APPLYING DEPTH DECAY FUNCTIONS TO SPACE SYNTAX NETWORK GRAPHS

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Keywords:

Space syntax
Radius
Justified graph

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Abstract

Core to the mathematical innovations of space syntax is the concept of graph-radius. In this paper, the authors propose a new mathematical mechanism to provide a relative measure for the local/global configuration of an axial line. We propose that cumulative depth be redefined as CD = Sum (1/((di-1)^k)) where d is the depth from node i to the origin and k is a constant factor. This method is based on the requirement that all nodes, within a graph must be included in the analysis. As a result of this stipulation, there is no need to relativize the results of a given axial map according to the total number of its axial lines (or nodes in its graph). The authors then demonstrate that larger factors of k are equivalent to smaller radii in standard integration calculations. By using different values of k such as 0 and negative values the authors go on to show that a number of different measures can be approximated by simple changes in the k factor. The authors conclude their paper by correlating standard 'radii measures' (at different radii) and the newly proposed 'decay measures' (for different values of k) results for a number of axial maps and hence clearly demonstrating that this mechanism produces strongly correlated results and that the concept of radius, as used in space syntax, may be unified with other space syntax measures, harmonising them within a single family of equations. This paper concludes that 'radius' may be replaced by a decay function applied to the network graph and identifies some optimal decay functions.

Introduction

Space syntax is the name given to a set of theories and techniques concerned with the relationship between complex spatial structures and the societies producing/inhabiting them. This approach can be applied to both large-scale urban areas and settlements as well as to complex buildings. However, at the heart of all space syntax analysis is the concept of the network graph. Although the application of graph representations to urban or social problems is common, the kinds of graphs utilized in space syntax are quite specific and, in some ways, unique to the field. This paper will be predominantly concerned with the kinds of space syntax graphs that represent urban areas although the methods presented in this paper could equally be applied to building-scale systems.

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In an urban space syntax network graph, the nodes of the graph typically represent what are termed 'axial lines', although, more recently, they may, alternatively, represent road segments or road centre-lines (Dalton 2000; Conroy Dalton 2001; Dalton 2001; Turner 2001; Conroy Dalton 2003; Dalton, Peponis and Dalton 2003; Dalton 2003; Hillier and Iida 2005; Iida and Hillier 2005; Turner 2005; Turner and Dalton 2005). An axial line map is a way of discretising a spatial system, whereby the fewest and longest lines of sight required to access every sub-space (and complete all circulation rings) in the system are represented as 2D lines on a plan. Wherever two such axial lines intersect, a link is made between the corresponding two nodes in the graph representing those lines. If road segments are used instead of axial lines, then these are broadly analogous to road centre-lines, but, in contrast to, for example, traffic engineers' models (which also depend on a graph meta-description), the nodes represent the road segments and the edges in the graph represent the abutment, at a junction, between any two road segments. An axial-line graph is non-directed and non-planar and a road segment graph is typically non-directed [i] and planar.

The question, underpinning this research, is whether there is a way to unify the variety of different methods for examining the local and global properties of a graph by permitting the same basic equation, or set of equations, to be applied across all graph-types. The need for such an approach has come about as a consequence of the growth in computational methods that has taken place in recent years; as the methods of space representation (axial line, road segment, road centre-line, continuity lines (Figueiredo), isovist/visibility graph analysis), of graph representation (non-weighted topological, weighted angular, weighted metric) and of relativization (D-value (Hillier and Hanson, 1984), vicinity (Dalton, 2005), Teklenburg relativisations (Teklenburg, 1993)) have increased so has the need to simplify and unify these approaches. An ideal solution would be for the same method to be applicable across the range of different space and graph representations.

Radius measures are of particular utility as they permit an examination of and hence comparison between local and global properties of the graph. In turn, these permit the calculation of secondary spatial measures, such as intelligibility and synergy (correlations between different local and global properties of a graph). What is particularly interesting is that the concept of radius, as used in space syntax graphs, represents a mathematical innovation unique to this field. The authors have used this concept of local/global properties of the graph, as the starting point for their endeavor to simplify the current, mathematical formulae.

The Depth Decay Function

A decay function is simply a power function, $y = f\ (a^{-x})$, in which the resultant value, y, decreases in proportion to x. Such formulae are particularly useful when modeling physical phenomenon, where a value of 'something' decreases in relation to 'something else' commonly time (i.e. radioactive decay) or distance (i.e. gravity).

Imagine what would happen if we began to consider the axial-line graph, which represents an axial map, as if it obeyed some kind of distance-decay model. Since every node in the graph represents a single axial line and each edge represents the connection of two lines, then by applying a generic distance-decay model equation, y would be proportional to $\frac{1}{d^2}$ where d is the distance between them and y could be considered a measure of 'contiguity'. Of course, there is no 'real'

distance between two axial lines, as they intersect. In space syntax analyses, the distance, or depth, between any two intersecting *axial lines* is always 1. The depth between any two non-intersecting lines is equal to the length of the shortest path in the graph connecting the two nodes (or the step depth). Angular or fractional analysis, in space syntax, utilises non-integer depths between the nodes in the graph, which represents the angle between the two lines. Therefore, for non-angular, axial line graphs, the contiguity between any two intersecting lines would be $\frac{1}{1}$, i.e. 1, and for angular analysis, it would be $\frac{1}{d^2}$, where d represents the approach angle between the two lines. In angularly calculated systems, if two lines connect obtusely, *d* approaches zero and contiguity is high; if two lines connect at close to right angles then *d* approaches 1 and hence producing a low contiguity value. This is the first basic stage for introducing the concept of distance decay into space syntax graphs. The next stage takes this further by looking at justified graphs and mean-depth calculations.

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Central to space syntax analysis is the concept of integration, which is approximately analogous to the measure of closeness as used in graph theory. For the purposes of this paper, it is necessary to explain how integration is calculated and, in order to do so, the concepts of the justified graph and of mean depth need to be clarified. Imagine that a graph has been created which represents an axial line map. Let us start from one node (or axial line) in the graph. All lines that immediately intersect with the initial line are deemed to be at depth 1 from the original line (i.e. 1 step away in the graph). All lines connected to any of these depth-1 lines are held to be at depth 2 from the original starting line, and so on. This can be represented graphically as, what is termed, a justified graph. See figure 1 below.

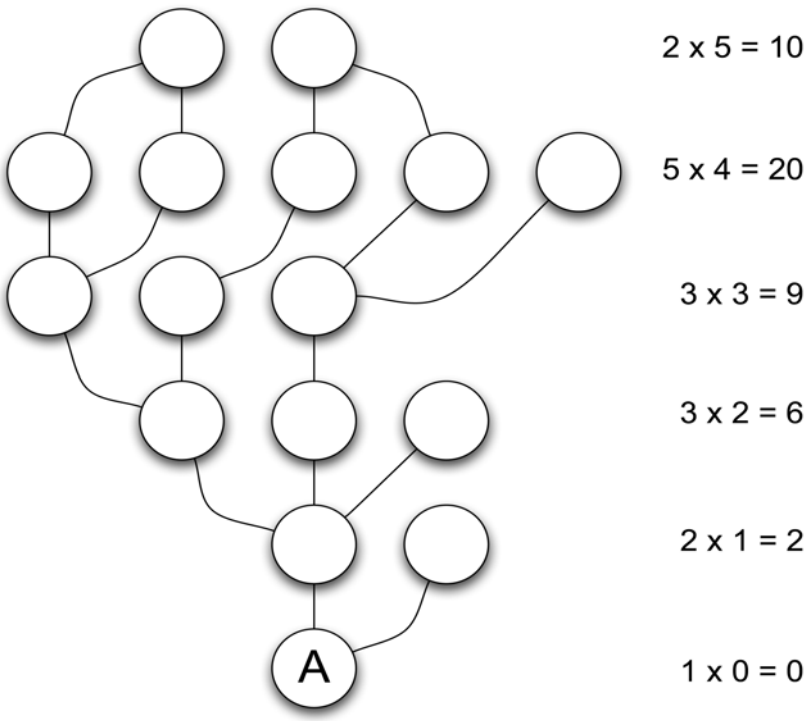

Figure 1:
Justified graph

If node A represents an axial line, there are two lines that are connected to it, at depth 1 from node A: these are drawn on a row above node A. There are three lines (or nodes) connected to one of the depth-1 lines, these are considered to be at depth 2 from node A

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and are shown arranged on a single row. The columns of numbers to the right of the graph indicate the number of lines (or nodes) at each incremental depth from node A. Usually, a justified graph 'grows' until every node in the system has been reached and accounted for. In order to calculate the mean depth of all lines (or nodes) from line A, the number of nodes at each depth is multiplied by its depth value (the starting node is held to have zero depth). Therefore, in figure 1, there is one node at depth zero (total = 0), two nodes at depth one (total = 2), three nodes at depth two (total = 6) etc. These values are added together to give a sum of 47 (0 + 2 + 6 + 9 + 20 + 10). There are 16 nodes in the graph, so, excluding the origin node, it can be said that the mean depth of all nodes from node A is 47/15 = 3.13. The space syntax measure of integration is proportional to the reciprocal of mean depth; the smaller the mean depth of a line the more integrated it is within the system and the larger the mean depth the less integrated, or more segregated it is within the system. However, integration is not purely the reciprocal of mean depth, as it is both normalized [ii] and relativized [iii] for the size of the system, a process that this paper shall readdress in its final section. For now, it is enough to know that it is proportional to it (on a range of 1 to 0 from the deepest to the shallowest it could possibly be given that number of nodes).

Equation 1 Mean Depth Formula

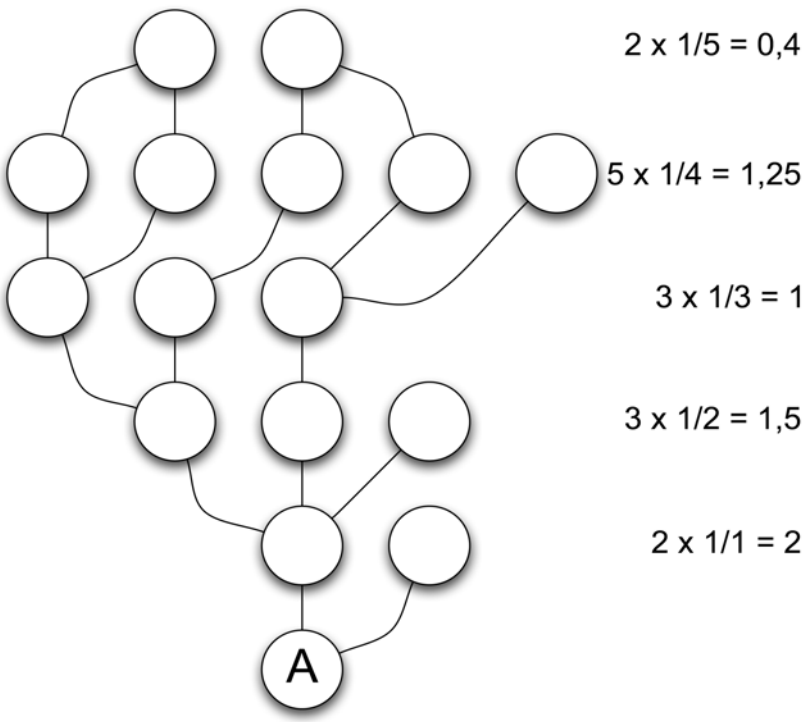
$$mean\_depth\_of\_node_k = \frac{\sum_{i=0}^{i=n} d_{i,k}}{(n-1)}$$

where n is the number of nodes in the system

From the mean depth calculation example above (refer also to Equation 1 for the formula) it should be immediately obviously that those nodes furthest from the origin node are adding more value to the measure and it is for this reason that integration is proportional to the reciprocal of mean depth. However, what would happen if a reciprocal function were to be introduced directly into the initial justified graph? The graph could easily be transformed into one of the forms below.

Figure 2:

Justified graphs with reciprocal depths



It is now clear that it is those nodes that are most proximal or closest in graph-steps, to node A that are adding most to the cumulative total, and those furthest away contributing least to the mean depth calculation. The sum for the reciprocal depths (for $\frac{1}{d^2}$), in this case, is now 3.48. The resultant equivalent to mean reciprocal depth, i.e. 3.48/15 would be 0.29. (The reciprocal of the previous mean depth value, 3.13, is 0.32). However, by introducing the reciprocal of the depth, or distances, between the nodes into the justified graph equation, we are effectively turning the mean depth calculation into a distance-decay model. This approach can be generalized into a more flexible, and hence more useful, version, but first a problem with the increments of the depths in the justified graphs must be remedied. It can be seen, in figure 2, that by assigning the starting node to be depth 'zero', a problem is introduced into the calculation, as the reciprocal of zero is infinity. This problem is encountered again, in a slightly different way, in the case of calculating fractional or angular mean depth, as two line segments that have no angular deviation between them are usually assigned a depth of zero from each another (i.e. proceeding in a straight line accumulates no added angular depth to the trip), (Dalton 2001; Dalton 2003; Turner 2003). Adding a value of 1 to all depths solves both of these problems: $d \rightarrow (1+d)$. Therefore, the equations for depth decay and mean depth decay may be generalized as:

Equation 2 General Depth Decay Function

$$\sum_{i=1}^{i=N} \frac{1}{(1+d_i)^x}$$

Equation 3 Mean Depth Decay Function

$$\frac{1}{(N-1)} \sum_{i=1}^{i=N} \frac{1}{(1+d_i)^x}$$

Note that, in equations 2 and 3, the square of the depth has been replaced with a power function of the depth, which can take the value of 2, but equally need not. By applying different values of x, different variants of decay functions may be applied. If we begin to investigate the effect of varying the value of x (the power to which the depth is raised) some interesting results can be noted. In the next section, this paper will document the effect of varying the power of x in the decay function, shown in equation 2.

Variations of the Decay Function and their Potential Applications

Some common variants of the distance decay function are shown below. A number of these will be discussed in detail, outlining their utility and their relation, if any, to existing space syntax graph measures.

Equation 4 Some Common Depth Decay Functions

$$\frac{1}{(1+d)^3}, \frac{1}{(1+d)^2}, \frac{1}{(1+d)}, \frac{1}{(1+d)^{0.5}}, \frac{1}{(1+d)^{-0.5}}, \frac{1}{(1+d)^{-1}}, \frac{1}{(1+d)^{-2}}, \frac{1}{(1+d)^{-3}}$$

In order to discuss the utility of the range of decay functions, it is important to understand the concept of radius, as used in space syntax and as briefly referred to in the introduction. Returning to the justified graph in figure 1, it can be seen that each row of nodes are

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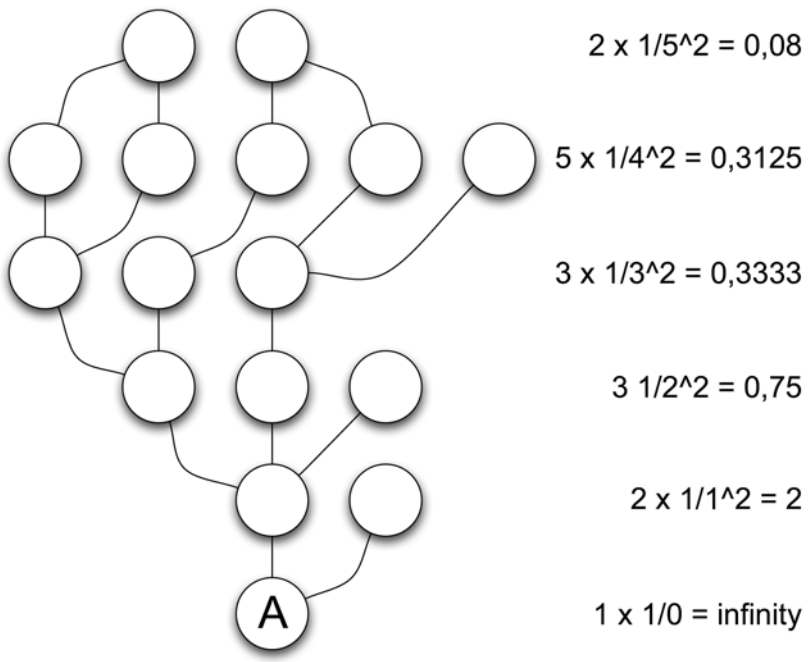
attributed incremental depth values until all nodes in the network have been reached. In space syntax, the concept of radius refers to the practice of truncating the justified graph after a maximum depth has been reached, see Figure 3. For example, the measure of radius three integration, applies the integration formula to all nodes that are depth three or less from a starting node. This is akin to placing a moveable 'window' onto the network graph and effectively disregarding all nodes falling outside the 'radius' or extents of the window. The concept of radius could be held to be a kind of decay model insomuch as it prioritizes nodes close to the origin node and ignores outlying nodes (the difficulty in making this assertion is that radius represents an abrupt cut-off and decay models are more gradual). It so happens, that in empirical tests (see section 3 and table 1) conducted so far, that one particular decay function, $\frac{1}{(1+d)^{6.5}}$ correlates highly with radius three integration. This is important for two reasons: first, radius three is a particularly useful radius as it is frequently shown to correlate well with observed pedestrian movement. Second, there have been some difficulties with respect to relativising radius measures (of which radius three is just one example); since the value of n, the number of nodes within each radius, constantly varies, it is impossible to simply divide by the size of the system. However if a decay function is used instead of a radius function, n remains constant and therefore relativising becomes far more straightforward, as will be discussed at the end of this paper. The higher the power of d (the larger the value of x in the equations) the smaller the effective radius and the smaller the power of d, the larger the radius until you reach a value of x = -1 which is approximately equivalent to total depth and inversely proportional to global integration (radius infinity).

Figure 3:

A justified graph with the equation 1/(d^2) applied to the step-depths



Normalisation, or relativisation, is important to space syntax as there is frequently a need to compare systems (cities, districts, neighborhoods) of differing sizes. Dalton has recently shown (Dalton 2005) that certain anomalies are associated with the current relativisation equations as used in space syntax (especially at radii greater than 'radius-radius [iv]'). One of the benefits of introducing the decay function into the justified graph is that not only does it unify

radius measures with mean depth/integration measures under the same family of equations, but it also simplifies the relativisation process in a manner that makes it applicable to both non-angular and angular analyses (which hitherto has also been problematic).

Another benefit of the decay function is that it allows more control over the radius selected. By varying the power of d, it becomes possible to examine non-integer radius effects, a notion that would have been un-computable and even nonsensical using the previous methods of calculation [v].

Finally, it might even be possible, by exploring variations on the basic decay function to arrive at measures with no prior equivalence. One such measure is, for want of a better word, the 'doughnut measure' whereby those nodes furthest away are given greater importance than those closest by (illustrated in the final row of table 2). This might be termed a 'true global' measure. One possible application to this might be found in the spatial analysis of crime. It has been shown (van Nes 2005) that burglars rarely commit crimes in their own neighborhood, but instead will travel a minimum distance from their home before committing a crime. A measure such as this could be valuable when investigating such anomalous spatial behavior. The 'doughnut' effect occurs where the value of $x < -1$, i.e. the spatial system becomes super-saturated. If there were a radius equivalent of this, it would be 'beyond infinity'. At this point, the nodes close by become relatively unimportant and all emphasis is placed on the boundary or the edge. Such an approach could be useful in the mapping of crime locations. The next section will present some preliminary empirical data that begins to clarify the correlations between different decay functions and radius measures.

Empirical Correlations between Measures

In this penultimate section, we will attempt to demonstrate the relationship between the depth decay functions and certain measures regularly used in space syntax research. It is the intention of this paper to demonstrate this relationship empirically through a number of real-world examples. First, figure 4 illustrates a typical 'axial line map'. This is the map for an area of London centered on a district called Barnsbury (North West London near Kings Cross and St. Pancras railway stations). Figure 5 shows the relationship between the axial line map and its underlying graph network. In figure 5, a node has been placed at the centroid of each axial line; vertices represent the intersections of any two lines. Figure 5 retains the geographic and metric layout of the original street system. Figure 6 illustrates a typical 'justified graph', in this case from the Pentonville Road (the most integrated road in this spatial system). Although far more complex, in terms of the number of nodes (or the order of the graph) the principal behind the creation of this justified graph is no different to those graphs presented in figures 1 and 2.

In order to empirically test the real world correlates of the various decay functions, a number of cities or urban areas were selected. First, each area was represented as a space syntax network graph (in the same way in which Barnsbury is illustrated in figures 4, 5 and 6). Then all depth decay measures were correlated with radius three measures. The results of these tests, along with their correlation values (expressed in terms of their r-squared correlation coefficients) are shown in table 1 below and are expressed graphically in Figure 7.

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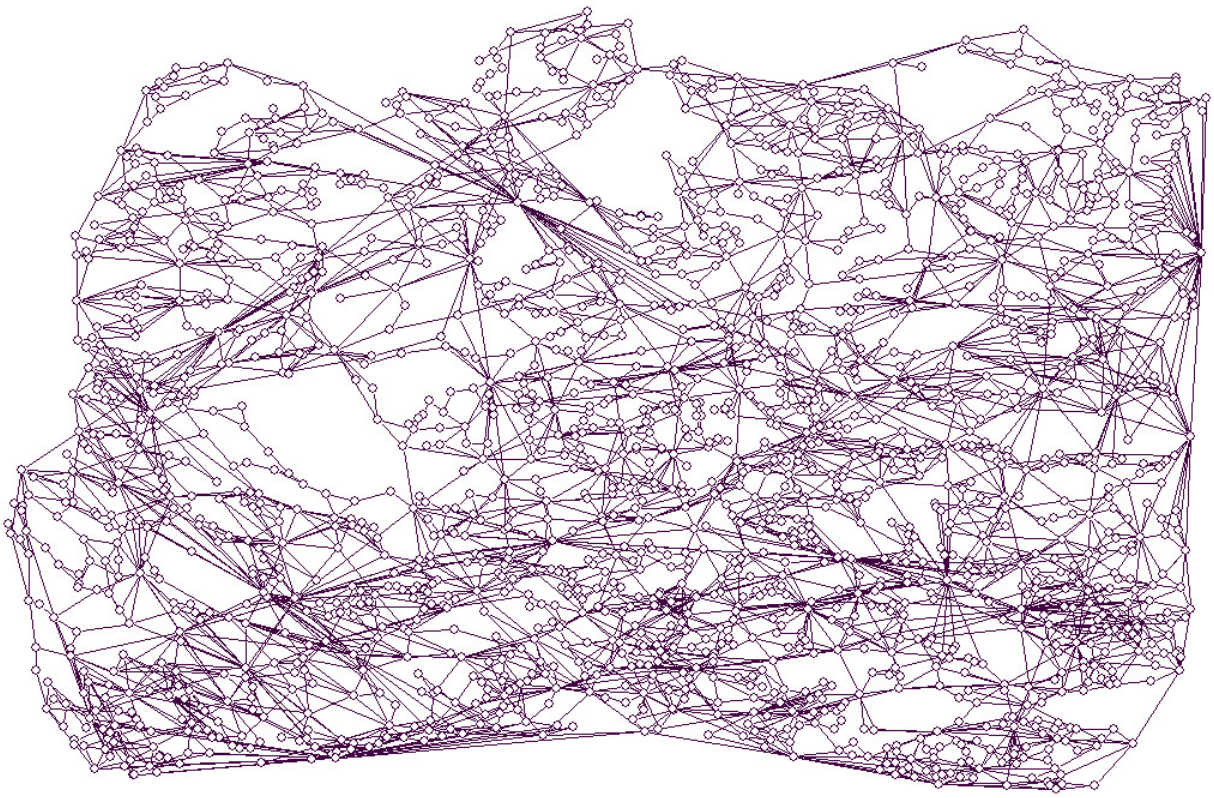
Figure 4:

Barnsbury axial lines network

Figure 5:

Network graph of Barnsbury; nodes placed at line centroids



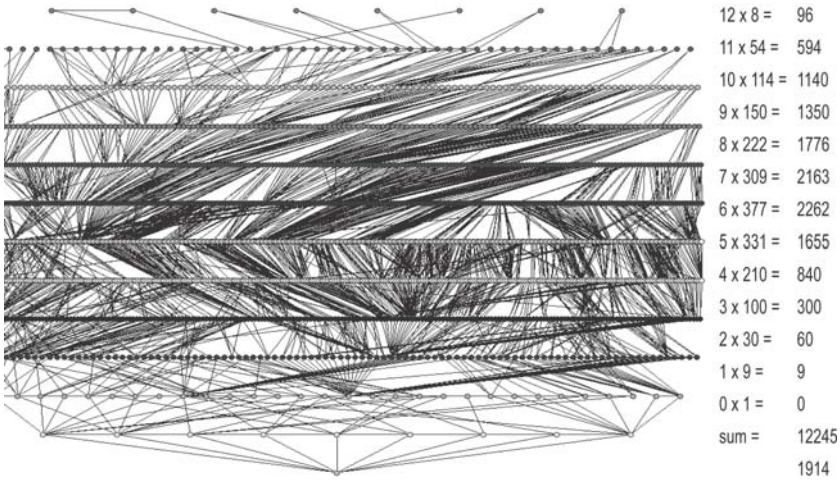


Figure 6:

Justified graph from the Pentonville Road

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Table 1:

Correlates with space syntax radii measures

Power, k, of (1+d)	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8
City											
Amsterdam	0.6388	0.7273	0.8087	0.8682	**0.8962**	0.8928	0.8661	0.8271	0.7844	0.7436	0.7075
Barcelona	0.5877	0.6349	0.6881	0.7448	0.8002	0.8487	0.8850	0.9066	**0.9138**	0.9091	0.8963
Birmingham	0.7103	0.7892	0.8577	0.9098	0.9433	0.9433	**0.9657**	0.9633	0.9567	0.9485	0.9400
Eindhoven	0.6539	0.7462	0.8289	0.8847	**0.9052**	0.8947	0.8645	0.8261	0.7873	0.7518	0.7213
Hamendan	0.5250	0.5732	0.6310	0.6973	0.7655	0.8272	0.8740	0.9013	**0.9093**	0.9023	0.8857
London	0.5152	0.6147	0.7149	0.8039	0.8772	0.9162	0.9382	**0.9438**	0.9390	0.9287	0.9162
New Orleans	0.6445	0.7114	0.7784	0.8382	0.8846	0.9145	0.9285	**0.9298**	0.9226	0.9106	0.8965
Nottingham	0.5278	0.6331	0.7376	0.8268	0.8909	0.9283	**0.9435**	0.9436	0.9350	0.9223	0.9083
The Hague	0.6895	0.7460	0.8035	0.8565	0.8993	0.9279	0.9417	**0.9429**	0.9353	0.9226	0.9079
Winchester	0.6641	0.7597	0.8405	0.9002	0.9382	0.9576	0.9636	**0.9608**	0.9530	0.9430	0.9323
Average	0.6157	0.6936	0.7689	0.8330	0.8801	0.9051	**0.9171**	0.9145	0.9036	0.8883	0.8712

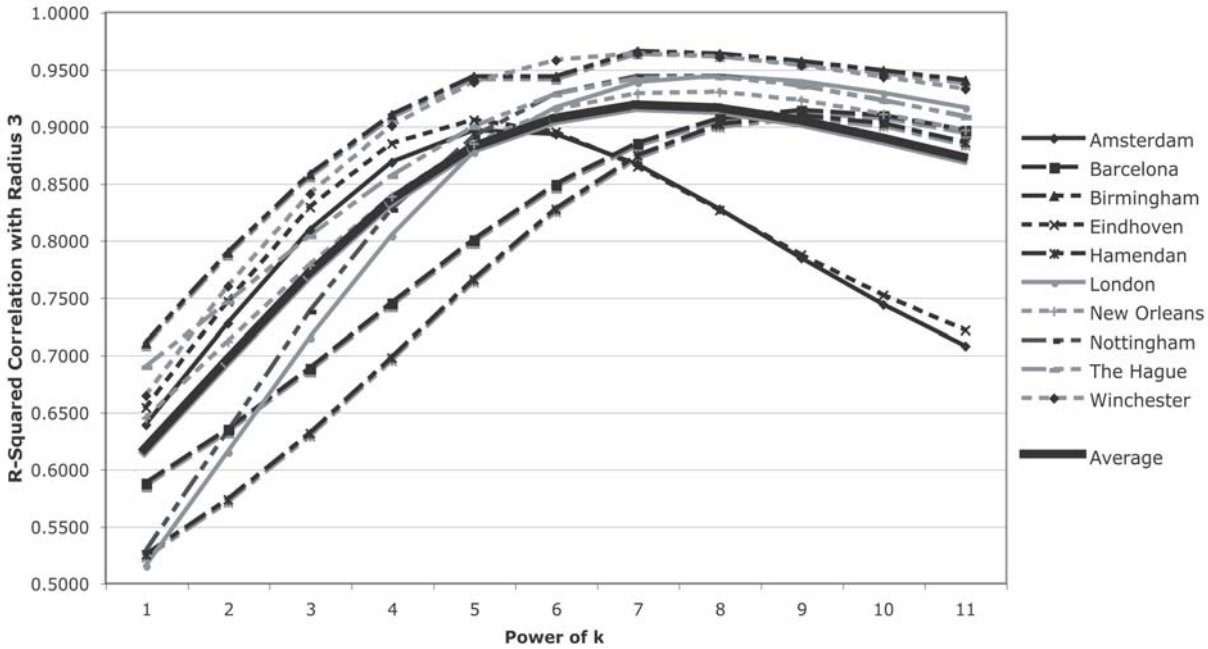

Figure 7:

Correlation coefficients of powers of k with radius 3 for ten cities

It can be seen here, although this is a small sample of cities, that there is some agreement between the radius three and radius seven correlates. Essentially, the average power, k, to which (1+d) must be raised, that correlates best with radius three is 6.5 Statistically, the r-squared value for this is high (between 0.9618). As a result of these good correlations, it is the authors' suggestion that the definition of radius be completely redefined as the 'act of placing different weights on far or near nodes'. This is in direct opposition to the original definition of radius, which could only make sense as an integer value, as it reflected the number of, whole, steps (or changes in direction) away from a starting location.

Using the real world data, we were also able to determine the effect of taking the power of (1+d) to a high positive or low negative value. Essentially, by using a high positive value of k, it is possible to examine 'ultra-local' areas, to an extent where, when k is between 10 and 15, you achieve an almost perfect correlation with the space

syntax measure, 'connectivity [vi], (when k = 15, r-squared with connectivity is 1.0000). When x takes on increasingly low negative values, we arrive at a 'hyper-global' measure: where all the depth is weighted at the extreme edges, this would be a sort of 'liminality' measure: a measure of the effect or shape of the boundary.

Conclusion

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The effect of inserting depth or distance decay functions into the justified graph has the result of producing an extremely flexible method that permits a comparison with existing space syntax measures in a uniform way, uniting all current measures under a single family of equations. The existing space syntax measures, which could be replaced by their new depth decay equivalents, are mean depth, integration, all radii measures and connectivity. Second-order graph measures, such as intelligibility (the relationship between 'local' measures and 'global measures') could be redefined in terms of the relationships between different decay functions (i.e. different powers of x) and could represent an expansion of the number of current ways of calculating intelligibility; the authors of this paper believe that by comparing low and high values for x in the generic depth decay function, such new forms of intelligibility could be developed. By plotting two continuously variable powers of (1+d), an 'intelligibility surface' could be created, permitting an hitherto unimaginable descriptor of the intelligibility of a system.

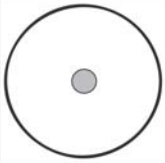
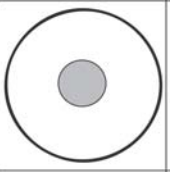
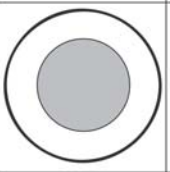
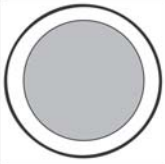
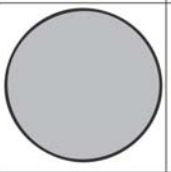
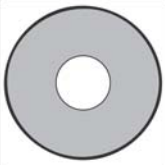
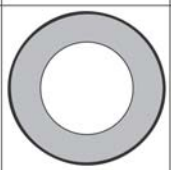
In table 2, overleaf, the primary decay equations are shown alongside their approximate equivalent measures in current space syntax terms. Column two shows a series of diagrams roughly illustrating these concepts. Note that the higher the power of d the smaller the radius and vice versa.

One of the benefits of using the depth decay function at the level of the justified graph is that it simplifies the process of relativisation (See Park 2005 for an full discussion of relativisation). To recall, relativisation was introduced in space syntax in order to facilitate the comparison of two spatial systems with differing numbers of spaces (or orders of graphs). In practice, the role of relativisation is used to perform three tasks. First, is to compare two different graphs, such as two separate cities or systems: for example London and Paris. Second, to study systems over time, as they evolve or as changes are introduced. The third use of relativisation is for the comparison of sub-systems at the same radius; when doing this, the number of items (lines, nodes) encountered within a fixed radius changes along with the total depth.

In his 2005 paper, Dalton, introduced the concept of 'micro structure', that is the observation that in most real world axial maps the correlation between total depth and the number of items encountered within radius three strongly correlates with the total depth within that radius (r2 > 0.998 typical). Dalton asserts that relativisation in space syntax depends upon this near universal 'micro structure' property of all axial maps. Recently, space syntax has seen a move towards new types of representations such as angular/fractional segmented axial lines (or road center-lines). It is not clear that this micro-structure property, which Dalton considers vital for the proper function of the RA, RRA and integration equations, will be found in all types of segmental maps. As such, the ability to calculate localised (radius three-like) measures within segmental systems, without some revision of the current relativisation equations, comes into question.

Table 2:

Summary of equivalence measures

Equation	Value of x	Diagram	Approximate Equivalent
$\frac{1}{(1+d)^x}$ Where $x > 6.5$	> 6.5		$<$ Radius 3 ('ultra-local') [Radii 10-15 is 'connectivity']
$\frac{1}{(1+d)^{6.5}}$	6.5		$\cong$ Radius 3 (local pedestrian)
$\frac{1}{(1+d)^{1.6}}$	1.6		$\cong$ Radius 7 (local vehicular)
$\frac{1}{(1+d)}$	1		$=$ *Basic decay function* $>$ Radius 7 (but less than $R\infty$)
$\frac{1}{(1+d)^0}$	0	Meaningless	$\equiv$ N, or the *order* of the network graph
$\frac{1}{(1+d)^{-1}}$	-1		$\approx$ Reciprocal of Integration Total Global
$\frac{1}{(1+d)^x}$ Where $x < -1$	< -1		$=$ 'True global'
$\frac{1}{(1+d)^x}$ Where x is *much less* than -1	$<< -1$		$=$ Liminal measure ('hyper-global')

Fundamental to the view of generalized relativisation is the observation that the operation must function both with and without 'micro-structure' properties. One method is to avoid the use of the count of number of lines encountered and the total depth encountered (which 'micro-structure' asserts will be proportional). It has already been seen that the new depth decay function takes the whole system into account when calculating local measures, but proceeds to take less interest in the depths of items that are further and further away. In effect, the decay function always examines the whole system and so effectively breaks the 'micro-structure' effect. Distance decay can do this and still produces values that are strongly correlated with the radius three or radius n measures. What also makes depth or distance decay interesting as a function is that it can operate with both rational and integer edge-weights.

Further work needs to be done on establishing, more precisely, the relationships between the current 'tried and tested' space syntax measures and this family of new depth decay measures. This is best

done empirically, in the manner which has been presented in this paper, namely through the use of graphs representing real-world areas, districts and cities rather than idealized or random graphs. Additional work needs to be done to establish which depth decay functions correlate best with observed flow, both pedestrian and different kinds of vehicular flow. The flexibility of the depth decay function also facilitates new areas of research, such as investigating the effect of assigning weights to the nodes in the graph. Finally, new methods of relativisation (across systems not within systems) may be applied uniformly to angular, non-angular, weighted and non-weighted graphs; however the best way to achieve this must be the product of future research and separate publication; it is beyond the scope of this paper to fully do justice to this topic.

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i. A road segment graph could be directed were the one-way road system to be entered into the model, as traffic engineers do.

ii. Normalisation is the process by which mean depth is transformed in order to set the limits between 0 and 1; the RA and RRA equations are used for this purpose.

iii. This is achieved by dividing by the D-value and is essentially performed to enable value comparisons between systems of different sizes.

iv. Radius-radius is where the radius limit is set to the same value as the mean depth of the system as calculated from the most integrated line in the system.

v. This is true for axial line maps as depths are restricted to integer values, however the concept of non-integer radii is currently applicable to fractional or angular analyses where non-integer depths are already being computed.

vi. In an axial map, the 'connectivity' value of a line is the number of other lines that one line intersects. In graph terms, it would be equivalent to the degree (in and out) of a node.

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