A Set of GIS-based Tools for Spatial Structure Analysis

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Abstract. This paper presents a set of tools we developed with ArcView GIS for spatial structure analysis. The tools are based on the fundamental principles of space syntax (a set of methods for urban morphological studies), and integrated with a new approach. We review related applications mainly from space syntax research community to show how such a set of tools can be used to explain social functions of space and predict human spatial behaviour. Such a set of tools extends existing GIS analytical function for the social sciences.

Keywords: structure analysis, space syntax, social functions of space, and spatial analysis

1. Introduction
Space has a certain structure. The structure refers to that of an urban street network or an architectural layout in this context. Human moving behaviour (on foot or by car) in a space is affected to great extent by the spatial structure. Thus through an effective structure analysis we are able to predict human moving behaviour in a space. On the other hand, social function of a space is likely based on the effective structure analysis. Over the past two decades, space syntax (Hillier and Hanson 1994) has evolved into an important method for such a structure analysis with considerable amount of empirical studies applied to both architecture and city systems. Originated from seminal work in urban morphology (March and Steadman 1973, Steadman 1983), space syntax proposed a graph theoretic method for spatial structure analysis that has special applications in urban studies such as pedestrian flow modelling (Hillier et al. 1993), urban crime analysis (Jones and Fanek 1997, Shu 1999) and spatial cognition research (Kim 1999, Penn 2001). Therefore integration of such a method into GIS can improve GIS functionality in spatial analysis.

We have introduced our initial package named Axwoman elsewhere (Jiang et. al. 1999, Jiang et al. 2000), which consists of partial implementation. More recently we have proposed a new approach (Jiang and Claramunt 2002) to improve the method from a point of view of integrating such a structure analysis into GIS. Now we provide an improved version of the package, as we believe such a set of tools could have special applications in social science studies concerned about spaces and places. So the aim of this paper is to introduce the set of GIS-based tools we developed for spatial structure analysis, and furthermore to stimulate cross analysis with socio-economic data.

The remainder of this paper is organised as follows. Section 2 presents the fundamentals of space syntax on which the set of tools is based. Section 3 describes the details of implementation based on ArcView GIS, involving major components, functions and algorithms. To show how the tools can be applied to social sciences, section 4 presents a selective overview of applications for urban studies identified from space syntax research community. Finally section 5 concludes the paper.
2. Spatial structure analysis based on space syntax

A good way to understand structure analysis is the use of the concept of graph. A graph consists of two basic elements: nodes and links. How nodes are interconnected through links give a sense of structure of a graph (undirected and unweighted graph is adopted in this context). Within a graph, each node has different status from a structural point of view. There are two perspectives to look at the status of a node, namely local and global perspectives. Local perspective focuses on how each node connects to other nodes within a few steps, while global perspective on how each node connects to every other node within a graph.

Let’s introduce some important parameters to measure the status of a node within a graph. For any particular node in the graph, the shortest distance far from the node is denoted by \( s \) (\( s \) is an integer), the number of nodes with the shortest distance \( s \) is denoted by \( N_s \), and the maximum shortest distance (diameter of the graph) is denoted by \( l \). Using the expression

\[
\sum_{s=1}^{m} s \times N_s
\]

we can describe the following space syntax parameters\(^*\) for the node:

\[
\sum_{s=1}^{m} s \times N_s = \begin{cases} 
\text{connectivity} & \text{iff } m = 1 \\
\text{local integration} & \text{iff } m = k \\
\text{global integration} & \text{iff } m = l 
\end{cases}
\]

Where \( k \) meets the condition \( 1 < k < l \).

Spatial structure analysis based on space syntax uses the graph view and apply it to different spatial situations. Let’s take a look at how a space is actually organised with the situations. At an architectural level, a space is partitioned into (or perceived as) small units (or places) such as rooms and corridors. At a city level, there is no obvious partitions as at an architecture level, but often a street can be perceived as a form of vista spaces. These two observations lead to two basic approaches of space syntax, namely area-based and axial line-based approaches. Both approaches take the perceived units as nodes of a graph, i.e. rooms and corridors in the former case, and vista spaces in the latter case (figure 1). As for the links of the graph, it depends on the visibility among the perceived units. If a room has a door linking to a corridor, then the two perceived units are considered to be visible each other, and there is a link between the corresponding nodes. Or alternatively if two vista spaces are intersected each other, then they are considered to be visible as well, and a link between the corresponding node is needed.

\(^*\) It should be noted that the integration here is a simplified one: Actual integration is based on a value of real rational asymmetry; refer to Jiang and Claramunt (2002) for details.
It should be noted that the area-based approach, initially called convex representation (Hillier and Hanson 1984), could be applied to a city level as well. We argued that whether or not a perceived unit is convex is not so important, key point is that whether or not it is small enough to be perceived from a single vantage point of view. If it is perceivable from a single vantage point of view, then we can represent a place as a node, even though it is not convex. With the representations, a whole space consists of perceivable places, and the status of each place can be computed from the corresponding graph.

Let us take the example of the axial line identified as number one (equivalent to node one in the dual graph) in figure 1b. This line intersects four lines, so the connectivity of the axial line one is 4. The immediate neighbourhood of line one are lines 2, 3, 4, and 5, and their respective connectivity values are 2, 3, 5, and 4. Overall this axial line number one has 4 neighbourhoods one step away, 5 neighbourhoods two steps away, and 3 neighbourhoods three steps away (herein the concept of steps is equivalent to that of shortest distances). So global integration is equal to $4 \times 1 + 5 \times 2 + 3 \times 3$ if $k = 3$. If $k = 2$, then local depth with two steps away is equal to $4 \times 1 + 5 \times 2$.

A valid representation is said to be the least number of the largest axial lines needed to cover the entire space (Hillier and Hanson 1984). Otherwise, the structural analysis would be less meaningful, because the overall number of lines will not be representative of the spatial structure. So far the derivation of an axial map still relies on human judgement to draw individual lines, so no automatic solution has been identified, particularly for large cities, within the space syntax research community (c.f. Peponis et al. 1998). To overcome this problem, we have proposed a point-based approach (Jiang and Claramunt 2002) that is based on characteristic points identified from a space. These points include road junctions and turning points (i.e., a turning point is defined as the peak of a curve). Based on how these points are visible, we can derive a visibility graph as shown in figure 2 for an example. Our experiments have shown that the approach is at least equivalent to the line-based approach in illustrating spatial structure. However the approach has several advantages over the line-based approach: the point representation is completely computable; and the structure analysis is more suitable for cross-analysis with socio-economic data that is mostly point-based.
3. The GIS-based tools for spatial structure analysis

The tools were implemented as an extension of ArcView GIS, thus provides an easy-to-use interface for the end users. ArcView is a desktop GIS with components including the view, table, chart, layout and script. Each of these serves different purposes for spatial data processing and presentation. Among others, Avenue script permits the customization of the ArcView interface, and provides some additional spatial functions. Avenue possesses important programming facilities such as lists and looping constructs for graphics manipulation, spatial queries, and basic arithmetic calculations. ArcView also has a set of extensions such as Spatial Analyst and 3D Analyst. The Spatial Analyst presents generic spatial analysis functionality on grid and feature themes such as proximity analysis, cell statistics and multi-map calculation, while the 3D Analyst allows users to create, analyze, and display surface data.

The GIS-based tools consist of three major components: identification of spatial units that could be point-, line- and area-based, computation of all structure parameters, and analysis of computing results and cross analysis with socio-economic data. The three components were implemented as toolbar as shown in figure 3. The identification of spatial units can rely on ArcView drawing tools manually, but for point-based approach the end users can directly import node file from ArcInfo and convert it from theme to graphics. Once the spatial units have been identified, users can compute all structure parameters and put them in an attribute table linked to a new created theme. With the analysis component, the users can explore data from different perspectives, or import observed data like pedestrian flow rates, and socio-economic data for cross analysis.

Worth noting is the software’s exploration capability. In order to conduct the structure analysis discussed above, a range of analytical components such as spatial units (namely axial maps, polygon maps, or characteristic points), tables, and charts are provided. All these components are dynamically linked to each other, so any action applied to one of the components will be propagated to any other. Figure 3 shows a typical interface.
Now let’s take a detailed look to major algorithms with the implemented tools. The first algorithm is to derive a matrix of the graph on which the subsequent computation is based. A key point is to determine how spatial units are interconnected or visible each other, i.e. $\text{CONNECT}(v, w)$ in the following algorithm. For the line-based approach it can be achieved through request $\text{Intersect}$, i.e. if one line intersects another line, then the two lines are interconnected. For the area-based approach, if two polygons are connected to a common line segment, they are interconnected. For the point-based approach, we adopt such a rule, i.e. one point is visible from another point if the line linking the two points does not intersect with any building polygons. The above process is time consuming, as it has to check for every spatial unit against every other. The algorithm can be described as follows:

Algorithm CREATE_MATRIX
// $V$ is a set of spatial units, assume that there are totally $n$ spatial units
// that are indexed from 0 to $n-1$
// $M$ is the output adjacency matrix for the representation of the graph
begin
    $A \leftarrow [0...n-1][0...n-1]$ // the $n\times n$ zero matrix
    $V' \leftarrow V$ // target set of vertices
    for every $v \in V$ do
        for every $w \in V$ do
            if $\text{CONNECT}(v, w)$ then
                $M[v][w] \leftarrow 1$
                $M[w][v] \leftarrow 1$ // the matrix is symmetric
            end if
        end for
    end for
end CREATE_MATRIX
Based on the above matrix, we can derive a range of structure parameters such as connectivity, local and global integrations. The integration computation is based on the algorithm for calculating the status of a node using Breadth-First Search (BFS) technique (Buckley and Harary 1990). For a connected graph, the algorithm begins at the first node and finds its neighbours, and then their neighbours, and so on until the algorithm has spanned throughout the whole graph and reached all nodes within the graph. Then this process continues with the second and third nodes until all nodes have been exhausted. Overall the tools were implemented as an extension and can be used together with some ArcView extensions. It complements spatial analyst and 3D analyst in spatial structure analysis.

4. Applications in urban studies

The spatial structure analysis can be used as both a design and an analysis tools for the built environments. As a design tool, it facilitates urban and architecture design to achieve best or optimal design scenarios. As an analysis tool, it can be used to determine social functions of space, and predict pedestrian and vehicle flows in a space. In this section, we focus on how the analysis results can be used to predict pedestrian flows, and crime analysis in complex built environments. By doing so, we hope to set up an image as to how the tools can be used for social science study, and diffuse the implemented tools within a GIS community.

The structure analysis is very important for understanding social functions of space. The title “the social logic of space” (Hillier and Hanson 1984) implies a logic or relationship between human activity and spatial structure. Let’s take a look at a simple example as illustrated in figure 5. It is a floor from a building complex functioning now as an educational institution. All rooms and corridors are represented as geometric shapes, and a short line segment represents their possible connections with a door or entry. Through the structure analysis, we found that the long corridor is most integrated or connected and it tends to attract more people moving in it. Indeed, crosscheck in reality confirms this observation; both teachers and students are likely to move along the corridor. On the other hand, rooms coloured with the lighted red are most segregated places, which are being as teachers’ offices. Other rooms and places with intermediate integration or segregation are used for other purposes. For example, the six parallel rooms are used for classrooms or labs. From the example, we can see that space has different functions in terms of how they are connected each other. Well-connected and well-integrated rooms are often used for meeting, while less connected and less integrated spaces for offices. Considerable amount of case studies have been carried out in this direction and they provide a good insight into urban and architecture design (c.f. Hanson 1998).

Figure 5: A building space (a) and its space syntax analysis result (b)
Prediction of pedestrian vehicle flows in urban systems is another important application aspect for the structure analysis. Some well established case studies have illustrated that local integration with three steps can be used to predict pedestrian flows (Hillier et al. 1993), i.e. pedestrian flow rate and local integration hold a significant correlation in a scatter plot. The same observation has been tested for vehicle flows as well. These findings about human movement behaviour are interesting, as it is based on spatial structure analysis without knowing individual behaviour. It should be noted that by movement behaviour we mean the average movement choice of a population, rather than individual ones.

![Figure 6: Crime distribution and street connectivity](image)

Not only human movement, but also crime activities such as burglary in dwelling, criminal damage and car crimes of all kinds are affected by spatial structure. A basic hypothesis is that spatial property is one of important factor to determine spatial distribution of crime activities in urban system, i.e. crime activities are more likely happened in well-segregated areas (Jones and Fanek 1997, Shu 1999). In this respect, we have made some case studies as well using crime data collected from local police station. Due to confidential nature of the crime data, we could not make a detailed report here. However our study confirms the above hypothesis, i.e. high density crimes are located at well-integrated areas or streets. Figure 6 shows a crime distribution, where the majority of crimes are around the three most connected streets.

5. Summary and outlook
This paper has introduced the integrated tools and the basic principles behind them. Through a selective overview on the applications of the structure analysis in urban studies, we have shown how human spatial behaviour can be analysed by structural parameters. It provides a solid evidence to diffuse the structure analysis into social sciences that are particularly concerned about spaces and places.

References
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