Extending Space Syntax towards an Alternative Model of Space within GIS

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Abstract. Although space syntax has been successfully developed and applied to many urban studies over the past years, its potential as an alternative model of space still needs to be demonstrated and diffused within the GIS community. This paper introduces space syntax approaches, and proposes several extensions that facilitate their computational integration within current GIS models and applications. These space syntax extensions model urban spaces at different levels of abstraction. Modelling primitives include discrete points that characterise the structure of the street network, and attractions that represent points of interest within the urban environment. Such an integrated representation provides a cognitive integration of large- versus small-scales spaces for the description of the morphological structure of an urban environment. This model also proposes some new indices for the representation of navigation knowledge.

1. Introduction

Over the past two decades, space syntax has been proposed as a new computational language to describe spatial patterns of modern cities (Hillier and Hanson 1984, Hillier 1996). From its origin in urban research, space syntax proposes a language of space that is of interest for many research and application areas involved in the description and analysis of spatial patterns. Typical applications, among others, include pedestrian modelling (Hillier *et al.* 1997, Jiang 1999), criminal mapping (Jones and Fanek 1997), and way-finding processes in complex built environments (Peponis *et al.* 1990). All these investigations tend to be based on the assumption that spatial patterns, or structures, have a great impact on human activities and behaviours in urban environments. Many empirical studies have demonstrated the interest of the space syntax for modelling and understanding of urban patterns and structures (Hillier 1997, Holanda 1999).

Based on the above potential, we believe that space syntax could provide a new vision of space for the representation of urban systems within GIS and more generally, for any system dealing with a spatial configuration. In a related work, we have introduced a framework for the integration of space syntax within GIS oriented to the analysis of geographic accessibility and urban morphology (Jiang, Claramunt and Batty 1999). However, more theoretical work and experiments are required to demonstrate and diffuse space syntax towards the GIS research community as an alternative computational approach to spatial modelling.

This paper briefly introduces the modelling concepts of the space syntax approaches, and their underlying spatial modelling principles. We propose several space syntax extensions that provide theoretical and computational supports for the integration of space syntax as an alternative spatial model within GIS. The remainder of this paper is organised as follows. Section 2 introduces the roles of large- versus small-scale spaces in the space syntax approaches. Section 3 develops the main principles of the space syntax, particularly properties used for structuring and analysing space. Section 4 introduces an alternative space syntax approach based on the discrete model of an urban space. Section 5 develops and illustrates an extension of the space syntax towards the integration of different levels of abstractions, and attractions in order to model navigation knowledge. Finally section 6 draws some conclusions

2. Large- versus small-scale spaces

From the point of view of cognitive perception, space can be considered at two scales: large- and small-scale spaces (Montello 1993, Egenhofer and Mark 1995). Large-scale space is beyond human perception, and cannot be perceived from a single vantage point; while small-scale space is presumably larger than the human body, but can be perceived from a single vantage point. The perception of small-scale spaces while moving through the large-scale space provides prerequisite for the perception of large-scale environment (in general the geographic space). As human beings, we perceive a small-scale space throughout interacting objects that constitute the structure of the physical environment and the empty space that support its perception. For instance, a room may be occupied by some furniture such as a table and a chair, but one can perceive the room’s structure without any difficulty. Small-scale spaces are continuous (not discrete) and interconnected. For example, when we are walking along a street, at every moment we perceive our surrounding environment as a small-scale space. As such, a large-scale space includes an infinite number of small-scale spaces. However, every individual can model a large-scale space as a finite set of connected small-scale spaces. The popular saying that all roads lead to Rome indicates that all cities are interconnected, that is, one can go from everywhere to everywhere else.

Small-scale space perception is very important for reasoning in large-scale spaces. Downs and Stea (1977) made an assumption that "larger units must be built upon smaller units, that 'atom' of experience must generate 'molecules' and so on". They further assumed that the cognition of small-scale spaces must inevitably precede the cognition of large-scale spaces. For instance, a child must fully comprehend his room before he can understand the surrounds of his house, and this spatial understanding must come before an understanding of his town and so on. A similar assertion has been made based on empirical study that judgement of whole spaces might be predicted from averaged judgements of their parts (Garling 1969). When a tourist recalls a visit to a place, he will most likely present a sort of sketch map, something like a graph including for example his home, and his sight-seeing visits which are all inter-connected in space and time. For instance, museums and shopping centres are considered as large-scale spaces, within a larger-scale space. In the above example, they are the nodes in the tourist's mental representation. Such a dynamic cognitive representation may be interpreted as a navigation learning process in a large-scale space. This cognitive environment gives the scope for the application of space syntax to navigation knowledge representation.

The above observations provide valuable insights into the space syntax model being elaborated here, that is, a large-scale space modelled as a set of individual small-scale spaces. The computational space syntax model that integrates the small-scale space perspective is based on a two-step approach. The first step is the representation of the large-scale space as a finite number of small-scale spaces. The second one is to link these individual small-scale spaces in order to form a connectivity graph. For instance, Figure 1 shows various closed building plans, and their related graphs, with each room or corridor represented as a small-scale space. This connectivity graph supports the computation of important spatial properties, e.g., how each node links to its immediate neighbours, and how each node links to every other node. Answers to these questions help us in understanding a large-scale space (here a building) from the perception of its the small-scale space components.

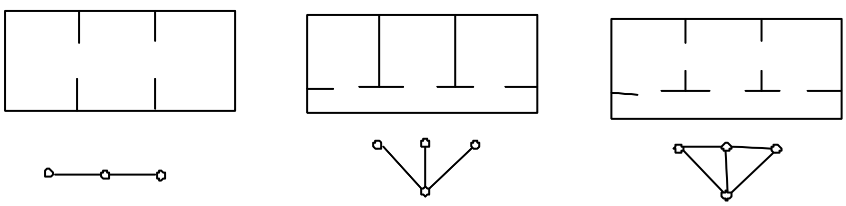

Figure 1: Closed building plans and their connectivity graphs

3. Space syntax approaches

Space syntax can be practically defined as a set of analytical and computational tools for the analysis of urban systems. Based on the computational representation of an urban space as a connectivity graph, two important measures can be derived. The *connectivity* gives the number of small-scale spaces to which a small-scale space is directly connected to. The second important measure is the *integration* that describes the way in which each small-scale space is overall linked to all other small-scale spaces. According to these definitions, a small-scale space is said to be more integrated if other spaces can be reached after traversing a small number of intervening spaces; it is less integrated if the necessary number of intermediate spaces increases. Additional space syntax parameters have been surveyed in (Jiang, Claramunt and Batty 1999), and they provide many useful indices for the description of urban space properties.

Let's examine how space syntax divides a large-scale urban environment to a finite number of small-scale spaces for computational purposes. One of the space syntax approaches is oriented toward urban environments in which the free space, defined as the parts of an urban space available for people movement, excluding by definition physical obstacles, is relatively linear. The linear property represents the fact that spatial obstacles are very dense so that a free space is stretched in one way at most points (if not all). Common examples of this type of environment are a city, a town, a village or an urban neighbourhood. When human beings are walking along this type of free space, at most points (if not all), such a free space is perceived as a "vista" which can be approximately represented as an axial line. The first representation, so-called *axial map*, is defined as the least number of longest straight lines. An axial map can be derived by drawing the longest possible straight line, then the next longest line, so-called axial line, until the free space is crossed; and finally "all axial lines that can be linked to other axial lines without repetition are so linked" (Hillier and Hanson 1984, pp. 99).

In contrast, a second space syntax approach is more oriented toward environments in which the free space is non-linear. A typical example of this type of environment is a building internal layout where most rooms are stretched in two ways, although corridors may have linear characteristics. This second representation partitions a free space as a finite number of convex spaces. (Note: a space is said to be convex if no line drawn between any two points in that space goes outside the space). For a standard building layout, each room or corridor can be approximated as a convex space (Figure 2). So the second representation, so-called *convex representation*, should comprise the least number of fattest spaces that cover the whole free space.

The third representation is also oriented to a non-linear free space, but with a finer visual representation. This representation is based on the notion of *isovist*, which is defined as a visual field that is wholly visible from a vantage point (Benedikt 1979) (Figure 2). A building plan is partitioned into a finer grid, e.g., 100x100. Each cell at the finer level represents a single vantage point associated to its isovist. Then a connectivity graph, whose edges represents visibility relationships between isovists, can be created. For representation purposes, Figure 2 illustrates a 3x3 grid with its associated isovists.

Theoretically the last two representations are also applicable to the representation of a linear free space. However, due to expensive computations for large spatial configurations, so far it is only applied to non-linear free spaces.

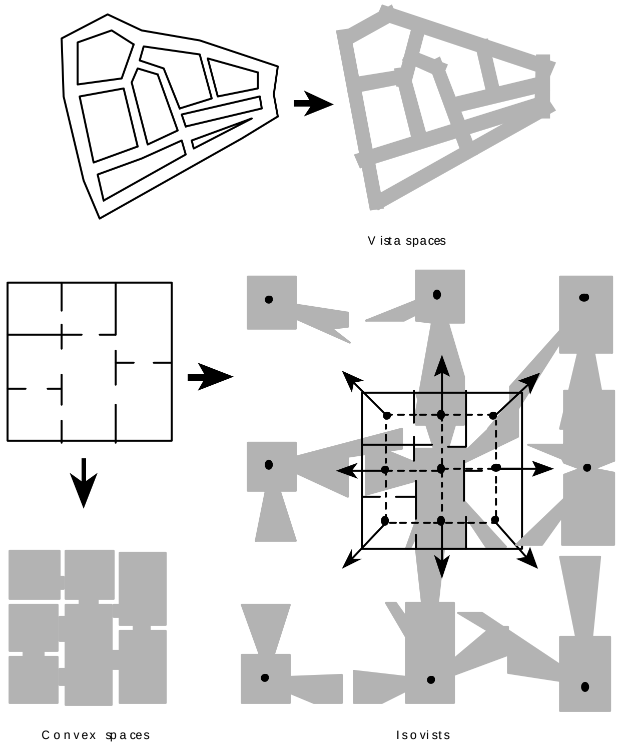

Figure 2: Discretisation of free space into small-scale spaces which are (a) vista spaces (b) convex spaces (c) isovists (note: isovists have been relocated far from their points for presentation purpose)

Based on previous representations, a free space is partitioned into a set of small-scale spaces. To derive a range of morphological measures for analytical purpose, a connectivity graph is constructed, taking small-scale spaces and their overlaps or intersections (i.e., connections) as the nodes and links of the graph, respectively (Figure 3, where the figures show individual vista spaces and their representations in the related connectivity graph). The graph is represented as an undirected and unweighted graph, which means that the distance of two directly linked nodes is of value one. This graph represents the interconnections between the small-scale spaces represented as nodes. Note that discrete points do not exactly represent network crosses in the axial map, but small-scale spaces derived from the urban map.

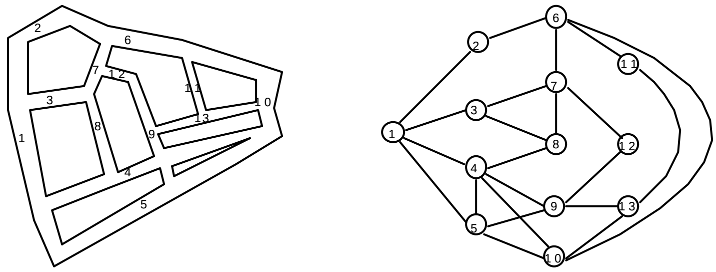

Figure 3: A fictive small town and its graph representation

In order to describe the following measures, let us assume some variables:
for any particular node in the graph, the shortest distance far from the node is denoted by i , the number of nodes with the shortest distance i is denoted by N_i, the maximum shortest distance is denoted by k. Using the expression $\Im = \sum_{i=1}^{k} i \times N_i$, we can describe the following space syntax measures[1]:

$$\Im = \begin{cases} connectivity \quad iff \;\; i = 1 \\ local\ integration \quad iff \;\; 2 \le i \le k - \boldsymbol{d} \\ global\ integration \quad iff \;\; i = k \end{cases}$$

where $\boldsymbol{d}$ is a large enough constant variable, usually $k - \boldsymbol{d}$ is less than 10 for a large city such as London.

4. Extending axial lines to discrete points

From the principles of the space syntax approaches presented above, we can remark that the axial line computation is ambiguous from a computational point of view. According to the sequential rule of deriving and drawing the axial lines, the computation starts from the identification of longest axial line, and then second longest axial line and so on so forth. Overall, the axial map provides the least number of axial lines. The computational complexity of such an approach is relatively high. On the other hand, a valid application of the space syntax approach is based on an axial map effectively composed of the least number of lines.

[1] We did not use the justified expressions such as RA and RRA in space syntax, as we believe that these justifications are less meaningful (see also Krugger 1979 and Teklenburg *et al.* 1993).

Otherwise, the analysis is less meaningful, because the overall number of lines will not be representative of the urban structure. So far no automatic way of deriving and drawing axial lines has been identified by the space syntax research.

A second practical problem with the axial line computation relies in the fact that axial lines do not exist in reality, that is, they are not explicitly represented within the GIS database. In many urban GIS databases, a street is often modelled as a simple object as it is not of preliminary modelling interest, whereas it may be partitioned into several lines in the corresponding axial map if the street is either curved or interconnected. Indeed, morphological properties obtained through space syntax are assigned to street segments (or axial lines), and not to the street object as a whole within the GIS database. Therefore, these incompatibilities lead to some critical constraints for an integration of the space syntax within urban GIS. If space syntax functions have been developed within GIS (Jiang, Claramunt and Batty 1999), such implementations do involve a large amount of computing developments that make the resulting application not very much integrated with existing GIS and urban databases.

Based on these computational and practical limitations of the axial line approach, we hereby advocate a spatial modelling alternative. Our approach is based on flexible concept of points, derived from urban maps (and not from the axial map). These points are representative of the network structure in the sense that, within an urban environment, people make a navigation decision on next heading when they reach these points. For example, if one comes to a cross, one would have three choices to make: to go left, right, or ahead. From a morphological point of view, the visibility of this cross point, or not, from every other in the connectivity graph determines the connectivity of this standing point. In the same way, the number of steps required to reach every other in the connectivity graph determines the integration value of this point. These points include characteristic points such as turning points (i.e., a turning point is defined as the peak of a curve) and road junctions. To illustrate this approach, let’s take the urban system presented in the previous section. The first step of this approach is to identify these points. This procedure is relatively easy compared to the computation of the axial lines, and computationally decidable. Taking the previous example of the urban street network, these points include road junctions, whose identification is straightforward in a street network, and turning points identified by the application of a simple algorithm (i.e., selection of turning points far from a certain threshold to straight lines between junctions).

Therefore, based on these points, one can determine whether each point is visible from others. This leads to a graph of inter-visibility (Figure 4). Then a variety of space syntax parameters can be calculated as for other space syntax approaches. For instance, each point is given a range of values as to how it is connected to other points and how it is integrated to other points. One can remark the similarity of this approach with the isovist representation. Each point in this approach can be compared to a standing point in the isovist approach, and all visible points from this standing point tend to the standing points of other isovists. Last but not least, a continuous surface can be derived from those points. The visual properties of such a continuous representation are also of interest as space syntax values are spatially distributed (Figure 5).

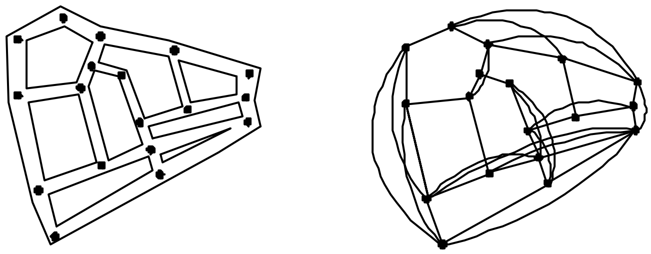

Figure 4: Urban map - Characteristic points and visibility graph

This new approach provides several advantages over the existing space syntax approaches. Firstly the continuous surface provides a genuine representation of spatial morphological properties. Assigning a morphological value to a straight street segment is relatively illogical, because accessibility along a long straight street should not be a same value. On the contrary, the point-based value is more appropriate as it supports the derivation of a continuous surface that reflect the spatial distribution of the accessibility (although its interpretation is limited to the network or network neighbourhood). Secondly, the semantics of point-based values is relatively precise, so the automation is completely possible compared to that of axial map. Finally, this approach nicely applies the isovist principles to large-scale urban environment, as this approach can be considered as a modified (simplified) version of the isovist approach.

It should be noted that, in the experiment as shown in Figure 5, contour lines within blocks are less meaningful until we consider different levels of abstraction and the built environment. However, such a continuous representation presents some valuable spatial properties at the street level. This approach is similar to ones made in many spatial analysis such as population density maps, often spatially generalised to the whole space although the distribution of people is constrained to residential buildings. Indeed, the denser the urban street network, the higher the validity of this continuous representation.

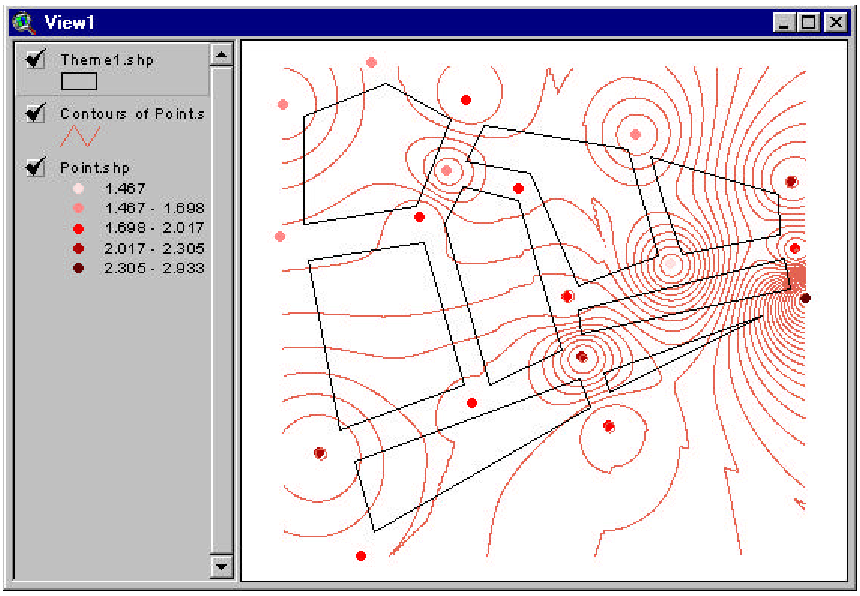

Figure 5: Continuous representation of spatial morphological properties (i.e., integration)

5. Extending space syntax to the concept of attraction and navigation knowledge

Space syntax is mainly orientated to the representation of free spaces, parts of urban or built environments through the definition of nodes and axial lines. Urban objects such as buildings are represented as an exterior part of the underlying spatial configuration. However, in addition to the spatial configuration influence, people's behaviours are also affected by the degree of attraction represented by these building objects. We can define an attraction as an object of interest within an urban network (e.g., museum, theatre). Then, an investigation of the properties of these urban attractions and their influence in human behaviours can be modelled.

In modelling intra-urban configuration, Krafta (1994) has recognised two basic components of urban environments: public spaces and built forms. She proposed a graph representation that integrates both public spaces (i.e., free spaces) and built forms as nodes, and their interrelation relationships described as links. Built forms are represented at a same level of perception unless they have a distinguished appearance or familiarity for an observer. Considering a daily routine task within an urban environment, e.g. a human being may organise his displacements using a priority order. Then, built forms of interest (e.g., shop, school) have an attraction function (and are also part of the spatial configuration), remaining objects have an obstacle function part of the spatial configuration. As such, both attractions and the spatial configuration influence subject movements.

Extensive studies have been made over the past two decades in using space syntax to simulate and predict pedestrian and vehicle movement. It is generally found that this method can account for more than 80% of the variation in traffic flows from street to street (Hamer 1999). Behind this conclusion, we believe that traffic flows, as one kind of human spatial behaviour, are not completely controlled by urban structure. There is at least an additional factor, attraction, to be considered for a more robust model of traffic flows modelling. In other words, structure and attraction are two important factors, which drive people's movement in urban system. Therefore, we propose an extension of the space syntax towards the representation of attractions in order to provide a finer modelling approach.

Our model considers an alternative connectivity graph that integrates attractions and free spaces. Figure 6 - left - shows the same fictive town, but two buildings have a modelling significance, that is, they are modelled as attractions within the graph. Thus, such a graph representation of the urban environment, from the point of view of the user, not only considers free space but also attractions as well. In the right side of Figure 6, two grey nodes represent two buildings considered as attractions by a subject, and integrated within the graph representation as connected nodes.

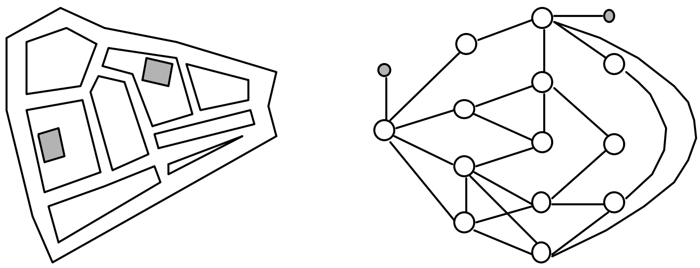

Figure 6: An illustration of the first extension of space syntax

We propose an extension of space syntax parameters to the concept of attraction. We characterise the various degrees of attractiveness of public spaces in relation with their built environment. In order to describe the following measures, let us assume some variables:

For any particular node in the graph, the shortest distance far from the node is denoted by i , the number of attractions with the shortest distance i is denoted by A_i, the number of nodes with the shortest distance i is denoted by N_i, the maximum shortest distance is denoted by k. Using the expression $\Im' = \sum_{i=1}^{k} i \times A_i$, we can describe the following space syntax measures:

$$\Im' = \begin{cases} local\ attractiveness & iff\ 1 \le i \le k - d \\ global\ attractiveness & iff\ i = k \end{cases}$$

Then the mean degrees of attractiveness of a node (i.e., *mean local attractiveness* and *mean global attractiveness*) are respectively defined as

$$\overline{\Im'} = \frac{\Im'}{N_i}.$$

Individuals generally behave within an urban environment from free space towards attractions that represent points of interest. So the characterisation of the attraction potential within a free space is of particular interest for navigation decisions. These attractiveness parameters qualify the degree of interest of the various nodes of an urban environment, at complementary levels, as suggested by the above defined attraction indices. While conventional space syntax parameters can be qualified as structural as they analyse the underlying spatial configuration of the city, attraction indices give a more functional representation. For instance, attractions represented can be oriented to the analysis of either commercial (e.g., shop as attractions) or tourism activities (e.g., museums) of an urban space. Additional attraction indices can also be defined as a function of time if the presence of attractions is related to their opening hours, or as gravity functions if their respective attraction potentials are considered.

Researchers from a variety of disciplines have investigated people's ability to acquire and represent spatial knowledge within spatial navigation. Generally, three kinds of spatial knowledge have been commonly recognised: landmark knowledge, route knowledge, and survey knowledge (Werner *et al*. 1997). Route and survey knowledge represent different levels of spatial knowledge. The former is at the local level when humans navigate in a large-scale space, while the latter provides an overall representation of an environment. In this connection, we believe that space syntax can be used to infer a hierarchical form of spatial knowledge that could be even adapted to biological spatial navigation as introduced in (Poucet 1993).

The second space syntax extension is oriented to the modelling of urban environments, represented at different levels of abstraction, as a unified graph. Urban environments can be defined at different levels of abstraction, e.g., at the scale of a city, a neighbourhood, and a building. We define a nested relationship among these urban environments. For a formal description, a city is defined as a set of neighbourhoods, $c = \{n_1, n_2, n_3, \ldots, n_N\}$, a neighbourhood as a set of buildings, $n = \{b_1, b_2, b_3, \ldots, b_N\}$, and a building as a set of rooms,

$b = \{r_1, r_2, r_3, \ldots, r_N\}$. Using such a hierarchical approach, urban environments can be represented as a graph with small-scale spaces and their connections as nodes and links, respectively.

In order to illustrate this concept, let us assume an urban environment, e.g., a museum, at the level of building scale, which consists of seven rooms. According to space syntax, this museum can be modelled using a connectivity graph as illustrated in Figure 7. Figure 8 shows a combined version of a connectivity graph of the museum and its surrounding, i.e., its location within the town. A network labelling function can be used to make a distinction between the different levels of abstraction within the graph, and attractions. Additionally, within the connectivity graph presented in Figure 8, the link that connects the building to the free space could be pondered by a different weight in order to model the change of level of abstraction. This offer an avenue to explore for the identification of additional space syntax parameters, based in higher-order distances as defined in graph theory (Buckley and Harary 1990).

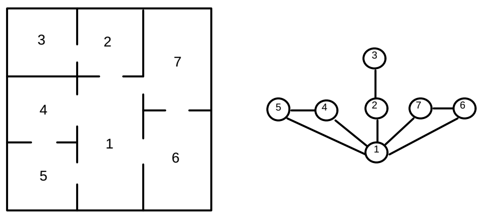

Figure 7: A museum layout and its connectivity graph

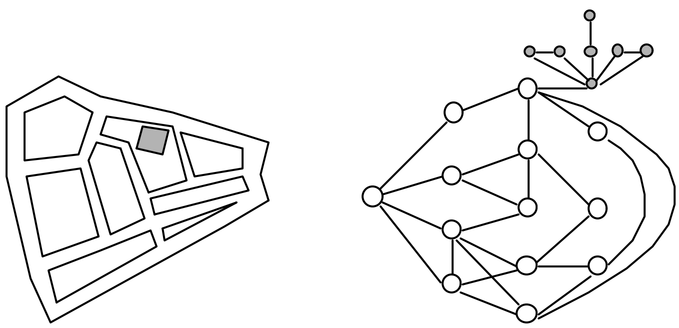

Figure 8: An illustration of the second extension of space syntax

6. Conclusions

This paper analyses space syntax in terms of its spatial modelling capabilities, and provides various extensions towards an alternative model of space within GIS. Cognition of large- and small-scale space provides fundamental support for the development of space syntax approaches. They give a cognitive support for the representation of navigation knowledge. The proposed discrete point-based representation provides a new perspective and nice properties to the space syntax approach. It also supports a continuous representation of the spatial distribution of space syntax indices. Last but not least, the point-based representation favours a computational integration of spatial syntax within existing GIS as an alternative model of space.

From a navigation knowledge representation, our model considers not only the morphological structure of an urban environment, but the built environment as well. Accordingly, our model extends the space syntax approach by the integration of the concept of attraction defined as an object of interest within an urban environment. Attractions extend the capabilities of the space syntax approaches to the description of urban environment properties at different levels of abstraction, and a finer description of navigation knowledge. We introduce new space syntax indices: *local attractiveness* and *global attractiveness* that characterise the different degrees of attractiveness of a node within an urban environment. Future work implies the validation of the proposed extensions with some empirical studies.

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