A proposed methodology to normalise total depth values when applying the visibility graph analysis

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Keywords
Visibility graph analysis, normalisation, size

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Abstract
The aim of this paper is fourfold:

To outline the problem of comparing graphs of different sizes in current techniques of isovist-based Visibility Graph Analysis (VGA) using the Depthmap software,

To establish the two considerations of "size" in VGA; the total number of nodes in the graph (which is dependent on the spacing set between grid tiles for analysis) and the actual scale of the spatial layout,

To demonstrate the variation between output results arising from using different grid sizes on the same spatial system and the incomparability of "Total Depth" and "Mean Depth" measures in spatial systems of significantly different scales, and

To experiment with transforming the output Total Depth measures, from Depthmap to RRA measures using "D-value" and "P-value" adjustments to normalise the effects of size.

This paper focuses on the use of VGA for building interiors. The results show that Total Depth measures, as the output values of Depthmap, are limited for syntactical comparative analysis of building layouts across a sample of varying sizes. It identifies the methodology, first described by Hillier and Hanson (1984) in the Social Logic of Space, for transforming (axial and convex based) Total Depth measures into Real Relativised Asymmetry measures (RRA or spatial integration), as applicable for VGA. Not only does RRA measures eliminate the effect of size but also it does not effect the distribution of output VGA Total Depth values, making it a suitable methodology for researchers undertaking comparative studies of building types using VGA.

1. Introduction

It has been widely acknowledged that Space Syntax is a powerful analytical tool for studying the relationship of building typologies to the pattern of spatial properties of integration, control or connectivity constructed within each configuration. Turner and Penn's (1999) seminal paper advocates a syntactic approach, using 'isovists' (or visual fields) to describe the configurational properties of space. They argued that the relationship between space patterning and space usage can be explored in finer detail than previous methods of space syntax analysis has allowed. Visibility Graph Analysis (VGA) has since gained considerable usage, particularly used as a complementary tool to Space Syntax methods, in research applying spatial analysis of configurational properties of building and urban space. Growth in this branch of spatial analysis of architectural space using VGA is expected, largely due to the recent advancements in the development of software written by Turner (2001) at University College London (UCL).

While more established Space Syntax methods such as axial analysis has been commonly and successfully used in the study of the morphology of single cities and in comparative studies between different cities of various sizes, VGA has mainly been employed in the study of smaller scale urban areas and building interiors, due to current computational power limitations. Up until now, the majority of published research using VGA is within single spatial building configurations or the comparison of a pair of buildings of similar size. As yet there has not been published research on a cross-comparison of building systems of varying scales using VGA. This paper addresses a specific problem within current VGA methodologies encountered when making comparisons between spatial systems of different sizes based on the global measures of Total Depth and Mean Depth, generated by Depthmap (Turner, 2001).

When considering building typologies it is not uncommon to find a wide range of system sizes. Take for example the real case of a dozen retail warehouse stores[1] with slight variations in their layouts, and varying in floor area, between 800 sqm to 1900 sqm. Each floor plan was imported into Depthmap 1.12b[2] for spatial analysis, with each graph analysed at the same grid size of 600mm x 600mm; as a control for consistency. By taking the mean value of Total Depth from the output table of each modelled floor plan one can get an idea of the syntactic "depth" within each system and compare it across the full sample. When each of these values is plotted against its total number of nodes in each system, which is representative of its metric size (i.e. larger floor areas will contain more nodes because the same grid was used), this immediately highlights the presented problem of "size." The following scattergram in Figure 1 shows a near perfect linear relationship between the mean value of "Total Depth" (along the y-axis) and its respective number of nodes (along the x-axis).

This relationship should not be at all surprising based on two reasons. Firstly Penn and Turner (1999) have made it clear that the measures for depth in VGA have not been normalised for comparisons among different size systems; and secondly that VGA has the tendency to be biased towards large open space areas (Turner, 2001), so what can be defined as "large open spaces" between buildings of different sizes employing the same grid dimensions will have different weighting. The question is how can the effect of size be eliminated in VGA?[3]

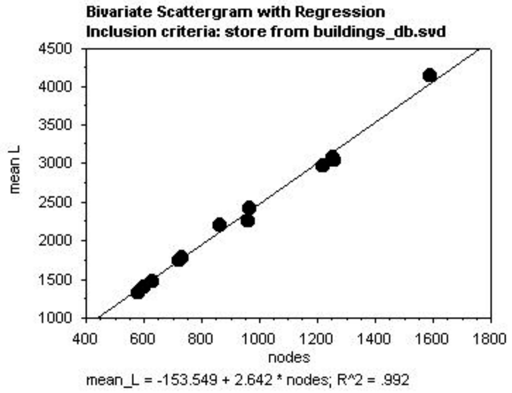


Figure 1: Scattergram showing the correlation between mean value of Total Depth "L" (along the Y-axis) and number of nodes for twelve retail warehouse stores (along the X-axis)

2. Methodology

In Chapter 3 of the Social Logic of Space, Hillier and Hanson (1984) proposed a methodology to transform Total Depth measure into a measure of "integration". Spatial integration was to reflect the mean depth of each axial line or convex space from all other axial lines or convex spaces of a system. Firstly, the Mean Depth of each space is calculated by comparing how deep or shallow a system is from a particular space and then in a second step, it is compared with how deep or shallow it theoretically could be, producing a measure denominated as "Relative Asymmetry" (RA). RA is calculated by the equation:

Relative asymmetry (RA) = 2(MD-1) / (N-2)
where, MD = Mean Depth and N = total number of spaces in a system.

Mean Depth is calculated by the equation:

Mean Depth (MD) = L/(N-1)
where, L = Total Depth and N = total number of spaces in a system

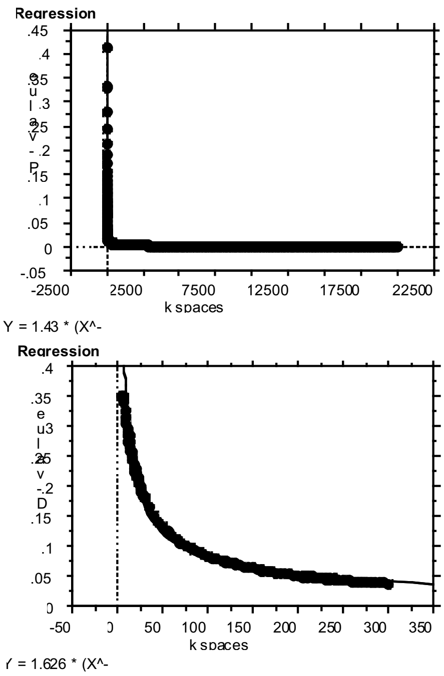
According to Hillier (1996), "The [RA] measure theoretically eliminates the effect of the numbers of elements in the system" (Ibid: 52). Hillier adds that an empirical normalisation formula was necessary to introduce to the equation to eliminate the fact that "both buildings and settlements tend to become relatively less depth as they grow" (Ibid: 52). This was achieved by dividing the RA measures of any given system by the RA value for the root of a diamond-shaped pattern or the "D-value". According to Hillier and Hanson (1984), "the D-value is the means to arrive at RRA [Real Relative Asymmetry] in all cases except when calculating RRA from X in a settlement" (Ibid:133). Hillier and Hanson add that when calculating the depth from a large number of roots (all buildings is system), a similar method is proposed by comparing the RA values with the RA values of a pyramid-shaped complex or the "P-value" (Ibid: 114).

The value of RRA[4] (Real Relative Asymmetry or integration) is therefore calculated by the formula:

> Real Relative Asymmetry (RRA) = RA/D*k* or RRA= RA/P*k*
> where, *k* = relative asymmetry of a diamond or pyramid shape pattern of *k* spaces, the D-value or the P-value.

The hypothesis to be tested in this paper is simply whether this transformation of Total Depth using D or P value adjustments can be applied to VGA measures of Total Depth. In the Social Logic of Space, the equations for working out the P-value and D-values for infinite k spaces were not published[5]. The D values and P values for a limited range of k spaces are provided in tabulated form (from 1 to 300 and from 1 to 1000 respectively.) The reader is instructed to "find the D-value for the system with the same number of spaces as in the real example"(Ibid, p.112). It was foreseen that the number of spaces (in this case grid tiles) will exceed those provided in the table hence the values from these tables on page 112 and 114, the D and P values were re-entered into a spreadsheet within a statistical package to compute their respective equations for the relationship between the two variables (Figures 2a and 2b).

In order to test the assumption that normalisation of Total Depth values using P or D values adjustments is critical for the analysis of systems of different sizes, six hypothetical building layouts (Models A to F) of identical sizes but different configurations were used (Figure 3). Each model was processed using Depthmap at nine different grid sizes, from the largest 10mm x 10mm to the smallest 2mm x 2mm grid (Figure 4).



Figures 2a and 2b: P-value equation (left image) and D-value equation (right image)

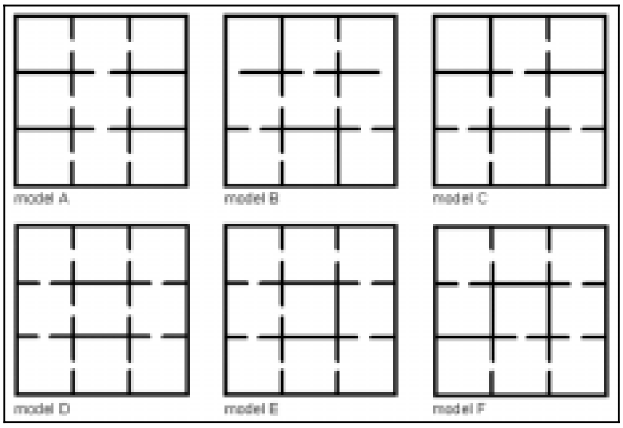


Figure 3: Models A to F unprocessed

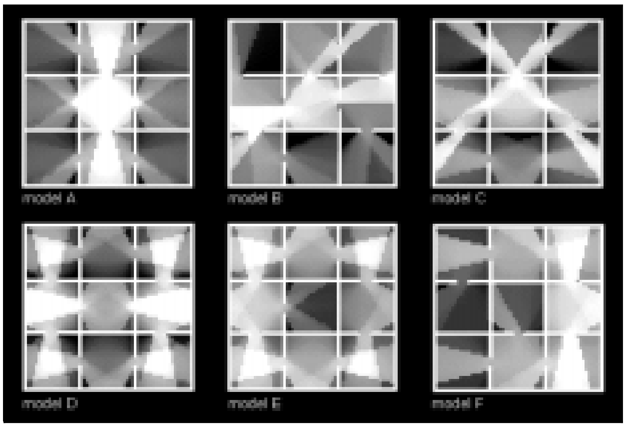


Figure 4: Models A to F processed for a 2mm x 2mm grid

Despite the different configurations, all models have the same number of nodes according to their respective grid size, ranging from 121 nodes (10mm x 10mm) to 3481 nodes (2mm x 2mm), as described in Table 1.

Grid size (mm)	Number of nodes
10 x 10	121
9 x 9	169
8 x 8	225
7 x 7	289
6 x 6	361
5 x 5	529
4 x 4	841
3 x 3	1521
2 x 2	3481

Table 1: Number of nodes according to grid size

A comparative data set was created where for each model and for each grid size when Total Depth and RRA using the P-value and D-value were calculated according to maximum, mean and minimum values.

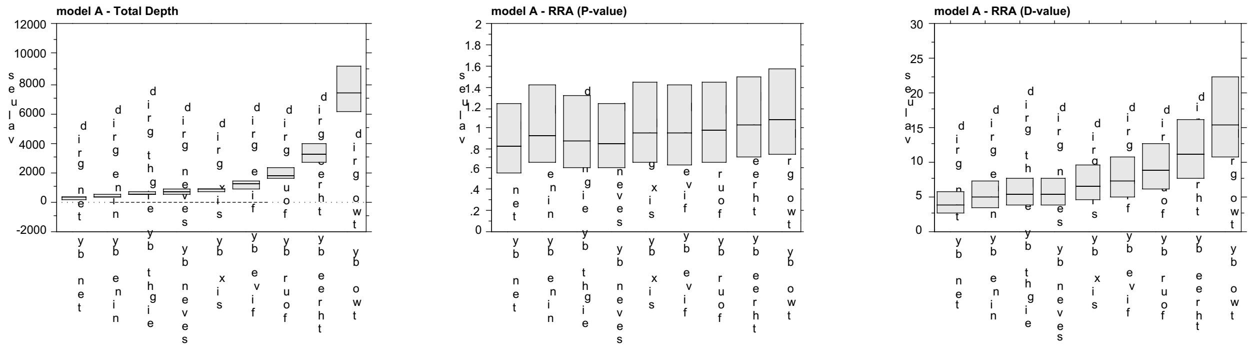
4. Results

4.1 Theoretical models

4.1.1 The problem of comparing across different grid sizes

The first objective was to analyse the effect of size, in this case, the number of nodes in a system, in relation to Total Depth values and to the proposed RRA measure calculated through the normalisation method using D and P value adjustments, adapted from the Social Logic of Space (Hillier and Hanson, 1984).

The charts below present the result of the VGA calculation of Model A plotted according to its maximum, mean and minimum values of Total Depth, RRA (P-value) and RRA (D-value) along the y-axis, and arranged along the x-axis according to the grid-size (the number of nodes), at which it was analysed, as seen in Figures 5a to 5c.



Figures 5a, 5b and 5c: Box plots showing the relationship between minimum, mean and maximum values for Total Depth, RRA (P-value) and RRA (D-value) for Model A according to the number of nodes.

It demonstrates the incomparability of mean Total Depth measure for a spatial system of the same configuration processed at different grid sizes (chart at far left). However comparability improves using the RRA normalised with D-value (chart at far right) and even better with the P-value (centre chart).

The results show very clearly the effect of size to Total Depth values (Figure 5a). Apart from the models which were processed with the two largest grid sizes (10 x 10 and 9 x 9) and the increase in the number of nodes was not significant (121 and 169 respectively), there is no overlapping of Total Depth values between the differently sized systems. For instance, the highest Total Depth value for the 3 x 3 grid (1521 nodes) model is lower than the lowest Total Depth valued for the 2 x 2 grid model (3481 nodes) as seen in Figure 5a. In other words, it is not possible to compare models where the number of nodes varies substantially.

Conversely, when the systems are processed where Total Depth values are normalised using the P-value and D-value, a much more comparable result emerges. Looking first at the RRA (D-value), we can see from Figure 5c that there is a significant overlapping of the Total Depth values for the different grid size systems. However, the normalisation of Total Depth using the P-value (Figure 5b) gives us by far the best results wherein regardless of the grid size, that is, the number of nodes, Total Depth values – RRA P-value - for all models are comparable. For all models, the maximum, mean and minimum values fall within a relatively more comparable range[6].

4.1.2. The problem of configuration

Another issue which arises from the analysis is about morphological comparison among buildings with the same number of nodes. When using Total Depth, unless the number of nodes is high in relation to the building sizeg, smaller models are not able to give a good descriptive measure of the morphological difference among configurations[7]. Figure 6a illustrates that only when models where analysed using a 2 x 2 grid, which has 3481 nodes (the total dimension of the model is 120 x 120, therefore the grid size is 0.017 of its total dimension), there is a substantial variation between average Total Depth values amongst models A to F (each column of dots shows models A to F according to the grid size). All models processed with grids 3 x 3 (1521 nodes) or above are almost meaningless for comparative purposes.

When the analysis is repeated but using RRA (P-value) and RRA (D-value) a much better comparison is afforded (Figures 6b and 6c). Still, as the previous analysis has already indicated, the RRA value when normalised using the P-value gives a far better result when comparing to the D-value. The variations among average RRA (P-value) for models A to F are far greater regardless of grid size, whereas for RRA (D-value), although the variations among models increase with the grid size, for small models in terms of number of nodes (5 by 5 grid or above) the results are not significant for a comparative analysis.

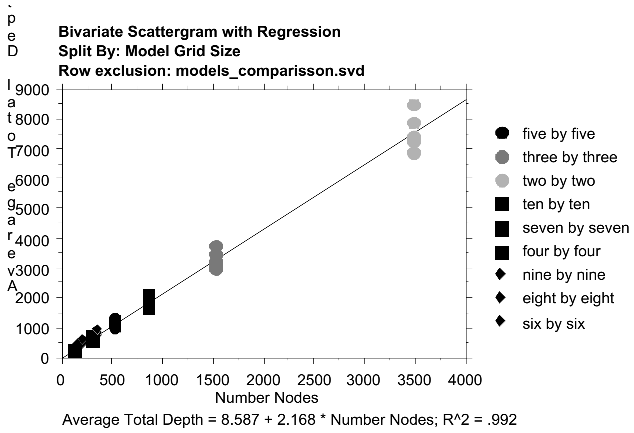
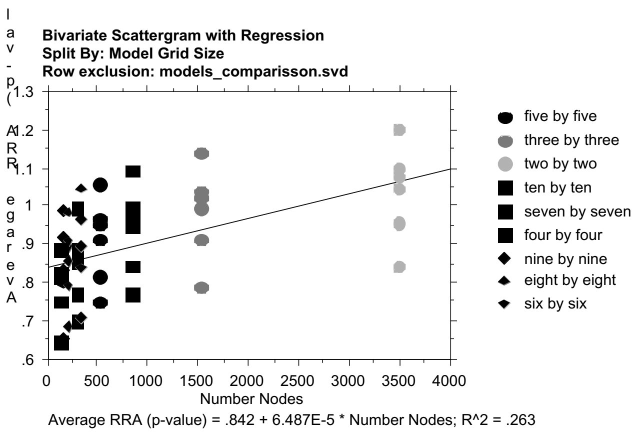
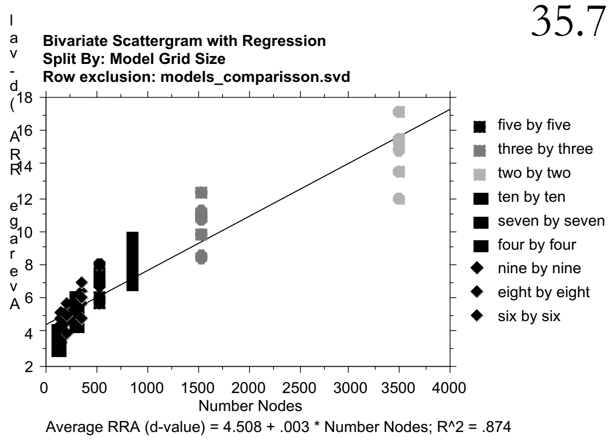


Figure 6a: Scattergrams showing the relationship between average. Total Depth and number of nodes for all models according to grid sizes





Figures 6b and 6c: Scattergrams showing the relationship between average RRA (P-value) (left image) and RRA (D-value) (right image) and number of nodes for all models according to grid sizes.

The correlation between the number of nodes with RRA (P-value) is relatively much weaker, (R squared = .26) compared with average Total Depth (Refer to Figure 6a) and RRA (D-value) (Refer to Figure 6c) This demonstrates that while the latter two measures have almost a perfect relationship with size (R squared close to 1), RRA (P-value) with such a low R-squared appears to be independent of size.

4.2 Application of method to a sample of real buildings

The same methodology of transforming the measure of Total Depth has been applied to the output graph files for a set 40 real building floor plans of various scales from three building types; retail stores, shopping malls and laboratories. The sample within each type is processed at different grid sizes at 1m x 1m, 1.2m x 1.2m, 3m x 3m respectively[8], and fall within a similar range in the number of nodes, approximately between 500 to 2000 nodes. When the mean value of Total Depth for each building model is plotted against its node size (Figure 7) it shows a significant relationship between these two variables.

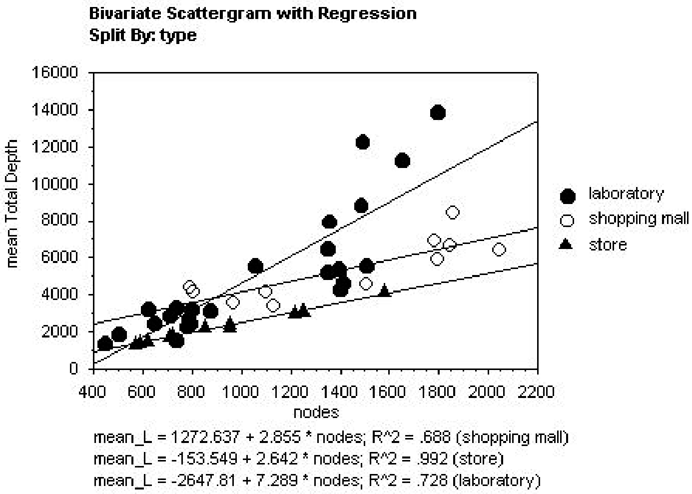


Figure 7: Scattergram showing the relationship between number of nodes (along the X-axis) and average Total Depth (along the Y-axis) for the sample of 40 buildings split according to types

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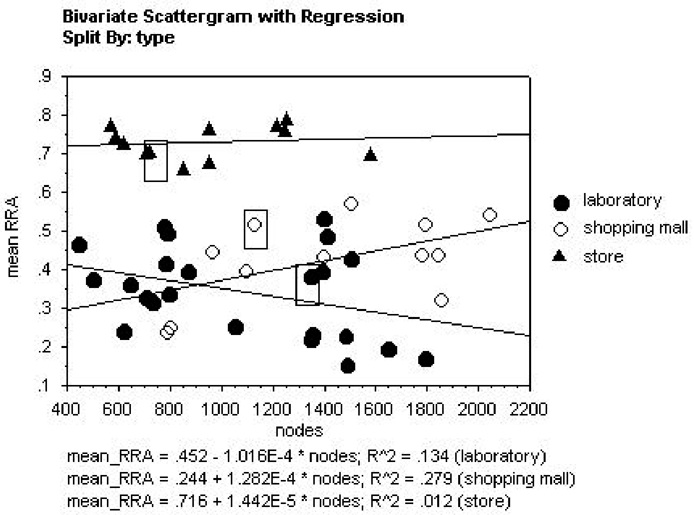
Figures 8 presents the results of the transformation of Total Depth using P-value adjustments as described in the previous sections. The scattergram indicates that the mean RRA measures for each building system is not directly relate to node size (size of the graph) and the range in mean RRA values demonstrate a reasonable level of comparability across the sample groups. The store building sample has on average a higher mean RRA (clustered between .65 to .8 along the Y-axis) compared with those in the shopping mall and laboratory groups. To ascertain whether this phenomenon is an effect of its configurational properties, the distribution of the RRA values of each case must be understood.

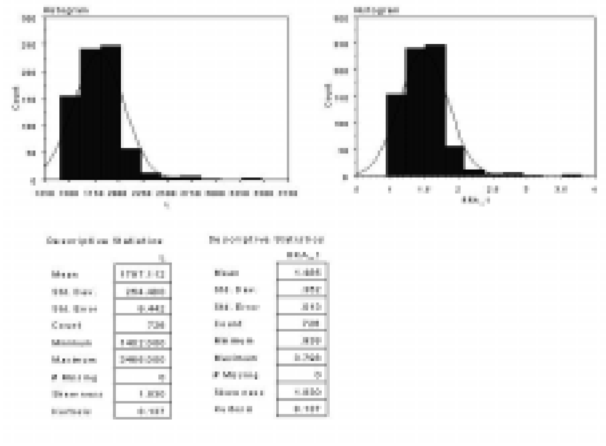


Figures 8: Scattergram showing the relationship between number of nodes and average RRA (P-value) for the sample of 40 building according to types

One case out of each building type has been highlighted, with a rectangular box, to illustrate that the transformed Total Depth values to a RRA measure has not changed the distribution of the values. See Figure 9a-9c.

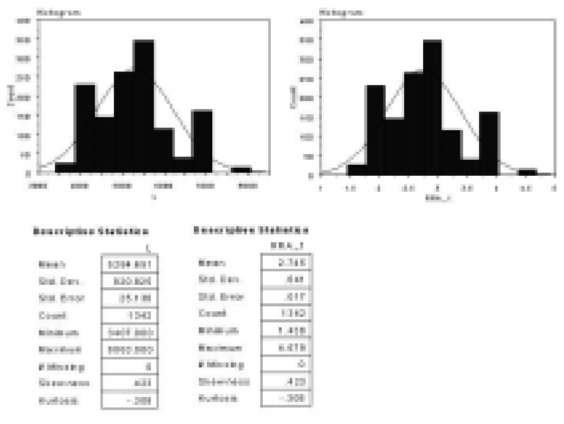
The distribution of Total Depth values were compared with the complete set of resultant RRA values of one building graph selected randomly from each building type, (see Figure 8 highlighted by the three rectangular boxes). As shown in Figures 9a to 9c, the coefficient for skewness and kurtosis is identical for the measure of Total Depth "L" and RRA, (adjusted by P-value and before the reciprocal was taken, Hiller and Hanson 1984). A note should be added that the transformation to eliminate the effect of size using P-value adjustment is on the values of Total Depth to arrive at a corresponding RRA measure and not in the distribution of the values.

From this analysis, the distribution of Total Depth and or RRA_1 values for the store sample group tend to have positive kurtosis values compared with those of the shopping mall and laboratory. (Only partial results shown.) Positive kurtosis signifies that the distribution of Total Depth are focused around the mean (peaky distribution) compared with a negative kurtosis value (tendency of the shopping mall and laboratory case studies for a flatter or more evened out distribution.) It is evident that the mean RRA value of stores are on average higher than shopping mall and laboratories is a fact due to configurational properties, rather than a factor of size.



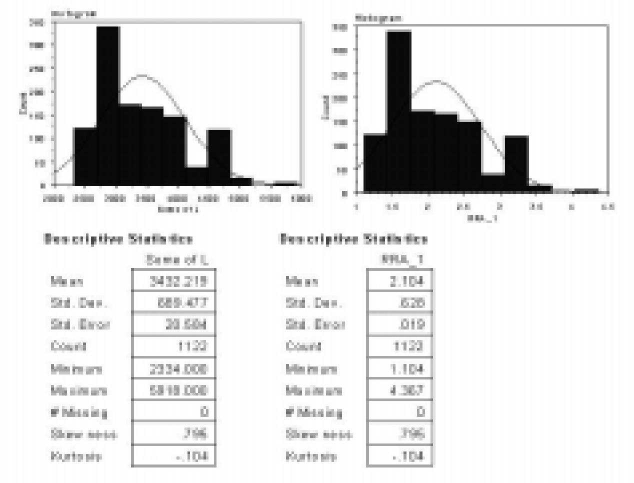
Figures 9a: Descriptive statistics for one case out of the retail warehouses stores sample.

(Note: Mean for RRA_1 is before the reciprocal was taken for the results in Figure 8. Coefficient for skewness and kurtosis are identical before and after transformation of Total Depth to RRA_1)



Figures 9b: Descriptive statistics for one case out of the laboratories sample.

(Note: Mean for RRA_1 is before the reciprocal was taken for the results in Figure 8. Coefficient for skewness and kurtosis are identical before and after transformation of Total Depth to RRA_1)



Figures 9c: Descriptive statistics for one case out of the shopping malls sample.

(Note: Mean for RRA_1 is before the reciprocal was taken for the results in Figure 8.Coefficient for skewness and kurtosis are identical before and after transformation of Total Depth to RRA_1)

5. Discussion

Size or the effect of area has become an immediate consideration in VGA methodology, and one that is not found in the topological measures used in conventional Space Syntax methodology. Although, Turner (2001) suggests the use of other "topological" measures in VGA such as relative entropy to overcome the problem of size, spatial integration remains the most useful in syntactic studies, as it is the one measure that has consistently correlated with movement.

It is hoped that this paper has highlighted the problem of size as a serious concern when using VGA methodologies and in particularly when comparing buildings of different sizes and processed at various grid sizes. It provides preliminary evidence that RRA measures with P- value adjustments, as adapted from the methodology set out in the Social Logic of Space for normalising RA values for convex spaces, may be a valid method to overcome the problem of size.

Notes

1. Project undertaken by the authors at Space Syntax Ltd during the summer of 2001.
2. The data was subsequently analysed using the more recent Depthmap 2.11r software with the same results.
3. A secondary question to this is of course, are larger size systems "meant" to be more integrated?
4. In this paper, all RRA values are before the reciprocal has been taken.
5. For an analytical deduction of these equations, refer to: Kruger, M., 1989, "On Node and Axial Grid Maps: Distance Measures and Related Topics", *European Conference on the Representation and Management of Urban Change*, University of Cambridge.
6. Our analysis showed that when these models are tested against RA, the RA measure is still size dependent and therefore the transformation method by adding the P or D value is necessary so that the effect of size can be eliminated and comparisons between spatial systems that differ significantly in size can be made.
7. This highlights another problem that requires more methodological investigation. What is the optimal grid size to use when analysing buildings of various floor area size in VGA?
8. The criteria for choosing the grid size used for each building type was that it could cover the narrowest width of space on all plans. The largest possible grid size was chosen to minimise the number of nodes per graph hence processing time (to under half an hour for each plan) on a 366MHz computer available for this experiment.

Acknowledgement

The co-author would like to acknowledge the Overseas Research Scholarship Awards Scheme.

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