the effect of near-by (for instance, between the car stop and the facility entrance). In this case, $x_a$ can be between 100m and 400m (walkability distance to the facility). The value of $x_b$ differs from facility to facility and from city to city. The value of $x_b$ represents the maximum distance that can be considered until the accessibility to the facility becomes unavailable. Points witch distances to the facility location are higher than $x_b$ are considered as being located outside the hinterland of that facility. So, the accessibility to that facility does not contribute to the global accessibility index.

## A vector gis-based implementation

The formal model presented before can be implemented within a GIS environment, making use of the available toolbox set. The implementation depends on the specific characteristics of the software adopted. The following paragraphs explain the several stages to be taken on to implement the methodology within a vector GIS-based environment. The detailed information presented for the implementation of each stage implies that the reader is familiarized with GIS environment and toolbox set.

The flowchart of Figure 2 shows the geographical database needs (GIS layers) and the sequence of operations required to complement the attribute table to assess the accessibility index for the network points. The first step of the model is to calculate the cost-distance for each point of the network to each of the key-destinations. This step consists in calculating the OD Matrix from all network points to each key-destination and storing the values as new columns in the attributes table. At the end, the attribute table of the evaluated point's layer must have a number of cost-distances columns equal to the number of key-destinations used in the study undertaken.

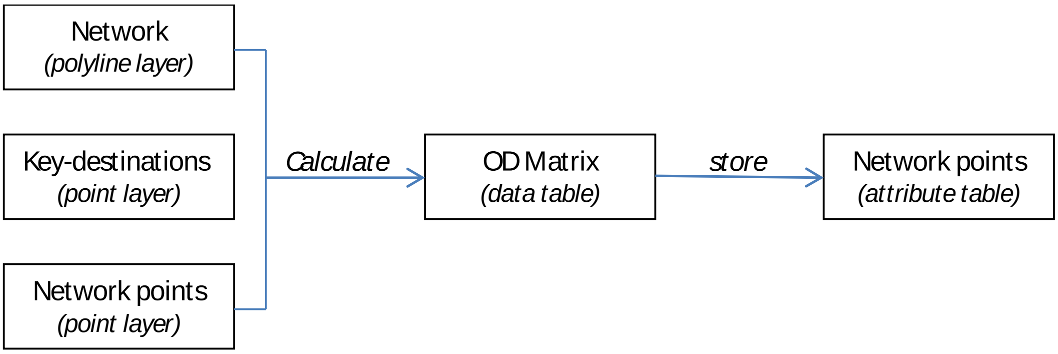


Figure 2 - Vector GIS model to calculate cost-distances

Having the cost-distance from network points to all key-destination, the multicriteria procedure is implemented following the flowchart of Figure 3. The sequence of operations starts with the standardization (i.e., the application of the selected fuzzy set functions) followed by the weighting. Afterwards, the accessibility index is obtained by the aggregation of the several weighted standardized cost-distance. This procedure is applied at the attributes level. Once again, new columns must be added to the table: 2 columns for each key-destination (standardization results and weighting results). One last column is added to the attribute table to store the accessibility index.

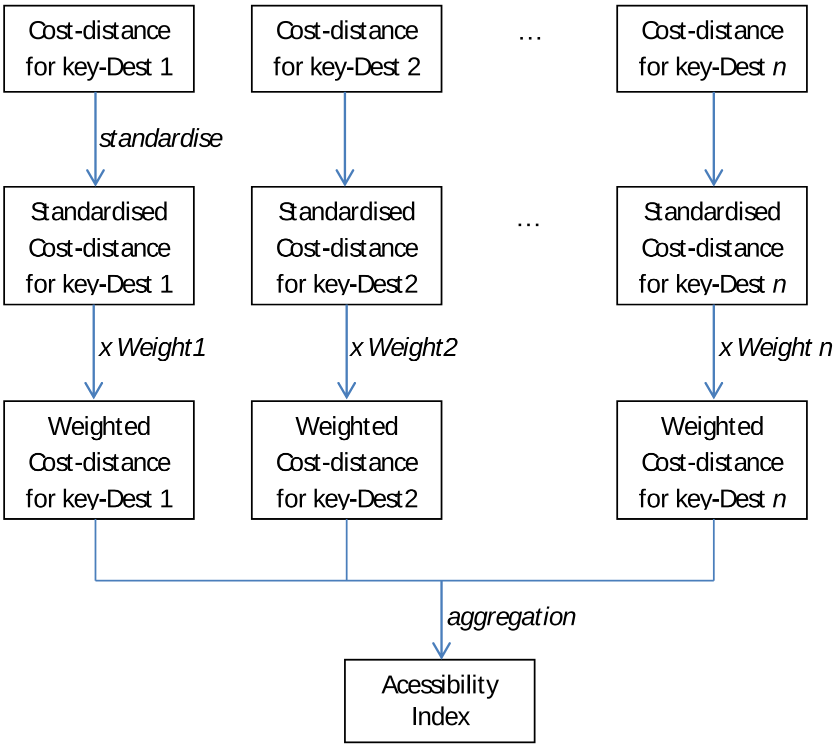


Figure 3 - Accessibility index calculation process

With all the spatial calculations concluded, it is possible to generate the accessibility map. The method adopted is building a triangulated irregular network (TIN) that will represent a surface covering the study area. Using as inputs the network points and applying their accessibility index as Z values, the resulting surface will show how accessibility values are distributed along the area by interpolating the obtained values of the network points. The same process can be implemented to create a map to show the accessibility to a specific key destination or a partial group of key-destinations. In this case, the TIN will represent as Z-values the weighted cost-distance for a specific key-destination or a partial group.

In order to use the accessibility evaluation model established in this paper, the model must be "customized" to be applied in a particular context under study. This means: (i) to identify the set of key-destinations; (ii) to establish the weights for each key-destination; (iii) to identify the fuzzy set functions to be used; (iv) and to set the control points a and b for the fuzzy set functions.

The proposed methodology can be implemented for any city to show accessibility evaluation in urban area. The evaluation can be put into practice by two different perspectives: as global index for the city area or as a partial index for facilities represented by a key-destination or a partial group. That allows a comparison between the several maps and an analysis of the relevance of partial facilities. Other possibility is to evaluate future scenarios in order to assess the impact of future investments: (i) increasing accessibility network to improve better connectivity (new roads or streets) or urban transport systems; (ii) building new facilities to improve the spatial attendance or to redefine a location.

# CASE STUDY: SANTARÉM, PA - BRAZIL

The city of Santarém is located in the Amazon floodplain, in the Brazilian State of Pará. The town is placed on the right side of the Amazon River at the confluence with the Tapajos River and was founded in 1661. Nowadays, Santarém is municipality with 294,774 inhabitants and occupies a territory of 22,887 km2 (IBGE, 2010). Most of the population is concentrated in the restricted urban area of the city of Santarém. The accelerated urban growth occurred from the 1940s (Figure 4) and, by the mid-1970s and until the present day, the population of the municipality became majorly urban (Figure 5).

The city economy is based on tourism activities, trade and services. Outside the urban area, farming and fishing are the predominant activities. Like other riverside or coastal cities, the urban morphology is radial and the central business district is located in the old town area along the riverside. The most important access is by boat, with direct links to other cities in the region. By land, the *Transamazonica* road is the major motorway infrastructure of the region. There is also a connection by air (commercial flights and private) to Belém, capital of the State of Pará.

Nowadays, mobility and quality of life are some of the most challenging issues that a development process of a city must take into account. However, the location of the most important facilities in Santarém are the result of previous public infrastructures policies or isolated private initiatives. Also, the central area of the old town preserves the importance for commerce and leisure activities. Hence, the accessibility evaluation is an important topic in the definition of future facilities buildings locations or in the definition of improvements in the transport infrastructures. The spatial assessment of accessibility to the city most representative facilities in inhabitants' daily activities (education, health, services, leisure and commerce) will be an important contribution to identify urban areas with lower level of accessibility. The results can contribute for future land-use policies and planning decisions that can overcome the actual inequity level of accessibility of the peripheral neighborhoods.

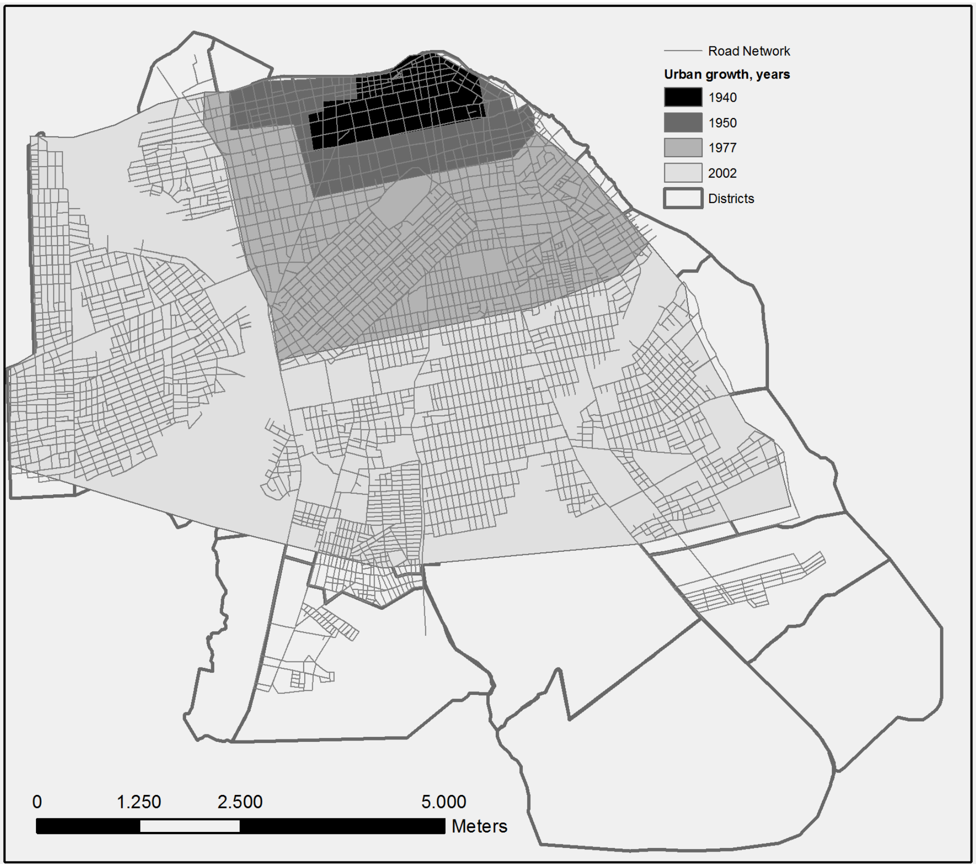


Figure 4 - Boundary evolution of the city of Santarém (1940-2002)

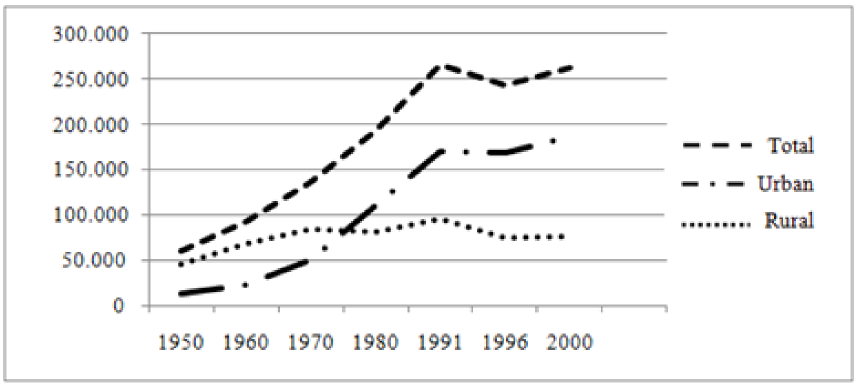


Figure 5 - Population growth of the municipality of Santarém - 1950 to 2000 (IBGE)

## Santarém road network and impedance

In a GIS environment, the first step was to generate the map of the streets/roads network and to extract the network points to be evaluated (figure 6). Those points will be used as origins in the accessibility evaluation process. Their distribution revealed to be adequate to guarantee a good coverage of the studied area, this having in mind that the global accessibility is intended to be mapped as a continuous surface.

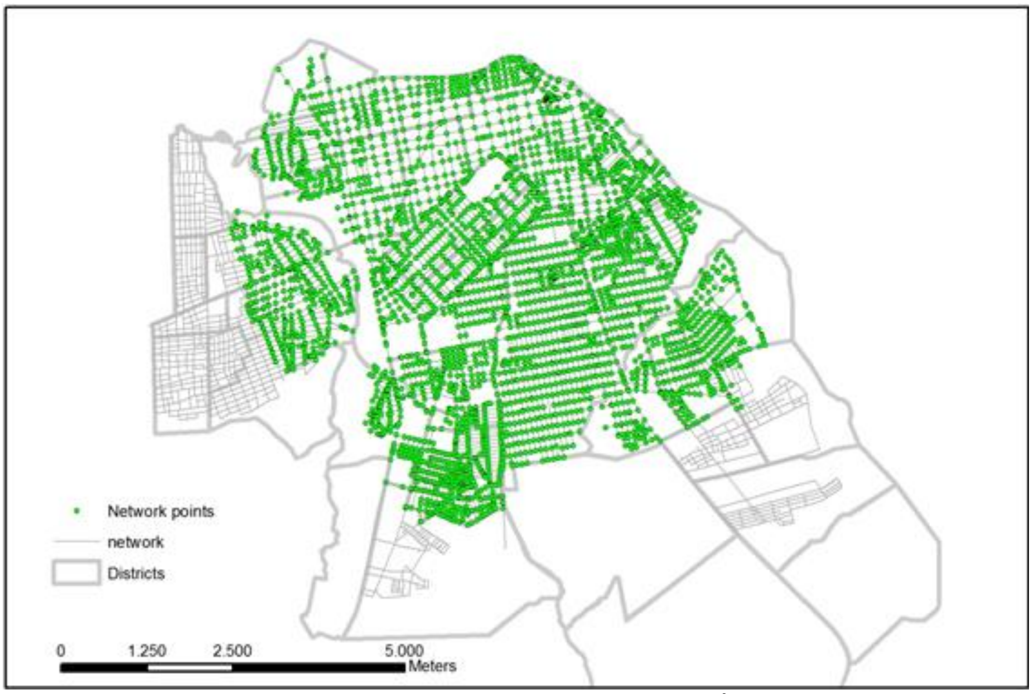


Figure 6 - Network points map for Santarém

Since a network is used to measure distances between origins and key-destinations, the inclusion of impedance was then considered. Combining available data and local observation, it was possible to define an impedance factor for network segments as follow: if the network segment is paved then no impedance factor is applied on the segment length; otherwise, if the network segment is not paved, the distance for travelling on this segment is doubled, corresponding to an effective reduction to half of the travelling speed on a paved segment. Circulation restrictions were also included in the final network model.

## Key-destinations in Santarém

In the case under study, the information needed to carry out the methodology was obtained by a survey. The survey was undertaken, as a pilot test, through a structured questionnaire that included the reasons and destinations listed previously by specialists. The interviewed was also able to suggest new destinations with-in the urban area. First, the pilot test was carry out only in two districts of the city: one in the center and another at the periphery. Then the survey was applied to a panel of specialists, technicians, professionals and a large random group of residents. It was composed by two phases: the first one to identify the location of the relevant key-destinations in the city of Santarém and to identify the modes of transportation in the city; the second one to obtain the data needed for the aggregation process.

Even not being directly relevant for the accessibility evaluation method, several issues about transports in Santarém, were analyzed in the survey undertaken. Some figures from that part of the survey are the following: 80% of urban trips are related to work, education, commerce, services and entertainment; Over 70% of trips are made by individual motorized transport (car or motorcycle).

From the results of the survey, the identified key-destinations within the city were grouped into functionalities, forming homogeneous sets of key-destinations to perform specific activities: education, health, services, leisure and commerce. Thus, all functionalities were populated by the most relevant key-destinations in the urban area, i.e. schools, hospitals, services buildings, public recreational facilities and shopping areas. The figure 7 shows the maps with the functionalities location adopted in the study. The Table 1 list and make a short description of the key-destinations.

Table 1 - List of the key-destination for the city of Santarém

| **Funcionalities** | **Key-destination – short description** |
|---|---|
| Education | Frei Ambrósio School<br>IESPES College<br>Integrated Colleges of Tapajós and Tapajós High School |
| Health | Aldeia/Fátima Health Center<br>Livramento/S. José Health Center<br>Imaculada Conceição Hospital<br>Municipal Hospital<br>Regional Hospital of West Pará<br>Unimed Hospital |
| Services | Bank of Brasil<br>Itaú Bank<br>Bradesco Bank<br>Caixa Econômica Bank<br>Bookkeeper of Rui Barbosa street<br>Central Post Office |
| Leisure | Shopping Centre of Santarém<br>Municipal Market<br>CR Supermarket<br>Candilha Fair<br>Mercadão 2000 Fair |
| Commerce | Santarém waterfront<br>Church of the Peace<br>Assemblies of God Church<br>Mariscada Bar<br>Mascote Restaurant |


Figure 7 - Key-destination maps for Santarém

### Fuzzy set functions and weights

The information required to define fuzzy set functions and weights for the several key-destinations was not directly available and, for that reason, an empirical approach was implemented.

The second phase of the survey, as referred in the previous section, served to define the key-destinations relevance (weights) and the maximum distance that interviewed were willing to travel to each one (value of $x_b$, as define in the section 2.2). This phase of the survey was taken in 24 districts of Santarém, which represented 50% of city districts and 84% of the number of households, equivalent to 46,239 households. The research was household, based assuming one person per household. A binomial probability sample was used, with 95% confidence level error estimated at 10%, with, 400 households interviewed. The relevance of functionalities and key-destinations was assigned by all the interviewees by scoring each item in a scale of 0 to 100 points. This process intends to capture the perspective of the participants about the importance of each key-destination for the realization of their daily activities.

Using data compiled from the interviewees answers, the weights of the key-destinations and the functionalities groups were obtained: for each evaluated item, the average value of points assigned was calculated and then transformed in a percentage corresponding to the portion of all points assigned to all items of the group. Interviewees were also asked to point out the minimum and maximum distances that corresponds to full and no accessibility for each key-destination. Reporting to the model application, those values are used to determine the control points for the standardization functions (equation 2).

The questionnaire for the second phase of the survey had the following fields:
- Identification of the basic socioeconomic interviewed;
- A column with the functionalities: a study, health services, leisure and commerce;
- Weights of functionalities;
- A column with the key-destinations;
- Weight of the key-destinations;
- Minimum distance to assume full accessibility for each available key-destination.
- Maximum distance to be travelled for each available key-destination.

The table 2 shows the relevant data that were used to feed the evaluation model as parameters values.

### Accessibility mapping

Applying the proposed model to calculate accessibility indexes for all points within a GIS platform is possible when taking advantages of database management. All key-destinations data must be stored in a table in order to perform further calculations that require standardization and weighting. Control points (minimum and maximum distances) must be assigned to each key-destination to allow the standardization of distance values through the fuzzy function. Then, the shortest distance to each key-destination must be identified and stored in the attribute table of the point layer. This step is performed using a tool for network analysis that generates OD Matrices. Network points are designated as origins and all the key-destinations (points) as destinations. The results are the shortest path over the network from each origin to each destination. To transpose those values into the attributes table of the network points layer, new columns were added and unique column identifier assigned in order to keep the relationship with the key-destinations. The existent one to one relationship between network points identifiers and key-destinations identifiers is used to ensure that the values transfer is applied successfully. This step was ran twice in order to obtain an OD matrix using each version of the network, i.e., including or not pavement impedance.

Table 2 - Weights and control distances for functionalities and key-destinations for Santarém

| Functionalities | Weights | Key-destinations | Weights | Min. Distance (m) | Max. Distance (m) |
|---|---|---|---|---|---|
| Education | 0.14 | Frei Ambrósio School | 0.38 | 721 | 2770 |
| | | IESPES College | 0.15 | 1261 | 3794 |
| | | Integrated Colleges of Tapajós and Tapajos High School | 0.47 | 1503 | 3764 |
| Health | 0.2 | Aldeia/Fátima Health Center | 0.08 | 598 | 1460 |
| | | Livramento/S. José Health Center | 0.06 | 3271 | 4579 |
| | | Imaculada Conceição Hospital | 0.08 | 1677 | 3362 |
| | | Municipal Hospital | 0.46 | 1525 | 3629 |
| | | Regional Hospital of West Pará | 0.07 | 850 | 2695 |
| | | Unimed Hospital | 0.25 | 1311 | 3697 |
| Services | 0.23 | Bank of Brasil | 0.18 | 1004 | 3556 |
| | | Itaú Bank | 0.38 | 1689 | 3528 |
| | | Bradesco Bank | 0.18 | 1121 | 3511 |
| | | Caixa Econômica Bank | 0.11 | 1962 | 4764 |
| | | Central Post Office | 0.07 | 470 | 2370 |
| | | Bookkeeper of Rui Barbosa street | 0.08 | 1528 | 4416 |
| Commerce | 0.26 | Shopping Centre of Santarém | 0.62 | 987 | 3804 |
| | | Municipal Market | 0.07 | 299 | 1792 |
| | | CR Supermarket | 0.14 | 695 | 3821 |
| | | Candilha Fair | 0.08 | 1017 | 4060 |
| | | Mercadão 2000 Fair | 0.09 | 609 | 2959 |
| Leisure | 0.17 | Santarém waterfront | 0.57 | 785 | 3942 |
| | | Church of the Peace | 0.25 | 681 | 3106 |
| | | Assemblies of God Church | 0.08 | 507 | 2472 |
| | | Mariscada Bar | 0.06 | 681 | 2517 |
| | | Mascote Restaurant | 0.04 | 643 | 2382 |

As the next calculation steps are associated to the standardization of values and the index calculation, once again, new columns were added to the network points attribute table: one column for each key-destination to store the standardized values and one extra column to store the final accessibility indexes values. The standardization was performed applying the chosen fuzzy function formula to each distance value using the “Field Calculator” tool. With all distances standardized, the accessibility indexes were finally calculated using the same tool to apply the aggregation formula from the proposed model.

With the conclusion of the calculation process, the map production started. To generate a continuous surface that can illustrate how the accessibility to key-destinations varies over the study area, a triangulated irregular network (TIN) was created. The network points were used as mass points, covering the study area, and the accessibly index values was designated as Z values. Using those parameters, the resulting TIN "filled" the study area with accessibility indexes values. Figures 8 and 9 shows the accessibility index map obtained by changing the TIN representation as a graduated color ramp that varies from red (lowest values) to green (higher values).

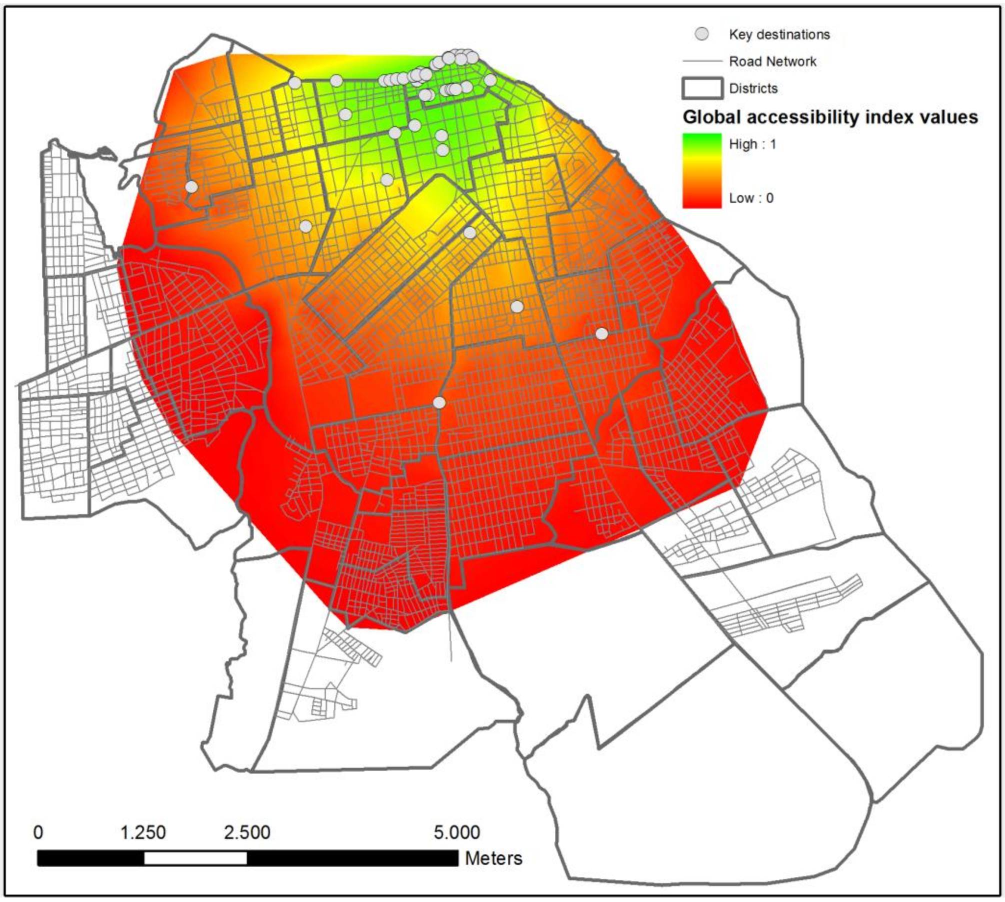


Figure 8 - Map of Accessibility Index for Santarém with pavement impedance

## Case study conclusions

The implementation of the methodology in Santarém indicates that an adequate number of key-destinations could be easily adopted to evaluate the accessibility index. Moreover, the GIS environment and the representation of the index in a map give the opportunity to analyse the spatial distribution and to understand how levels of global accessibility index to key-destinations vary along the studied area.

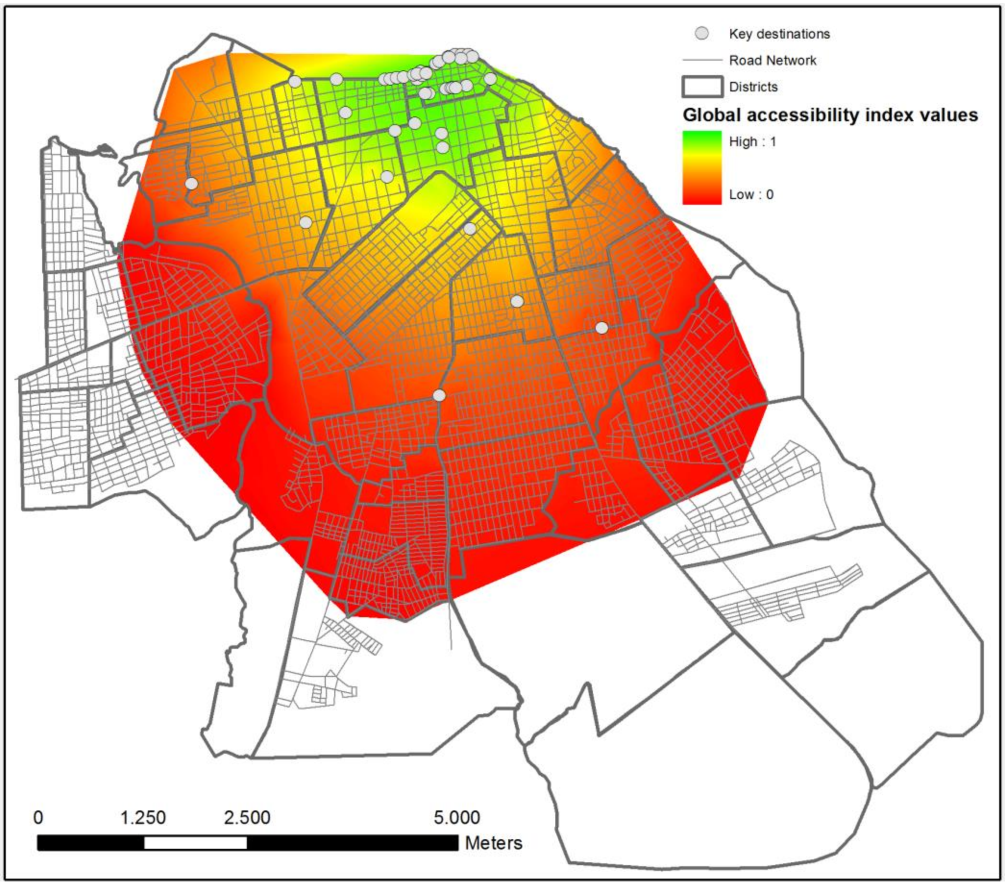


Figure 9 - Map of Accessibility Index for Santarém without pavement impedance

A detailed analysis of the map show in figure 8 and 9 highlights the following aspects of the case studied:

- The concentration of key-destination for several functionalities in the central area of the city gives high level of accessibility for that part of city;
- Outside the central area, about 2km, we found some facilities distributed along a peripheral arc;
- In the outside peripheral area, between 2.5km and the limit of the city, there are none relevant facilities for the city;
- The accessibility values found in the central area and in the area inside the arc of 2 km are relevant and identifies good access to the most important facilities in the city;
- However, outside the 2.5km peripheral arc the accessibility to the facilities is very low;
- The spatial distribution of the accessibility index highlights the maintenance of the importance of downtown area (the old town) and the necessity of long trip for the inhabitants' daily activities.

For better understanding the results differences achieved when pavement impedance is including or not in the calculation process, figure 10 is presented. It is the result of the algebraic difference between the previous maps (figures 8 and 9). It can be seen that global accessibility indexes values can differ in worst cases almost 0.2, near 20% of the full scale. It confirms that details about the network that has influence on accessibility must be integrated in the evaluation process.

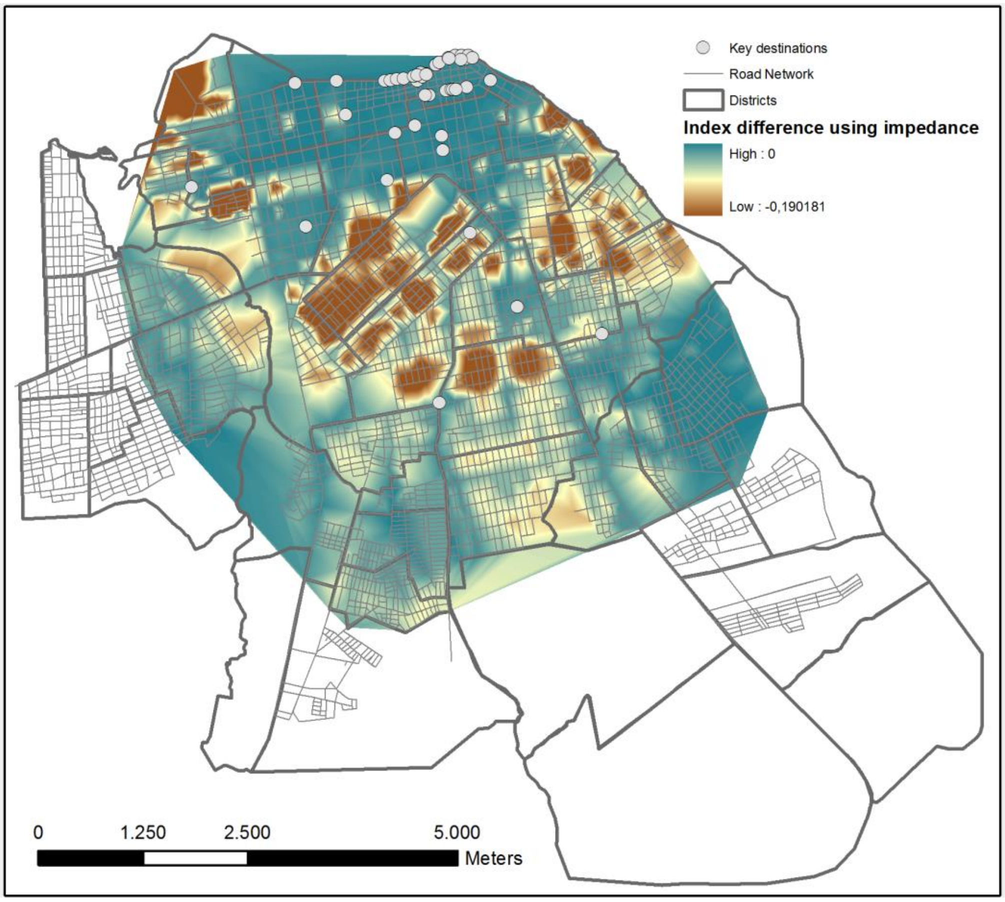

Figure 10 - Map showing index differences setting or not pavement impedance on the network

# CONCLUSIONS

In this paper a multicriteria accessibility evaluation model was developed within a GIS environment. The proposed model calculates an accessibility index given by the weighted summation of cost-distances to a number of key-destinations. Relevant elements in this model include:

- The calculation of cost-distances making use of a road network with friction that represents the resistance to movement.
- The standardization of cost-distances using fuzzy set membership functions that, when calibrated, represent much better the effect of distance in the evaluation.
- The combination of cost-distances taking into account the relative weight of key-destinations in the evaluation.
- The implementation in a GIS environment, taking advantage of the map algebra and visualization toolbox.

In that context, the methodology proposed for the accessibility index evaluation within a GIS framework forms a tool for an easy and ample assessment of urban spatial distribution of the most relevant facilities access. Moreover, it helps to identify the relationships between street patterns and urban morphology related to big traffic generators/attractors, i.e. hospitals, schools, services, leisure or shopping areas. In such way, the method can be used for monitoring and supporting transport policies and facilities location.

Hence, the results of this model application can support city administration decision-making for new investments in order to improve urban quality of live. In addition, the model can simulate and analyze several planning proposal for the city, e.g., expansion of the transport network, the construction of new education and health services, helping to understand which will be the consequences of those actions.

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