URBAN ACCESSIBILITY ESTIMATION AT THE INTRACITYLEVEL: SPATIAL GIS ANALYSIS APPROACH

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Abstract- This paper proposes a method for accessibility evaluation of urban elements (buildings, places) with using GIS. The technique operates with a complex system of urban attributes – transport network, buildings and actual distances between elements of the urban form. All these elements can be treated differently during the calculations according to the purposes of the analysis. For instance accessibility can be calculated for all buildings in a city along the existing road network or for a certain establishments along the pedestrian paths based on a walking distances. Buildings and spaces can be included in the analysis taking into account their area, population, type of use, etc. We present an approach for the accessibility analysis with using distance decay parameter for pedestrian and automobile trips and weight of endpoints. We offer a tool for ArcGIS software for calculating the accessibility index.

Keywords- Accessibility, GIS, Transport Network, Buildings, Urban Form.

I. INTRODUCTION

The idea of investigating spatial relations in self-organized systems through the use of network and graph theories remains very popular since the last century. Representation of the system in the form of nodes (objects of research) connected by edges (interactions, connections) seems logical and easy to understand. This technique has been successfully used in different areas such as social networks, biology, information science, economics, geography, etc. In the last two decades, it has become widely used for urban studies as well. Using the principles of graph theory and its main measures, the spatial patterns of urban environment can be analyzed to help designers and planners to understand better the mechanism of urban system for the efficient design of new spaces. These measures can be useful in urban traffic flow estimation [1, 2]; to evaluate the integration or connectivity of particular street in transport network [3, 4, 5, 6]; accessibility of certain road junctions or urban spaces [7, 8, 9].

Probably one of the best known approaches for the network analysis applied to urban studies is Space Syntax, proposed by Hillier and Hanson in 1984 [5]. The main principle of this approach is to analyze the degree of integration or importance of the network elements (streets) based on their location in the system. This technique is a way of centrality assessment well-known in graph theory. Since Space Syntax was proposed, the centrality measures (closeness, betweenness, gravity, accessibility, etc.) have become the main focus of interest in urban studies. To calculate their value, several algorithms as toolsets for GIS software were proposed: Confeego [10] developed in Space Syntax laboratory, Axwoman toolbox developed by Jiang [11], and methodology called Place Logic based on multiple centrality assessment [6]. However, these techniques have one common disadvantage - the main attention is given to the transport network elements, while buildings are left out of account. In our daily trips around a city, we do not set a goal just to reach a particular street, but a building or space which may be located close to it. Moreover, the high centrality index for the street does not mean the same for spaces or buildings along it if we just take into account the distances. Therefore, the results of analysis based only on street segments do not entirely explain the degree of space integration to the urban environment. A more successful attempt to implement the urban analysis in GIS was the Urban Network Analysis toolbox for ArcGIS developed by Sevtsuk [8]. This technique allows to include a buildings layer in the calculation of different centrality measures. For the accessibility analysis the toolbox uses the principle of potential accessibility measure with a standard value of the cost sensitivity parameter. This parameter controls the distance effect in the network, so more distant points will have less influence on the result. Nevertheless, the use of standard parameter value can significantly distort the final results. It can vary widely depending on the type of human activity, type of settlement (inner city, suburban areas) as well as type of travel mode. The other limitation of the toolbox is the accessibility radius, which is limited for the reach measure to only 2 km. In the next sections, we will discuss some features of urban accessibility and provide a description of main principles of calculation. We then present a way to analyze automobile and pedestrian accessibility at a city level. Finally, we will illustrate the application of the tool to the case of Dejvice municipal quarter in Prague, Czech Republic.

II. ACCESSIBILITY MEASURE IN URBAN AREAS

Accessibility is one of the main indices of smart city development and transport sustainability. It has a direct impact on social and economic performance of
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the territory. Change of transport accessibility leads to changes in the existing system of population displacement. If it increases so does the attractiveness of the territory, causing the influx of population and trade development.

The main parameters involved in the accessibility evaluation are a transport network and a set of points representing destinations and origins. Currently, many of urban accessibility studies use the dual graph representation principle, which replaces a transport network with an abstract model consisting of links and nodes.

The network elements can be both the origins and destinations in such a model. These simplifications allow to significantly reduce the computation time, the amount of input data, and to apply this analysis to large networks. Over the past 70 years, more than 100 techniques have been proposed for transport accessibility evaluation on different scales, from the neighborhood scale to the country level. In this study, we focus on the intracity scale analysis, so we do not consider the techniques used at the large network scale. The following text summarizes description of the main accessibility calculation methods, their advantages and limitations.

2.1. Topological Accessibility
Topological accessibility (TA) is a generalized method, which is suitable for the analysis of all types of networks and widely used for transport systems. The graph elements are presented by any street segments connected with transport network as well as by end-start points of each segment and road intersections. The node accessibility depends on the sum of the shortest paths between the analyzed one and the rest of the vertices in the graph. It is defined as follows:

$$TA_i = \sum_{j=1}^{n} d_{ij}$$  \hspace{1cm} (1)

where $TA_i$ - topological accessibility of a node $i$, $d_{ij}$ - topological distance between nodes $i$ and $j$, $n$ - number of nodes in the graph.

Topological method analyzes the existence or lack of links between the vertices, while the quantitative characteristics of the system are not involved in the analysis. This makes this method only useful for simply illustration of network connectivity but not for complex urban analysis.

2.2. Spatial Separation Measure
This type of measure computes the node accessibility as a weighted average of the travel times or distances to all other destinations [12]. The Euclidian or a network distances are used in the analysis as a space impedance parameter. This measure is defined as follows:

$$SSA_i = \frac{1}{n-1} \sum_{j=1}^{n} d_{ij}$$  \hspace{1cm} (2)

where $SSA_i$ - accessibility index of node $i$, $d_{ij}$ - distance between nodes $i$ and $j$, $n$ - number of points under consideration.

This measure is easy to calculate and does not require a large amount of information. In contrast to the topological accessibility, this technique allows to include some spatial parameters in the calculation: the real distance, travel time or transport costs. However, the origins and destinations are treated equally during the calculation, which can hide from the researcher some important dependencies.

2.3. Cumulative Opportunities
The next accessibility measure is cumulative opportunities, which take into account distances as well as the objective of a trip. Point accessibility in this case is calculated as the sum of potential activities that can be reached within a specified distance or travel time threshold [12]:

$$COA_i = \sum_{j} O_j$$  \hspace{1cm} (3)

where $COA_i$ - cumulative opportunities accessibility of node $i$, $O_j$ - opportunities that can be reached within a threshold.

There are many improvements and additions to this measure for the specific purposes of the analysis, however, destinations remain the major object of a study. This measure is often used for evaluation of accessibility to employment. The only data required for the analysis is the location of jobs within a search radius. The main disadvantage of this measure is that with the increase of the threshold, close and far opportunities are treated equally, it does not consider transportation behavior.

2.4. Potential Accessibility Measure
The most widely used measure for urban accessibility is potential accessibility, also called gravity-based measure. The potential accessibility evaluates point reachability to any other points in urban system, where more distant or less weighted points will have a lesser impact on the final result. This is achieved by introducing distance decay parameter and weight of destinations [12, 13]:

$$PA_i = \sum_{j} W_j f(c_{ij})$$  \hspace{1cm} (4)

where $PA_i$ - potential accessibility of node $i$, $W_j$ - weight of node $j$, $f(c_{ij})$ - function of overcoming spatial separation.

This measure allows to describe a number of interesting urban phenomena, but requires more data for the analysis. Distance decay parameter can explain a travel behavior, but it is very sensitive to the distances and has a great impact on the final results.
After reviewing of accessibility measures, which are used for urban studies, we have chosen the potential accessibility method since there are several reasons for this. Firstly, using function of overcoming spatial separation makes this group of methods flexible in relation to the study purposes. It allows to change the value of distance decay parameter for estimation of accessibility and to use the weight of destinations. Secondly, with the development of GIS and availability of spatial geographic data it has become possible to analyze spatial interactions on real city models. Today, instead of abstract representation, we can use the real parameters of buildings (height, volume, population) and transport network (length, directions, obstacles). The following section provides more detail description of the used function for the potential accessibility method.

III. METHODOLOGY

The type of the overcoming spatial separation function which determines the value of distance decay parameter is selected in accordance with the objectives of the study, and therefore in the scientific literature there are a large number of its variations. In general, they can be divided into two groups: threshold (Fig. 1) and exponential (Fig. 2) functions.

Exponential function implies the inverse relationship between distance and function value. Distance decay parameter will be proportionally decreased with larger distances. Exponential functions proposed by Hansen [7] remain the most widely used in the accessibility analysis. Based on the purpose of our study, we have chosen the Hansen exponential function (Fig. 3) as a compromise in terms of the results objectivity and the ease of perception.

Fig. 3 illustrates two types of the Hansen function. According to sociological studies the behavior of these functions is close to the actual behavior of the individuals in the analysis of transport accessibility at the intracity level [13]. The value of the first function tends to infinity and becomes essentially equal, which makes it effective in the analysis of pedestrian accessibility focused on the objects located close to each other. Then the equation (4) takes on form:

$$PA_i = \sum_{j=1}^{n} W_j \cdot e^{-d_{ij}}$$

where $PA_i$ - potential accessibility of node $i$, $W_j$ - weight of node $j$, $d_{ij}$ - distance between nodes $i$ and $j$, $e$ - base of the natural logarithm.
We used the equation (5) to evaluate pedestrian accessibility of buildings which will be discussed later in this section.

The second function is flatter; it allows to compare close located points with farther ones and to use this function in the analysis of automobile accessibility at the intracity level. Equation (4) in this case takes on the form:

\[
PA_i = \sum_{j=1}^{n} W_j \cdot e^{-\frac{d_{ij}}{e}}
\]

where \(PA_i\) - potential accessibility of node \(i\), \(W_j\) - weight of node \(j\), \(d_{ij}\) - distance between nodes \(i\) and \(j\), \(e\) - base of the natural logarithm.

Selection of function type and methodology to quantify urban accessibility, which corresponds to the study objectives, was the theoretical basis of this paper. The next step was to develop an algorithm allowing to implement accessibility computations with using GIS. The main input data for the analysis are: transport network, the geographical location of the analyzed points (buildings) and their properties to be used as the weight parameters. ArcGIS 10.2 was used to develop the algorithm, which consists of four steps: (1) creation of origin-destination cost matrix layer allowing to determine the actual distances between all origins and destinations in the network; (2) definition of weight parameter for each endpoint; (3) using equations (5) or (6) to calculate accessibility index for each point in the analyzed system; (4) implementation of the analysis results into the point attribute table. Using ArcGIS ModelBuilder and Python script allowed to implement the algorithm into the add-in tool for ArcGIS 10.2. The methodology was applied to a small part of a residential area (to save the visual perception due to the large number of buildings) located in Dejvice municipal quarter of Prague in the Czech Republic to demonstrate visually the tool we developed.

Fig. 4 and 5 illustrate the outcome of automobile and pedestrian accessibility analysis respectively. 800 meter walking distance limit and pedestrian network including all walking paths were used for the pedestrian accessibility analysis. For the automotive accessibility only road network with unlimited distances was used. Building floor area served as a weight parameter in both cases.

We can see that the higher values of accessibility appear in areas with the highest density of buildings and road network. Denser housing means that more destinations can be reached within the area, thus, there will be higher value of accessibility index. In the case of automobile accessibility the index value is much higher than the pedestrian one due to no distance limitations. These figures show how the accessibility can be quantitatively described by using spatial analysis in GIS.

CONCLUSION

The method proposed in this paper can be used to analyze the attractiveness of urban spaces for different individuals or stakeholders as well as a compactness of urban form in terms of accessibility. Through the spatial analysis of the main urban components the tool helps to evaluate the reachability of new construction and to improve its efficiency as well as to identify weaknesses in the existing urban form. With increasing availability of spatial geographic data, the new methods of urban analysis are also needed. We believe that our tool will help urban planners, architects and municipal government to achieve the main goal of sustainable urban development - creation of comfortable living conditions for the citizens; economic growth and the preservation of the environment.
REFERENCES


