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Geometric accessibility and geographic information: extending desktop GIS to space syntax

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Abstract

Accessibility indices which measure the relative 'nearness' or 'propinquity' of geographic locations, one to another, are not well-developed functions in proprietary geographic information systems (GIS), notwithstanding their evident usefulness for urban analysis. In this paper, we develop procedures for embedding such measures within desktop GIS, focusing on the measurement of geometric accessibility which is applicable to fine-scale urban structure at the street-building level of representation. The particular type of accessibility that we examine is based on the theory of space syntax, although our presentation generalises to many other types, and the way we embed measures of space syntax within GIS is applicable to a much wider class of measures. We first review the general class of geographic and geometric accessibility measures, defining those in space syntax as special cases. We then outline our implementation of these through a software extension within the desktop GIS *ArcView*, showing how the analyst can input street systems within the software through new drawing tools, generate accessibility measures through new computational functions, and present these visually using standard *ArcView* outputs. The extension we propose enables accessibility measures to be integrated with the more conventional functionality of GIS analysis which is embodied in the basic software and its extensions. We illustrate the analysis using a standard space syntax example based on the street pattern of a small French town. © 1999 Published by Elsevier Science Ltd. All rights reserved.

Keywords: Accessibility; Geographic information; Desktop GIS; ArcView Extension; Space syntax

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1. Introduction

Although there has been considerable progress in extending geographic information system (GIS) technologies to embrace spatial analytic techniques during the last decade, methods which involve relations, connections, interactions, or flows between locations have rarely been developed (Fischer, Scholten & Unwin, 1996; Fotheringham, 1992; Fotheringham & Rogerson, 1994; Longley & Batty, 1996; Zhang & Griffith, 1997). This is partly because the conventional mode of representation within GIS depends on ascribing all geographic phenomena to the simple triad of points, lines and polygons or some combination thereof, and phenomena which builds relationships on top of these elements adds a new layer of complexity to analysis which GIS vendors regard as being too specific to the wide range of applications that their software purports to address. However, it is largely recognised that the extension of GIS to embrace and integrate analysis and modelling methods which directly deal with such spatial interactions is essential if the technology is to achieve its potential as a general-purpose tool for environmental and urban planning (Goodchild, Haining & Wise, 1992; Openshaw, 1991).

This lack of tools to address problems of spatial interaction is being remedied in the development of GIS specific to transportation modelling (GIS-T) but measures which draw on transportation analysis such as those involving the measurement of accessibility are still required in the more general forms of GIS. In fact, it is not difficult to develop measures of accessibility within most proprietary GIS for the elements of their definition are already implicit in many standard functions and extensions. For example in *ARC-INFO*, tools which enable location–allocation modelling invoke such measures while in the desktop GIS *ArcView*, the Network Analyst extension involves the same. However, what is dramatically absent are tools for developing accessibility measures at fine spatial scales which involve the geometry of urban structure in terms of streets and buildings in contrast to the measurement of accessibility at the geographic or thematic level which is simpler and more direct. In fact, this lack of spatial analytic tools at the building scale has hardly been addressed at all in the development of GIS for most spatial analysis is predicated at a larger scale where statistical rather than geometric relationships are more significant.

In this paper, we will show how ideas of geometric accessibility based on the connectivity of locations and places, one to another, rather than their physical distance, can be developed within GIS. This is part of a wider project in developing new technologies for urban design based on GIS (Batty, Dodge & Jiang, 1999). Specifically, we will develop measures based on the connectivity of street networks, using a theory of local accessibility called 'space syntax' which in turn is based on examining relationships between street segments used to define the elements of urban structure (Hillier & Hanson, 1984). Over the past two decades, space syntax theory has provided computational support for the development of urban morphological studies based on defining space between buildings by 'axial lines' through their graph-theoretical properties. A series of syntax measures of street accessibility based largely on pedestrian movement have been developed and applied, but in all cases these measures have not been related to other important elements of urban structure such as building uses, the configuration of land parcels, and related network structures such as telecommunication and rail lines. Besides defining additional functionality for GIS which embraces spatial connectivity, it is possible to extend the spatial analysis of this syntax to many other geographic and geometric layers of information by embedding such analysis within GIS. For the first time, this also ensures that such analyses are conducted using the precision and accuracy that GIS enables.

We first present a formal theory of accessibility, detailing how geographic differs from geometric accessibility. Space syntax is a special case of geometric accessibility and we show how its various measures called connectivity, control and integration are derived. The heart of the paper involves implementing these measures in the desktop GIS *ArcView* which we achieve as an extension to the software. We take an hypothetical example involving 13 streets which intersect in 19 places and we show how the algebra of this syntax can be programmed into the software using the *Avenue* scripting language. The extension involves three related functions: a drawing capability which the user invokes to define the urban structure as a set of streets and their intersections, a computational function which enables various accessibility measures to be calculated, and an analysis function which draws largely on the existing functionality of *ArcView* and enables these measures to be related to other layers of information represented in the software. We illustrate all these functions for the standard example of a small French town which has been widely used in presenting space syntax (Hillier & Hanson, 1984). We conclude with ideas as to how we might generalise our implementation to other measures of accessibility.

2. Geographic and geometric accessibility

Accessibility is a widely used spatial analytic measure defined as the relative 'nearness' or 'propinquity' of one place i to other places j. Usually such measures of nearness balance the benefit of locating at or visiting a place j with the costs of moving or travelling to that place from a fixed location i around which accessibility is being calculated. In generalised terms, the measure can be defined as:

$$A_i = \sum_j f\left(W_j, d_{ij}\right), \tag{1}$$

where W_j is some index of the attraction of j and d_{ij} is a measure of the impedance, typically the distance or travel time of moving from i to j. In land use–transportation modelling, the traditional form of accessibility is based on a gravitational equation of the following form:

$$A_i = K\sum_j P_j \, d_{ij}^{-\alpha}, \tag{2}$$

where P_j is the population at j, K is the gravitational or scaling constant and α is a friction of distance parameter. This is the traditional measure of population potential defined originally for geographical systems by Stewart and Warntz (1958) and central to the definition of competition in spatial interaction models. It is also linked to measures of utility and consumers' surplus in contemporary treatments of discrete choice and related travel demand models (Wilson, Coelho, Macgill & Williams, 1981).

Accessibility is a derived measure. It is rarely, if ever, calibrated to any observed data although it is computed in spatial interaction models to maximise their fit to existing movement patterns. Usually it is regarded as a measure of potential or latent interaction, useful in predicting the implicit outcome of spatial processes or in allocating land use so that propinquity is maximised (Hansen, 1959). Eqs. (1) and (2) assume that accessibility is homogeneous in that it can be defined for every location i or j in a system of n places $\{i, j = 1, 2, \ldots, n\}$ where it is possible to move directly from any place i to any other place j. Accessibility in these terms is a measure of the nearness of a place (area) or a point location approximating that place. In this form, it is not used to measure the accessibility of lines or routes. It is not usually defined in this form for spatial systems whose geometric properties are critical and thus we will refer to the measure in Eqs. (1) or (2) as *geographic accessibility*.

At a finer scale where buildings and streets form the system of interest, the relative location and nearness of locations one to another is more structured and we, therefore, need to define an analogous concept to geographic accessibility which we will call *geometric accessibility*. In this case, physical distance is much more important and often the attraction of a point cannot be defined. Setting the attraction $W_j = 1, \forall j$, Eq. (1) becomes:

$$A_i = \sum_j A_{ij} = \sum_j f\left(d_{ij}\right), \tag{3}$$

where A_{ij} is the accessibility of j with respect to i which must clearly decrease as distance increases for the measure to be meaningful. This can be formalised in several ways such as in the inverse power function in Eq. (2) but a more general approach is to assume the distance is weighted in such a way that the weights w_{ij} decrease as distance increases. Then:

$$A_i = \sum_j w_{ij}\, d_{ij}, \tag{4}$$

where $w_{ij} < w_{ik}$ if $d_{ij} > d_{ik}$. There are many forms in which to structure these weights but the central issue is that the further places j are from i, the lower their individual accessibility A_{ij}.

The measure in Eq. (4) is still too general to account for the fact that the connectivity of the network must be reflected in the measurement of distance and hence accessibility. Geometric accessibility must account for movements that occur through different places i which appear as nodes in the network and this suggests that the measure must be defined in relation to its planar graph $G(V, E)$ where V is the set of vertices or nodes defining places $\{v_i, v_j \mid i, j = 1, 2, \ldots, n\}$ and E is the set of edges, arcs or links $\{e_{ij}\}$ defined from:

$$e_{ij} = \begin{cases} 1, & \text{if } v_i v_j \in E \\ 0, & \text{otherwise.} \end{cases} \tag{5}$$

Each edge can have a physical distance d_{ij} associated with it, although in simple networks where the emphasis is on connectivity rather than extent, the distance is sometimes taken as the unit edge $e_{ij} = 1$ or 0. Several new measures of accessibility can now be defined which are standard to graph theory (Buckley & Harary, 1990). One step connectivity C_i is defined as the number of edges to which node i is directly connected as:

$$C_i = \sum_j e_{ij}, \tag{6}$$

and from this the one-step distance D_i can be defined as:

$$D_i = \sum_j e_{ij}\, d_{ij}. \tag{7}$$

The mean one-step distance $\overline{D}_i$ can then be computed as:

$$\overline{D}_i = D_i / C_i. \tag{8}$$

Other measures based on higher-order distances are widely used in graph theory and we will define the most common of these here.

If we change the emphasis slightly from distance through different paths between the nodes in the network to the number of paths traversed from any node i to any other node j, then a measure of structural distance S_{ij} can be computed as follows. This in fact will be a measure of how deep different nodes are from any given node and this structural measure can then be used as the basis for a measure of geometric accessibility. There is a simple algorithm for computing the depth S_{ij}^z where z is the depth of node j from i. First set $S_{ij}^1 = e_{ij}$. Then compute the following sequence:

$$S_{ij}^2 = \begin{cases} 1, & \text{if } \sum_k S_{ik}^1 e_{jk} \text{ and } S_{ij}^1 = 0 \\ 0, & \text{otherwise} \end{cases} \quad \cdots\cdots\longrightarrow \quad S_{ij}^z = \begin{cases} 1, & \text{if } \sum_k S_{ik}^{z-1} e_{jk} \text{ and } S_{ij}^{z-1} = 0 \\ 0, & \text{otherwise} \end{cases}$$

$$\Uparrow \qquad\qquad\qquad\qquad \Downarrow$$

$$\longleftarrow\longleftarrow\longleftarrow\xleftarrow{z=z+1}\longleftarrow\longleftarrow$$

until $\sum_z S^z_{ik} > 0, \forall ij$. We can now define the overall step distance or depth of j from i as:

$$S_{ij} = z, \text{ if } S^z_{ij} = 1. \tag{9}$$

A precise definition of geometric accessibility using the step distance in Eq. (9) above can now be given as:

$$A_i = \sum_j S^{-1}_{ij}, \tag{10}$$

where it is clear that the step distance is weighted in simple inverse fashion. A more complete measure is provided by the sum of the raw path lengths where the weights decrease as the path lengths and their number increase. Such a measure can be computed as:

$$A_i = \sum_j \left\{ \sum_z \lambda^z \sum_k S^z_{ik}\, e_{jk} \right\}, \tag{11}$$

where the generalised weight λ is set between 0 and 1, that is $0 < \lambda < 1$.

3. The accessibility of streets: space syntax as geometric accessibility

One of the most widely applied measures of geometric accessibility is based on the theory of urban morphology which is called 'space syntax' (Hillier & Hanson, 1984). However, space syntax defines the accessibility of streets, not nodes linking streets or defining locations along streets although the vertex–edge/node–arc representation is central to its conceptualisation and operation. To extend our concept of geometric accessibility to embrace this theory, we need to extend our definition of vertices and edges one stage further, so that we can define not only the accessibility of vertices but also the dual problem—the accessibility of edges where we will treat edges as streets. To develop this, we now need to distinguish between two distinct sets: vertices $V(v_i, v_j \in V \mid i,j, = 1, 2, \ldots, n)$ and edges $E(e_k, e_l \in E \mid k, l = 1, 2, \ldots, m)$. Note that there are now n vertices and m edges and that there is no immediate definition of edges in terms of vertices and vice versa.

We define a relationship between a vertex or node and an edge as follows using the unit measure as a criterion of the presence or absence of such a relation. Then:

$$x_{ik} = \begin{matrix} 1, \text{ if } v_i e_j \in X \\ \\ 0, \text{ otherwise,} \end{matrix} \tag{12}$$

where X is the set formed by the union of V and E. To fix ideas, then all we need say is that the set of vertices are places or locations in the space and the set of edges are streets, and if x_{ik} is positive, then this means that a location is related to a street. This will *usually* mean that the location and street are geometrically adjacent or coincident in some way, but this geometric property is not essential to the definition. From X, we can form two sets of relations: first how vertices or nodes are related to each other through their common edges or streets, and second how edges or streets relate to one another through their common nodes. These problems are in one sense duals of one another and are formally defined as follows.

First, relationships between the nodes i and j can be defined as:

$$\overline{E}_{ij} = \begin{cases} 1, \text{ if } \sum_k x_{ik} x_{jk} > 0, \; i \neq j \\ 0, \text{ otherwise.} \end{cases} \tag{13}$$

Note that the relations $\{\overline{E}_{ij}\}$ are not the same as the edges of the planar graph $\{e_{ij}\}$, for we have not made it a condition of the relationships defined on X that vertices always bound edges and vice versa. The new graph that is composed of the new edges $\{\overline{E}_{ij}\}$ may well be mappable in terms of the associated planar map but this is now a graph of relations between distinct objects which, although grounded in the geometric properties of the space, may not coincide with the street network. The dual of this graph is another graph of relations based on the relationships between the original streets k and l. Then:

$$\widetilde{E}_{kl} = \begin{cases} 1, \text{ if } \sum_i x_{ik} x_{il} > 0, \; k \neq l \\ 0, \text{ otherwise.} \end{cases} \tag{14}$$

All the various measures of connectivity and accessibility defined earlier in Eqs. (6) – (11) can be applied to either of the graphs defined from the relations $\{\overline{E}_{ij}\}$ or $\{\widetilde{E}_{kl}\}$. In fact we will develop measures based entirely on Eq. (14), for this is the set of relations that is used in space syntax. However, it is important to note that accessibility as defined in space syntax is but a special case within the set of geometric accessibility relations which in turn can be related to the even wider and less structured set of relations defined in terms of geographic accessibility.

As space syntax has not been developed using the formalism presented here, there is a final simplification that must be made. The set of relations $\{x_{ik}\}$ is invariably defined from the planar graph which constitutes the street layout $\{e_{ij}\}$ and thus nodes are always associated with streets and are only defined if two or more streets intersect. In short, there are no nodes that exist independently of the junctions of street. Where the street pattern is represented as a planar graph, each street is defined between two nodes whereas in space syntax no such requirement is imposed. There may be any number of nodes located in a single street and any number of streets associated with a single node. Streets are always treated as bi-directional and thus any graph formed from $\{\overline{E}_{kl}\}$ or $\{\widetilde{E}_{kl}\}$ will be symmetric. Finally all relations are non-reflexive, that is $\overline{E}_{ii} = 0, \forall ii$ and $\widetilde{E}_{kk} = 0, \forall kk$. However, for any non-trivial system of interest, then the graphs associated with Eqs. (13) or (14) are always strongly connected and thus their overall step distances $\{\overline{S}_{ij}\}$ and $\{\widetilde{S}_{kl}\}$ are always positive.

The more controversial elements of space syntax involve the definition of junctions (nodes) and streets. The urban pattern is first divided into convex spaces centering on significant points of interest and then axial lines, one for each space, are then specified as the least set of longest lines that span these spaces and which provide the requisite connectivity. Needless to say, this is not a well-defined criterion and most applications in fact trace out a set of longest lines intuitively. It is not our purpose here to discuss these issues, for the method can be used in less ambiguous contexts where lines are defined, e.g. as simply the smallest set of 'straight' line-segments that approximate the street pattern, or as the set of lines which the designer 'perceives' to be most important in defining the space.

Three graph-theoretic measures, all pertaining to geometric accessibility are usually defined. The connectivity $\widetilde{C}_k$ gives the total number of streets connected to a particular street k:

$$\widetilde{C}_k = \sum_l \widetilde{E}_{kl}, \tag{15}$$

which is a measure of local accessibility in the graph—the one step distance in this case where the measure of distance between two streets is the unit measure. The measure of control Λ_l is the sum of the apportionments of this connectivity associated with k over all other streets l, i.e.:

$$\Lambda_l = \sum_k \frac{\widetilde{E}_{kl}}{\widetilde{C}_k} = \sum_k \frac{\widetilde{E}_{kl}}{\sum_l \widetilde{E}_{kl}}. \tag{16}$$

As the measure of one step distance in space syntax is assumed to be $\widetilde{E}_{kl}$, then the overall distance is computed using the algorithm which leads to Eq. (9). The next step in computing accessibility is to compute the mean overall step distance for each node k as:

$$\widetilde{D}_k = \sum_l \widetilde{S}_{kl}/(m-1), \tag{17}$$

where the term $m-1$ reflects the fact that there are at most $m-1$ links to any node k. This mean distance is then normalised and referred to as the 'relative asymmetry', R_k. It is computed as:

$$R_k = 2(\widetilde{D}_k - 1)/(m-2), \tag{18}$$

and it is easy to show that it varies between 0 and 1. However, this measure increases as the distance from any street to all others increases and thus it acts in the opposite way to the usual index of accessibility. In many published applications of the method, Hillier and his colleagues appear to invert the measure and refer to it as "integration", I_k, which is given as:

$$I_k = (m-2)/2(\widetilde{D}_k - 1). \tag{19}$$

Finally, it is easy to show that integration, I_k, is a kind of accessibility, for Eq. (19) can be written in proportional form as:

$$A_k \sim \sum_l \left\{ \widetilde{S}_{kl} \right\}^{-1}, \tag{20}$$

which is similar to the measure of geometric accessibility defined in Eq. (10) above.

4. An overview of the software implementation in *ArcView*

Space syntax applications were originally implemented using purpose-built software on the Macintosh platform. The basic data consists of a set of line segments which intersect with each other and which the user defines directly. Until quite recently all applications involved users defining such lines on a hard copy base map. This map of so-called axial lines was scanned and then input to a program called '*Axman*' which enabled calculations of the connectivity $\{\widetilde{C}_k\}$, control $\{\Lambda_l\}$ and relative asymmetry measures $\{R_k\}$ in Eqs. (15), (16) and (18) to be generated. Outputs from the program provided measures of integration [$\{I_k\}$ from Eq. (19)] for each axial line which were represented in value terms on a colour spectrum from red (highest value of integration) through yellow to green thence to blue (lowest value). In fact, there is an additional set of analyses usually invoked in space syntax which enables relative asymmetry and integration measures to be computed at different 'depths' within the syntax graph. In short, it is possible to compute the integration measure at different levels of distance from each street in question, thus providing some idea of the way the values of integration change as the scale increases (i.e. as the depth or step distance from the street in question increases). Eq. (19) can thus be generalised across different measures of depth z as:

$$I(z)_k = \{m - 2\}/2\{\widetilde{D}(z)_k - 1\}, \tag{21}$$

where the distance variable is now defined as:

$$\widetilde{D}(z)_k = \sum_l \widetilde{S}(z)_{kl}/(m - 1). \tag{22}$$

$\widetilde{S}(z)_{kl}$ is a measure of relative distance defined as $\widetilde{S}(z)_{kl} = z$, noting that z can take on any value less than m. Strictly speaking when the depth z is less than the total number of streets m, then m should probably be based on the maximum number of streets which are accessible to any of the m streets at this depth and, in this way, relative integration measures at different depths would be comparable. However, no such correction is invoked in the current theory. $I(z)_k$ is thus a measure of local integration which can be compared to any other measure such as global integration I_k, connectivity $\widetilde{C}_k$, or control Λ_k. These comparisons are usually performed through a linear regression of local integration on any one of these variables, interpretations then being made as to the relative strength of correlation between any two. In the case of a regression of local on global integration, it is argued that if the correlation is high, then the area in question is said to be highly ‘intelligible’, i.e. the local area or part is similar to the whole. The *Axman* software, however, does not contain any drawing or scanning functions for input, nor any analysis functions such as those based on correlation analysis. However, in the implementation developed here, all these functions are embodied within the GIS software.

We have implemented the space syntax procedure in an *ArcView* extension. *ArcView* was chosen because of its user-friendly graphical user interface (GUI) and its potential to extend spatial analysis using the built-in scripting language *Avenue*. This desktop GIS combines different analytical measures and data representation capabilities through a number of output representations, namely View, Table, Chart, Layout and Script. Each serves different purposes for spatial data processing and presentation. Amongst others, the *Avenue* scripting language which is object-oriented, permits the customisation of the interface, and provides useful built-in classes for graphics manipulation, spatial queries, and basic arithmetic calculations. In contrast to the Macintosh software *Axman*, we have called this extension *Axwoman*. This has been designed as a specific graphical environment by modifying existing *ArcView* controls (menus, menu items, buttons and tools), and linking scripts which embody the calculations necessary to implement space syntax with new controls created in any of the available windows (Project, View, Table, Chart, Layout or Script). The friendly GUI which is created enables simple statistical and morphological analysis through the point and click interface standard to all contemporary software.

The three main functions of the space syntax software—drawing, computation and analysis—are linked to each other and to the graphical media of their input and output in *ArcView* as shown in Fig. 1. These three functions are implemented using *Avenue* scripts, each associated with different window functions: drawing with View, computation with View and Table, and analysis with Table and Chart. All these *Avenue* scripts are packed as the *Axwoman* extension (Axwoman.avx) which uses standard features of the *ArcView* Script Library, namely Extension Install, Extension Make, and Extension Uninstall. A set of icons summarising these functions are

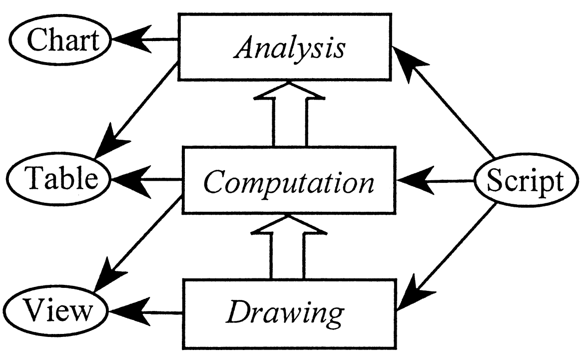

Fig. 1. Schematic structure of the *Axwoman* software extension.

also created on the second level toolbar which are linked to respective *Avenue* scripts. Online Help is implemented using Microsoft Help authoring tools.

To illustrate the interface, the user first opens the Extension Menu from the Project stage of the interface and then specifies that *Axwoman* be loaded through a single 'click' which is shown in Fig. 2.

This adds all the space syntax functions to *ArcView* and customises the toolbar. A series of morphological analyses can then be developed. First, tools for drawing axial lines can be used either directly on a plain canvas, on a scanned map or an *ArcView* feature theme. The user simply draws each axial line according to his or her own criteria but making sure that the system of lines is connected, i.e. that it is always possible to traverse the system through the system of lines. The space syntax measures are generated directly from the *Doit* icon on the drawing toolbar. Computed results for connectivity, control, relative asymmetry [labelled integration in the software but actually the inverse of integration defined above in Eq. (19)] are stored in a table corresponding to the axial map theme. A user can then explore how the measures of integration relate to other feature themes and layers such as flow rates, building uses, densities and volumes, and any other data that is geographically and geometrically coincident to the set of axial lines.

The software also allows local areas to be selected for analysis through a range of *selection tools* which are implemented using different polygon shapes. Users can define different shapes around sets of axial lines, and in this way, scale can be controlled, and integration computed to different depths within the syntax graph. Worth noting is the software's exploration capability. In order to conduct

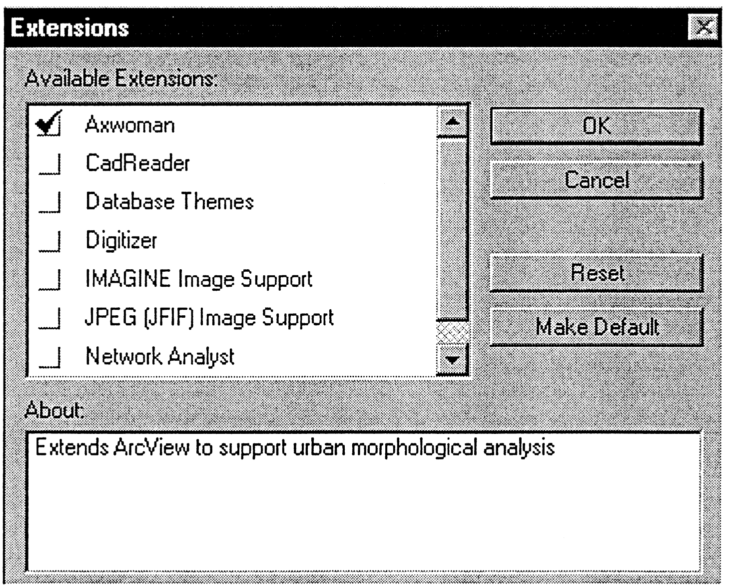

Fig. 2. The Extension Menu based on *ArcView 3.0*.

accessibility analysis, the entire range of visual media, axial maps, tables, charts, and so on are dynamically linked to one another, so any action applied to one of these components is propagated to any other. A typical interface showing the output of the axial map coloured by levels of integration, the table of attributes of this map in terms of the accessibility measures computed for each street or polyline, and the scatter graph linking showing the relations between connectivity and (global) integration is presented in Fig. 3.

5. The technical implementation

To illustrate the way accessibility measures are computed within the extension, we will define a hypothetical street system composed of 13 axial lines or street segments which intersect with each other at 19 nodes or junctions. This system is shown in Fig. 4, where it is clear that the spaces defining streets in Fig. 4a are first approximated visually by a set of axial lines—the planar graph in Fig. 4b—which in turn make up the more abstract space syntax graph of relationships between streets shown in Fig. 4c. It is this latter graph on which all the measures of accessibility are computed.

The mapping of each axial line to a vertex as in Fig. 4c can best be seen using the formal node-street representation defined by the set $\{x_{ik}\}$ in Eq. (12). Using this

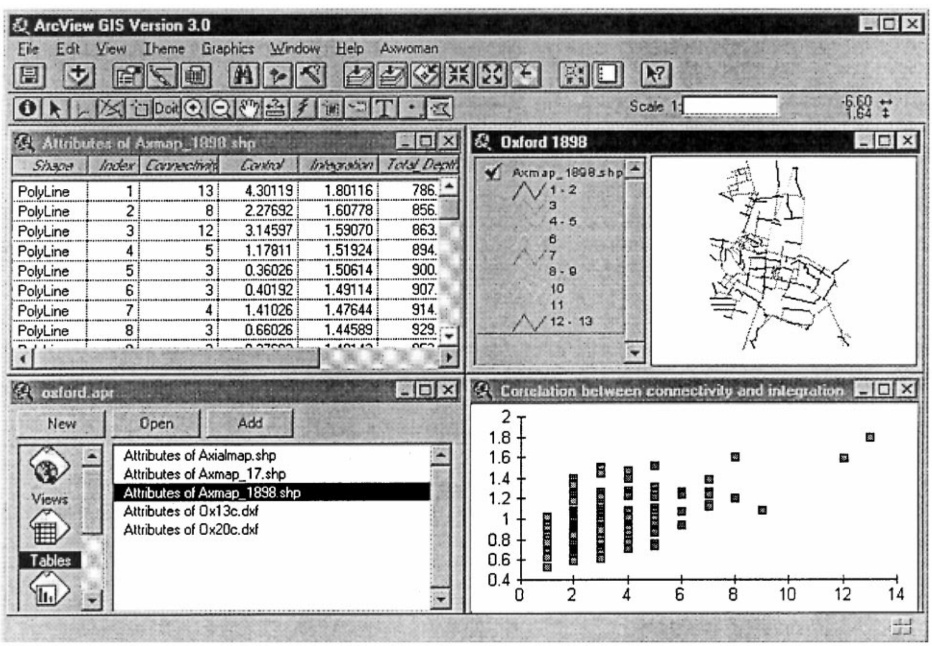

Fig. 3. Typical windows illustrating drawing, computation and analysis.

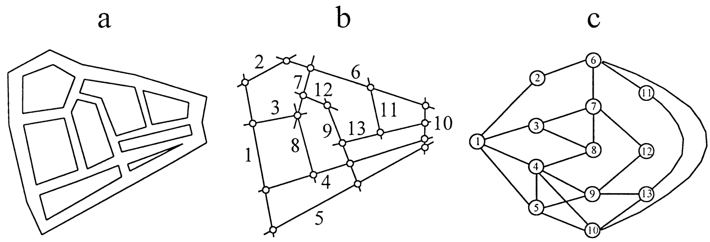

Fig. 4. (a) Streets, (b) planar graph of streets and street intersections, and (c) the space syntax graph of relationships between streets.

definition, the bipartite form of the planar graph in Fig. 4b and the space syntax graph $[\widetilde{E}_{kl}]$ as defined in Eq. (14) can be written out fully as:

$$[X_{ik}] = \begin{bmatrix} 1&1&0&0&0&0&0&0&0&0&0&0&0\\ 1&0&1&0&0&0&0&0&0&0&0&0&0\\ 1&0&0&1&0&0&0&0&0&0&0&0&0\\ 1&0&0&1&0&0&0&0&0&0&0&0&0\\ 0&1&0&0&0&1&0&0&0&0&0&0&0\\ 0&0&0&0&0&1&1&0&0&0&0&0&0\\ 0&0&0&0&0&0&1&0&0&0&0&1&0\\ 0&0&1&0&0&0&1&1&0&0&0&0&0\\ 0&0&0&1&0&0&0&1&0&0&0&0&0\\ 0&0&0&0&0&0&0&0&1&0&0&1&0\\ 0&0&0&0&0&0&0&0&1&0&0&0&1\\ 0&0&0&1&0&0&0&0&1&0&0&0&0\\ 0&0&0&0&1&0&0&0&1&0&0&0&0\\ 0&0&0&0&0&1&0&0&0&0&1&0&0\\ 0&0&0&0&0&0&0&0&0&0&1&0&1\\ 0&0&0&0&0&1&0&0&0&1&0&0&0\\ 0&0&0&0&0&0&0&0&0&1&0&0&1\\ 0&0&0&1&0&0&0&0&0&1&0&0&0\\ 0&0&0&0&1&0&0&0&0&1&0&0&0 \end{bmatrix}, \text{ and } [\widetilde{E}_{kl}] = \begin{bmatrix} 0&1&1&1&1&0&0&0&0&0&0&0&0\\ 1&0&0&0&0&1&0&0&0&0&0&0&0\\ 1&0&0&0&0&0&1&1&0&0&0&0&0\\ 1&0&0&0&1&0&0&1&1&1&0&0&0\\ 1&0&0&1&0&0&0&0&1&1&0&0&0\\ 0&1&0&0&0&0&1&0&0&1&1&0&0\\ 0&0&1&0&0&1&0&1&0&0&0&1&0\\ 0&0&1&1&0&0&1&0&0&0&0&0&0\\ 0&0&0&1&1&0&0&0&0&0&0&1&1\\ 0&0&0&1&1&1&0&0&0&0&0&0&1\\ 0&0&0&0&0&1&0&0&0&0&0&0&1\\ 0&0&0&0&0&0&1&0&1&0&0&0&0\\ 0&0&0&0&0&0&0&0&1&1&1&0&0 \end{bmatrix}.$$

Of course, the dual problem where the syntax graph $[\widetilde{E}_{ij}]$ is derived with respect to the nodes or street intersections could just as easily be formed, but as space syntax has not developed to embrace such dualisms, the current generation of this software deals solely with accessibility between streets.

The *Avenue* language does not have specific objects that directly store such two-dimensional arrays of values. However, the matrix $[\widetilde{E}_{kl}]$ can be expressed as a one-dimensional array using the List Class of *Avenue*. A list is an ordered collection of heterogeneous objects. Each element in a list is referenced through a list index number with 0 representing the first index. Thus, an $m \times m$ two-dimensional square array such as matrix $[\widetilde{E}_{kl}]$, can be represented as a one-dimensional list structure as follows:

$$\begin{matrix} \widetilde{E}_{1l} & \widetilde{E}_{2l} & \widetilde{E}_{3l} & \ldots & \widetilde{E}_{ml} \\ 0 & m & 2m & \ldots & (m-1)m \\ 1 & m+1 & 2m+1 & \ldots & (m-1)m+1 \\ 2 & m+2 & 2m+2 & \ldots & (m-1)m+2 \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ m-1 & 2m-1 & 3m-1 & \ldots & m(m-1) \end{matrix},$$

where the above matrix is arranged in a list of 169 (m^2) elements with an index range from 0 to 168. However, when the matrix becomes much larger, search processing through a one-dimensional list is time consuming, and this matrix representation is not efficient from the point of view of a graph algorithm, particularly for sparse matrices. An alternative to the adjacency matrix is the adjacency list as shown in Fig. 5. The nodes in the linked lists have fields *vertex* and *link*, where *vertex* contains a vertex number and *link* contains a pointer. Each node represents an edge in the graph. As a list is an ordered collection of heterogeneous objects, it can be defined as a list of list, i.e. each element of the adjacency list is a list. Therefore, the adjacency matrix $[\widetilde{E}_{kl}]$ can be represented as follows:

$$\left\{ \begin{array}{c} \{2,3,4,5\}\{1,6\}\{1,7,8\}\{1,5,8,9,10\}\{1,4,9,10\}\{2,7,10,11\} \\ \{3,6,8,12\}\{3,4,7\}\{4,5,12,13\}\{4,5,6,13\}\{6,13\}\{7,9\}\{9,10,11\} \end{array} \right\}.$$

Such a structure provides a relevant representation which is effective and efficient from a computational point of view, as Fig. 5 indicates.

We can now illustrate segments of the code used to implement the entire functionality. Readers can in fact retrieve this code in its full form from the ESRI web site. The package can be downloaded from:

http://andes.esri.com/arcscripts/details.cfm?CFGRIDKEY = -2057687617

Drawing an axial map is relatively easy since *ArcView* has the facility to draw geometric shapes including straight line-segments. The following code is used for axial line drawing:

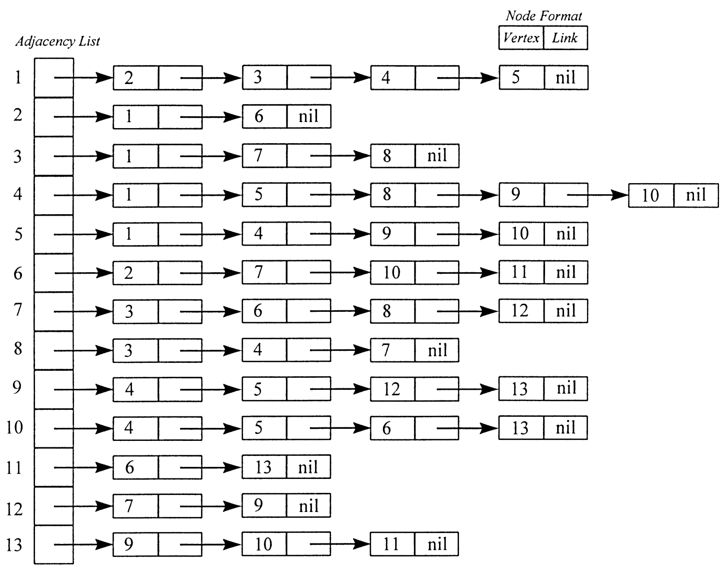

Fig. 5. The adjacency list structure for the syntax in Fig. 4.

```
theView = av.GetActiveDoc
1 = theView.ReturnUserLine
if (l.IsNull) then
  return nil
else
  gl= GraphicShape.Make(l)
  theView.GetGraphics.UnselectAll
  gl.SetSelected(TRUE)
  theView.GetGraphics.Add(gl)
  av.GetProject.SetModified(true)
end
```

Before the computation, all axial lines should be stored in a graphic list as follows:

```
'to get the GraphicList
theView = av.GetActiveDoc
theGraphicList = theView.GetGraphics
theGraphicList.Invalidate
shapeList = List.Make
for each aGraphic in theGraphicList
  aShape = aGraphic.GetShape
  shapeList.Add(aShape)
end
```

Each line has to be checked to see how many other lines intersect with it using request *Intersects*, which leads to the connectivity and control values.

```
theIndex = 0
for each theShape in shapeList
  thetheIndex = 0
  connectivity = 0
  adjacencyList = List.Make
  for each thetheShape in shapeList
    if ((theShape.Intersects(thetheShape)) AND
((theShape=thetheShape).not)) then
      connectivity = connectivity + 1
      adjacencyList.Add(thetheIndex)
    end ' end if
  thetheIndex = thetheIndex + 1
  end ' end internal for
  _List_of_adjacencyList.Add(adjacencyList)
  connectivityList.Add(connectivity)
  theIndex = theIndex + 1
end
```

Using *Avenue*, the calculation of integration is rather time consuming as it involves the calculation of the total depth. The total depth, also called step distance and termed status in the social network theory (Buckley & Harary, 1990; Harary, 1959) shows the positional status of each node within the graph. Assume that the status $s(\text{root}, v_k)$ from the root to node v_k is stored in list s. Let V track nodes not yet visited, C records the current neighbourhood being processed, D accumulates next neighbourhoods, and $N(v)$ (w is an element of $N(v)$) denotes the adjacency list of node v. The following pseudo-code describes the algorithm for calculating distance (or total depth), from which relative asymmetry, global and local integration are obtained. The main principle of the algorithm is the Breadth First Search traversal approach which begins at the root, finds the root's immediate neighbours, and then their neighbours, and so on, until one has spanned the graph reaching all nodes.

```
Begin
  s(root) = 0; i = 0;
  C = root
  V = V(G) - {root}
While C≠0 do
  Begin
    i = i + 1
    for each w ∈ N(C) do
      Begin
        D = D ∪ {w}
        remove w from V and all adjacency lists
        s(root) = s(root) + i
      end
      C = D
  end
end
```

Once the computation is done, all results are stored in an attribute table as shown in Fig. 3. From these values or whatever other morphological measures are defined, a new map theme is created and the axial map coloured using the red–yellow–green–blue spectral legend.

With regard to scale and locality analysis within the syntax graph, different shapes of selection tool are implemented using an adaptation of *ArcView's SelectRect*. The difference is that they return different geometric shapes such as irregular polygon, circle, line, polyline and so on, rather than rectangles. It should be noted that this set of functions is not available in *Axman*, but as they are important for spatial data analysis, they have been implemented within *Axwoman*. For instance, in exploring local–global relationship (intelligibility), a local area should be selected with respect to the global area. This integration within a GIS environment enables syntax analysis to be related to widely available digital georeferenced data, and it enables considerable precision in the comparison of different applications of accessibility. Users no longer need to scan paper maps for syntax analysis and it is thus possible to consistently explore the effects of scale and aggregation. However, as an extension to *ArcView*, the current computational efficiency of *Axwoman* is low for very large urban systems with greater than 200 axial lines. A version of the software written in C is available for large-scale applications.

6. An illustration of the procedure: applications to G-Town

In demonstrating this method of analysis, we will derive accessibility measures using the *Axwoman* extension for the small town of Gassin (hereafter referred to as G-Town) in southern France which was initially used as an exemplar for space syntax by Hillier and Hanson (1984). This example illustrates the essence of space syntax analysis in that the axial lines defined for the town are based on first defining the smallest set of 'fattest' convex spaces which span all the spaces between the buildings of the town. The various morphological measures—connectivity, control and integration—have been computed using the software and these are presented in Fig. 6 by colouring the streets according to the spectral colour legend. In the G-Town, the two best 'connected' streets pass through from west to east, and in effect these are likely to be the main streets. However, from the viewpoint of how each street (or space) 'controls' its neighbours, the right main street tends to be weaker than the left one. In terms of global integration, which measures the extent to which any street is linked to every other, the right side street keeps its highest value but not the left one. In a system with 41 streets, the correlation between connectivity and relative asymmetry is likely to be quite high, and this increases the more local is the asymmetry. In fact, when asymmetry is computed for one step

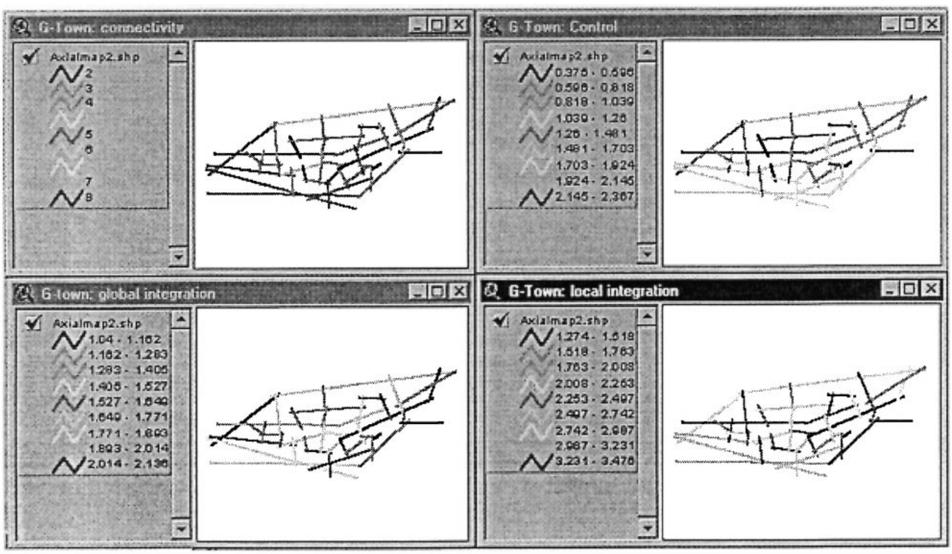

Fig. 6. Spatial patterns with (a) connectivity, (b) control, (c) global integration, and (d) local integration.

distances, then it is clear that connectivity is identical to asymmetry as a comparison of Eqs. (15), (17), (18) and (22) reveal. Finally, a measure of local integration based on three step distances ($z = 3$) has been computed and it is clear from Fig. 6 that there are quite strong relationships between connectivity and global integration.

What space syntax is beginning to show is that connectivity is a much more obvious morphological measure than was thought hitherto. It has been used in a temporal GIS model in order to trace urban growth at different complementary levels of abstraction (Claramunt & Jiang, 1999) and it can also be used to generalise plots on different map scales where connectivity could be used as a change indicator. Local integration is a relevant indicator for pedestrian and vehicular movements in urban systems. Pedestrian and vehicular movements in urban environments are confined to the street layout for usually there is no way to go from one location to another directly, unless they are in a same street. Highly integrated streets usually tend to attract more people than segregated ones and it has been found that pedestrian and vehicular movement rates in urban environments are significantly correlated to local integration values (Hillier, Penn, Hanson, Grajewski & Xu, 1993).

Many arguments have been made concerning the design of environments where it is difficult to commit criminal acts because of higher risks encountered by criminals as a consequence of the raised social physical interaction. Related empirical studies have investigated the relationship between the crime rates and integration (Jones & Fanek, 1997), with correlation coefficients being strong and statistically significant. For example in the G-town, those houses and apartments located in the least integrated streets are more likely to be the subject of crime and vandalism, as those streets occupying the most segregated spaces. In addition, traffic pollution control and way-finding can be modelled using the morphological properties of integration (e.g. Penn & Croxford, 1997; Peponis, Zimring & Choi, 1990).

7. Conclusions: future research

In this paper, we have demonstrated how simple measures of geometric accessibility can be easily incorporated into desktop GIS by defining relationships between points and lines and computing measures of distance in the various graph-theoretic characterisations of these relationships. We set this in a wider context of accessibility analysis in general and this immediately suggests that there are many other measures that might be integrated into GIS in a similar manner to those implemented here. Specifically in terms of space syntax, there is the dual problem involving accessibility of different street intersections that has barely been recognised to date but which in the form adopted here, can easily be computed in the same manner. A wealth of different interpretations of spatial structure awaits such further extensions which we hope will be picked up and developed by researchers working in urban morphological analysis and urban design.

As in any integration of spatial analysis and GIS, there is more than a single research programme which emerges from such synthesis. In terms of spatial analysis using space syntax, such a research programme has barely begun. There is much work to do in defining a proper and consistent algebra of relations as well as in defining the geometric elements of interest. To date, the definition of axial lines is subjective to the point of ambiguity while their relationship to more objective measures of urban structure defined by street segments, building outlines and land parcels as well as other networks which contain topological as well as Euclidean properties needs clarification. These ideas need to be set in the wider context of accessibility theory which we have indicated here and this suggests that a more extensive module of such measures covering both geographic and geometric elements needs to be devised.

This implementation also shows how tricky it is to develop explicit interaction phenomena within GIS. The extension to accessibility analysis is but a first step and what is now required are consistent modules which link networks, flows, and graphs to locations as points and polygons. In one sense, a more general formalism is required to handle such relations so that processes might be defined over networks. To date, network representations within GIS are quite static depending simply upon sets of lines which do not mirror the functional relations which characterise typical systems of interest such as cities and ecosystems. Nevertheless, what we have also shown here is how important it is to develop such relational analysis within GIS so that the conventional functionality of GIS can be exploited in accessibility analysis as well as providing an underpinning to the rigorous analysis of scale, aggregation, and accuracy in such analyses. Future research will be concerned with extending these functions further and in demonstrating that important and new insights into urban structure can be generated when such accessibility analysis is cast within a GIS framework.

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