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The convex decomposition of a defined urban area provides a practical spatial framework to support a range of methods, which provide useful insights into aspects of *urban ambience* - the experienced physical and psychological qualities of the urban environment. This paper describes the integrated implementation of three such methods, convex, isovist and fractal analysis, to a densely built university campus. The convex space is employed as the fundamental unit of urban form; the starting point is the derivation of the convex map of the site. The centroids of the constituent convex spaces are taken as origin points to generate conventional two-dimensional isovists, and to photograph hemispherical images of the surrounding surfaces, representing a type of three-dimensional isovist. This latter construct opens a variety of analytical opportunities, only two of which are explored here - determination of skyline and surface fractal dimensions as indices of *visual diversity*. In addition to the standard convex and isovist metrics, two new measures are introduced: isovist fractal dimension, as an indicator of *complexity*; and isovist area divided by convex area, as an indicator of *intervisibility*. The outputs of this composite evaluation are redefined as a set of comparative indicators of several key ambience properties: physical and visual permeability, configurational and informational legibility, and visual diversity and *stimulance*, or exposure to new visual information. Multivariate statistics are applied to explore the relationships among the variables, and the similarities and differences between convex spaces in terms of the variable set. It is concluded that at neighbourhood scale these methods appear to identify real distinctions among convex spaces from the perspective of the occupant inhabiting and moving between them. Further, it is argued that convex decomposition offers a viable basis for comparative evaluation of a variety of significant urban ambience properties, with potential to inform design intervention.

Keywords: Convex space; Urban ambience; Urban structural unit; Isovist; Fractal analysis

1. Introduction - the urban structural unit

Frameworks for describing and classifying urban form are innumerable - every local town plan or urban design guide plays this role. Invariably such instruments conflate *descriptive* morphological factors with *explanatory* land use or functional criteria. More focused taxonomies have been devised for particular classes of urban elements such as streets (Marshall, 2002), utilities (Kohler, 2003) and building stocks (Thuvander, 2002). Such specific-purpose frameworks can help inform a more universal descriptive scheme, but they lack the generality to order urban form from 'room to region'. A viable classification framework to support morphological analysis in the broadest sense of 'city as human habitat' (Moudon, 1997) must be comprehensive, consistent, coherent and transferable if it is to have value beyond the idiosyncratic. Consideration of the multiple scales of investigation, implying multiple levels of resolution, is a logical starting point. Similarly, multiple *types* of investigation must be accommodated within a single system boundary.

The *urban structural unit*, (USU), originally devised to facilitate evaluation of urban metabolism (Pauleit & Duhme, 1998), offers the basis for such a framework. USUs are broadly defined as areas of relative homogeneity with respect to the type, density and arrangement of built form and open space, which delineate distinct configurations of the built environment. Each discrete domain - form and space - can be subdivided *hierarchically* in terms of the part-to-whole relations of its constituent elements (Kropf, 1993; Osmond, 2010), according to the scale and type of investigation [Table 1 columns 1 and 2; Figure 1 a-g]. For example, a life cycle assessment may focus on construction materials, while a hydrological study will be more concerned with the extent of paved and unpaved surfaces.

1: Built form hierarchy	2: Open space hierarchy	3: Space syntax
URBAN	STRUCTURAL	UNIT
Blocks Street segments, intersections and squares		
	Built form Open space	
Plot series		
Plots		
	Paved surfaces Unpaved surfaces	**Convex map** **Axial map**
Buildings		
Rooms/circulation		
	Vegetation structure	
Building structures and systems		
Construction materials	**Vegetation species**	**Convex spaces** **Axial lines**

Table 1: Three-way disaggregation of the urban structural unit.

Space syntax offers a third way to decompose the USU: into its convex and axial representations [Table 1 column 3; Figure 1h and 1i]. The space syntax description of the configurational properties of the street network complements the morphological definition of streets in terms of segments, intersections and squares. Further, differentiation of an environment into the least set of 'fattest' convex spaces (Hillier and Hanson, 1984) provides an expedient framework for application of analytical methods *additional* to those of space syntax.

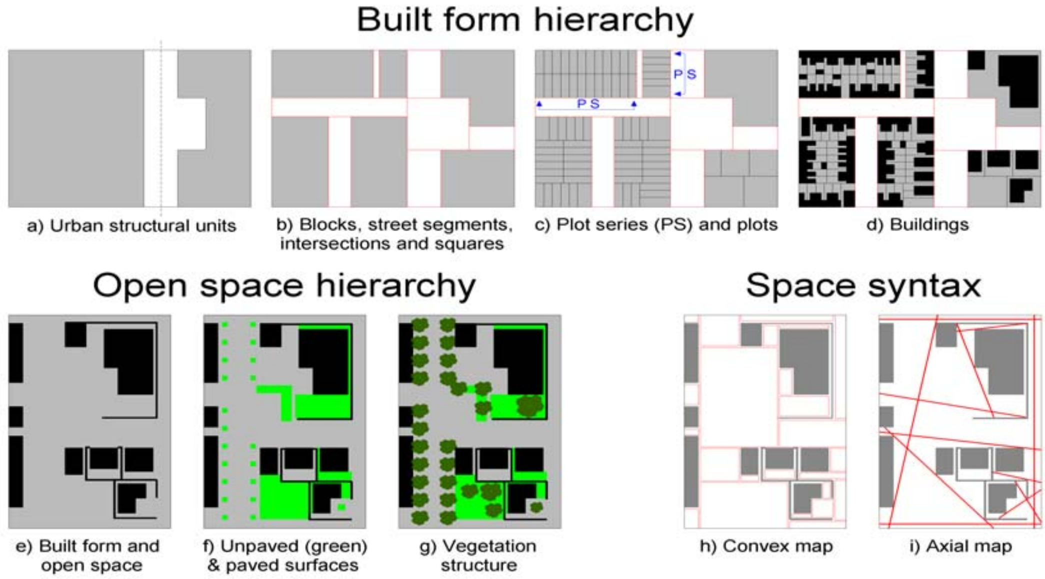

Figure 1: Decomposition of the urban structural unit.
a)-f): Four levels of the built form hierarchy, adapted from Kropf (1993). The hierarchy may be continued at finer resolutions to include: rooms; structures (walls, roofs etc) and systems (mechanical, hydraulic etc); and construction materials.
a) Two discrete USUs. The intervening space may be treated as shared.
b) The blocks (shaded) and street segments/intersections/squares (outlined in red), which comprise the two USUs.
c) Blocks disaggregated into plot series and plots. A plot series is the set of plots fronting a given street segment, bounded by streets at either end. Two examples ("PS") are shown.
d) The buildings contained within the plots.
e)-g): Subdivision of the open space hierarchy for the USU on the left in 1d.
e) Three dimensional built form (buildings, walls) vs. undifferentiated open space.
f) Differentiation of paved and unpaved surfaces.
g) Vegetation structure within unpaved areas. This level may be further disaggregated to indicate vegetation species.
h)-i): Space syntax decomposition of the USU into its convex (h) and axial (i) maps.

2. The convex space as the object of analysis

Convex decomposition of the USU links space syntax to other analytical frameworks - in the present case, isovist and fractal analysis. The convex space thus becomes the unit of description or 'atom' of urban structure for this suite of methods, just as the plot may fulfil a similar role for a study relating to land use or tenure. The common denominator is the urban structural unit.

Notwithstanding the mathematical intractability of identifying a *unique minimal set* of 'fattest' convex spaces (e.g. Batty and Rana, 2002), it is proposed that convex decomposition as per Hillier and Hanson (1984), to enable selection of a *representative sample* of convex spaces, offers a pragmatic basis to support initial evaluation of certain properties pertinent to a given USU.

This research addresses only a subset of available convex metrics. The focus is on how the convex space may be utilised as the fundamental unit to explore some aspects of *urban ambience*, a synthesis of the experienced physical and psychological qualities of an urban environment. Additional methods applied to this end are *point isovist analysis*, using the centroids of the convex spaces as reference points; and determination of the *fractal dimensions* of skylines and surrounding surfaces, based on analysis of hemispherical photographs taken from the same centroids.

Benedikt (1979) describes an isovist as the set of points visible from a given point in space with respect to the surrounding surfaces. Isovist analysis involves measurement of the geometric attributes of the isovist associated with different spatial configurations, such as area and perimeter (how much space or surrounding surface one can see from a given vantage point), and maximum and minimum radials (how far one can see from the vantage point), which relate to the visual experience of a place.

Fractals are objects of irregular but self-similar form that is the irregularities are repeated over many scales. Measurement of this property determines the object's fractal dimension *D*. Real world objects exhibit fractal characteristics over a limited range of scales, so the methods used to identify *D* must allow for upper and/or lower cut-off points. The fractal dimension is identified by evaluating the increase in measured length of an entity (or surface or volume for higher dimensional objects) when subjected to measurement at incrementally decreasing scales. The resulting data are plotted on a log/log graph of measured values vs. measuring units, and the slope of the curve corresponds to the fractal dimension (Peitgen *et al.,* 1992).

Fractal analysis of urban form has provided insights into city growth (Batty and Longley, 1994), architectural design (Bovill, 1996) and also *urban character* (Cooper, 2000; 2003), which is especially relevant to the present investigation. Cooper found that the fractal dimension of street skylines, represented as line tracings from photographs, provides a composite measure of character, which can inform a comparative evaluation of urban places. His work also suggests the fractal dimension of street vistas provides a valid measure of visual diversity, based on comparison with subjective judgements.

Cooper's research involved analysis of images captured with a camera viewing angle corresponding to the human field of view (≈50^o). The present research extends this to explore 180o 'fisheye' images of skylines and surfaces - a type of 3D isovist - which it is argued contains more visual information than a 50^o 'slice'.

3. Methods

The study site is the main campus of the University of New South Wales (UNSW), located about six kilometres from the Sydney, Australia CBD. The campus covers 38 hectares and accommodates some 40,000 enrolled students and 5000 staff. The morphological characteristics of the campus USU, derived from morphometric analysis of aerial photographs and site plans [Figure 2a], verified through field observation, are summarised below:

- o Change in underlying geology and topography between the upper (east) and lower sections of the campus;
- o High density of built form (plot ratio = 1.3);
- o General alignment of buildings along an east-west grid;
- o Orthogonal pattern of open space between buildings;

- Dense network of pedestrian and shared vehicular circulation routes;
- Buildings predominantly of four to eight storeys;
- 71.2% impervious (paved or roof) surfaces;
- Tree canopy cover of 18.9%.

3.1. Convex decomposition and analysis

417 convex spaces > 5m^2 were identified on a campus plan, current at September 2007 [Figure 2]. Figure 2b illustrates the convex graph, constructed with UCL Depthmap v7.12 (Turner, 2004; 2007). A section of the public road, which bisects the campus is included to link the two areas. The isolated building at bottom left of Figure 2a is embedded in a block of non-University buildings and is excluded from the analysis.

The assessment focused on connectivity, integration R^n and integration R3, defined similarly to the corresponding axial metrics (Hillier and Hanson, 1984; Hillier, 1996). Two supplementary measures, *control* (Hillier and Hanson, 1984) and *controllability* (Turner, 2001) were added to assist in identifying convex spaces for further investigation, and are included in the final statistical analysis. As explained by Turner (2004: 16):

> '…control picks out visually dominant areas, whereas controllability picks out areas that may be easily visually dominated. For control, each location is first assigned an index of how much it can see; the reciprocal of its connectivity. Then, for each point, these indices are summed for all the locations it can see.'

Controllability is simply the ratio of the total number of nodes up to radius 2 to the total number of nodes at radius 1.

Following convex analysis of the full dataset, a subset of spaces for isovist and fractal analysis was selected based on:

- Exclusion of 32 spaces ≤ 20m^2 in extent, assumed not to contribute greatly to overall ambience.
- Identification of individual spaces deemed worthy of further attention because of particular syntactic properties.
- Inaccessibility of spaces due to redevelopment works (49 excluded), or location on private property such as residential college grounds (66 excluded).
- The UNSW 2020 Master Plan (DEGW, 2005), which describes the 'campus experience' with reference to existing buildings and spaces.
- Sufficient coverage to enable effective point isovist analysis of most of the site while avoiding significant overlap.

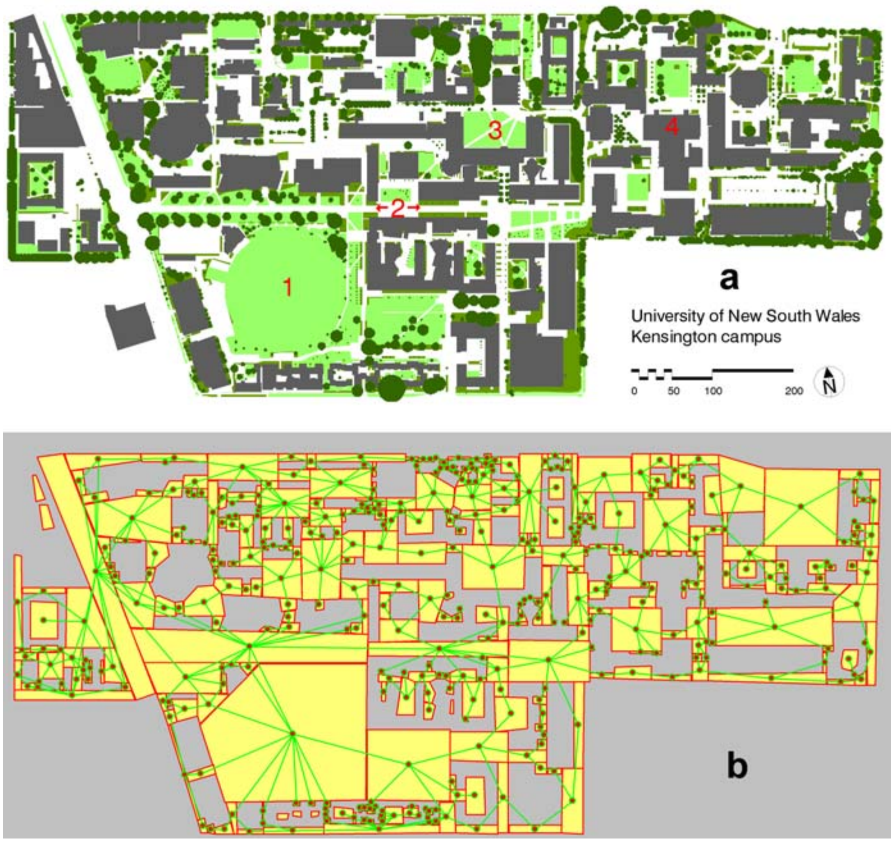

Figure 2: UNSW campus urban structural unit.
a - Campus plan, current as at September 2007. White = paved surfaces; Grey = buildings; light green = lawn; mid green = shrubs; dark green = trees. 1 = "Village Green" sports field; 2 = University Mall; 3 = main quadrangle; 4 = Library (see text).
b - Convex graph of the UNSW USU; convex spaces are outlined in red, and centroids are shown as red circles.

This sifting process produced a sample of 90 convex spaces. The centroid of each space was defined in AutoCAD 2000 to provide the digital references for generating point isovists in Depthmap, and to establish observation points on the ground for hemispherical photography.

3.2. Isovist analysis

The principle that visual barriers define the line between open and closed space (Dara-Abrams, 2006) lies at the core of visibility-based modelling. A variety of obstacles other than buildings and walls can block visibility, notably vegetation. Trees and shrubs are of different heights, shapes and foliage densities. Each variant conveys different information to the observer. However, visibility analysis software currently cannot represent such *partially* occluding objects. Practical options are to assume that: a) incident vegetation is visually permeable at the height at which the isovist is taken (typically average eye level or ≈ 1.6 metres); b) visually impermeable; or c) each vegetation element may be individually evaluated. Option 'b' is chosen here, being more time efficient than 'c' and more accurate than 'a'. As 13 of the centroids were located in the middle of dense vegetation, assumed to be visually impermeable in any direction, no isovists were generated from these points.

Point isovists were taken from the centroids of the remaining 77 spaces, using Depthmap. Five standard isovist metrics were calculated: area a_i, perimeter p_i, maximum radials d_i^{max} and occlusivity Q_i, (Benedikt, 1979), and Batty's isovist compactness index T_i, defined as the ratio of average to maximum distance from each vantage point (Batty, 2001). Two additional metrics were developed for this research:

1. The area of the isovist generated from the centroid of a given convex space divided by the area of that space, a_i/a_c. This is an indicator of point isovist *intervisibility*, since all points within a convex space are intervisible, but all points within an isovist may not be. The higher the a_i/a_c value, the more new visual information is accessible from the centroid of the convex space. Values < 1 indicate that discrete obstacles such as vegetation elements obscure some of this visual information. Conversely, observers located in a space with an intervisibility value ≈ 1 will generally be able to see one another, suggesting the potential for the space to function as a 'people place'. Since derivation of this point metric relies on prior convex decomposition, there is no equivalent isovist field metric.

2. The isovist fractal dimension D_i, calculated from the slope of the $\log p_i/\log a_i$ regression line, indicates the 'spikiness' or *complexity* of the isovist with respect to variation in view lengths and occluding surfaces. Isovists, which incorporate a variety of near and distant views demonstrate a high D_i while a circular isovist will have a *Di* of one. In the present study, point isovist perimeter traces from Depthmap were converted to 1486 x 1486 pixel bitmap images. These were processed in the fractal analysis program Fractal 3e (Sasaki, 2005), which includes an algorithm for thinning lines to single pixel width, to determine *Di* via the box counting method (Bovill, 1996).

3.3. Fractal analysis

Perpendicular hemispherical photographs were taken from the centroids (+/- 1 metre) of 157 of the 417 spaces identified in the convex decomposition of the campus. 143 spaces were excluded on the basis of area (≤ 20m^2), construction works or location on private property. A further 117 spaces were eliminated as redundant (centroids ≤ 10 metres of each other), or where the fisheye view would be dominated by a single building. Ninety of the 157 images were selected for fractal analysis, the same dataset as employed in the convex analysis.

A Nikon Coolpix 990 digital camera with a FC-E8 fisheye lens was used to capture the images at 2048x1536 pixel resolution. The photographs were taken during overcast conditions to ensure relative uniformity of sky luminance with respect to the zenith angle, and were overexposed approximately one stop to maximise the contrast between sky and foliage in determining the skyline fractal dimension.

The public domain image processing software ImageJ v1.33 (Rasband, 2007) was used:

1. To convert the colour photographs to binary and extract the skyline edge traces for determination of the skyline fractal dimensions D_{sky}. The resulting images were thinned to one pixel width and analysed in Fractal 3e via box counting.
2. To adjust the gamma factor, which describes the relation between light intensity and pixel brightness (Macfarlane *et al.*, 2007), to compensate for the initial overexposure prior to determining surface fractal dimensions D_{surf}.

Fractop, a java-based program developed for biological image analysis (Cornforth *et al.*, 2002) was used to calculate the D_{surf} values. Fractop was selected in preference to Fractal 3e for consistency with previous research relating to surface fractal dimension (Osmond, 2005; 2007) and because it permits manual adjustment of box sizes to maximise the contrast between low and high D_{surf} images. The maximum box length recommended by the software for a 2048x1536 pixel image is 768 pixels, but testing a range of box length configurations indicated that addition of two further exponential increments (556 and 1012) to the default box length set {2, 3, 4, 6, 8, 16, 32, 64, 128} ensured the greatest contrast.

4. Results

4.1. Convex analysis

Figure 3 shows global and local integration, control and controllability for the campus USU. The University Mall (shaded red in 3a) provides the global integration 'core', with the main quadrangle (red circle) also scoring highly. The analysis indicates that a densely built area (yellow circle) including the Library, Medicine, central administration and Bioscience buildings is poorly integrated with the rest of the campus. This coincides with the change of grade between the upper and lower campus zones, with fewer spatial connections between than within the zones. Global integration agrees fairly well with observed patterns of occupation and usage, with the important exception of the Library (red circle in 3b). This building is a major attractor for students and staff, but although the convex analysis suggests the adjacent spaces, which provide access to it are neither well connected nor integrated, observation does not support this finding.

The local (R3) integration map confirms the local integrating role of the Mall and adjacent spaces and identifies two other areas of above average R3 value (circled in blue in 3b). The area to the left includes several locally well connected vehicle routes and car parks, set among a number of undistinguished single-storey buildings, with limited connection to the rest of the campus. The 2020 Master Plan identifies it as a suitable location for a major new entry hub. The circled area to the right is now part of a student housing development. The Village Green (red, 3c) is identified as the most controlling space, from which much of the campus can be seen. Highly controllable (visually dominated) areas, circled in red in 3d, include an at-grade car park (left) and the Library lawn.

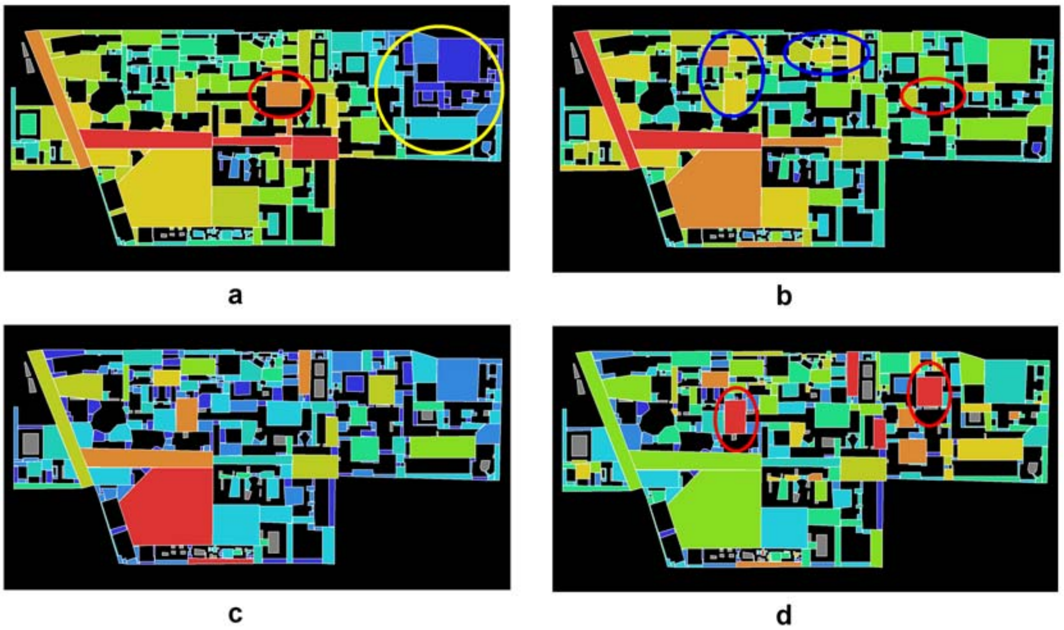

Figure 3: a) Convex integration Rn; b) Integration R3; c) Control; d) Controllability.
Red indicates the highest values for each metric, blue the lowest. In c and d, the grey areas represent convex spaces, which have only one connection to an adjacent space, and are therefore ignored in the calculations. See text for explanation of circled areas.

4.2. Isovist analysis

Figure 4 illustrates a) area, b) perimeter, c) maximum radials, d) isovist area divided by convex area and e) isovist fractal dimension, as seen from the centroids of the selected convex spaces. In Figure 4a, b, c and e, red indicates the highest values of the given metric and dark blue the lowest, with intermediate values spread across the spectrum. In Figure 4d, red represents isovist area > convex area, indicating availability of new visual information within the isovist; green represents isovist area ≈ convex area (highest intervisibility); and blue represents isovist area < convex area. The University Mall and Village Green dominate in terms of *how much* area [4a] and bounding surface [4b] is visible. The relatively high p_i of the isovists circled in Figure 4b result from the complex boundary geometry created by buildings and vegetation. However, spatial complexity does not guarantee desirable ambience - whereas the circled areas in the centre of the figure include varied and interesting views, the circled isovist on the right covers a partially landscaped at-grade car park abutting a 'brutalist' five-storey car park. The d_i^{max} map [4c] highlights significant views and routes into, out of and within the campus, again dominated by the Mall. The isovist to the south-west (circled) is of particular interest - the extensive views across the Village Green into the campus from this point suggest the potential for an additional gateway.

Observers located within the spaces coloured green or cyan in Figure 4d are likely to be mutually visible, a prerequisite for physical interaction. Most of these spaces already function in this way, as active or passive recreation places. Two interesting exceptions (circled) represent leftover' spaces behind and between buildings, currently used mainly for vehicle deliveries, which potentially could be redesigned to encourage human interaction.

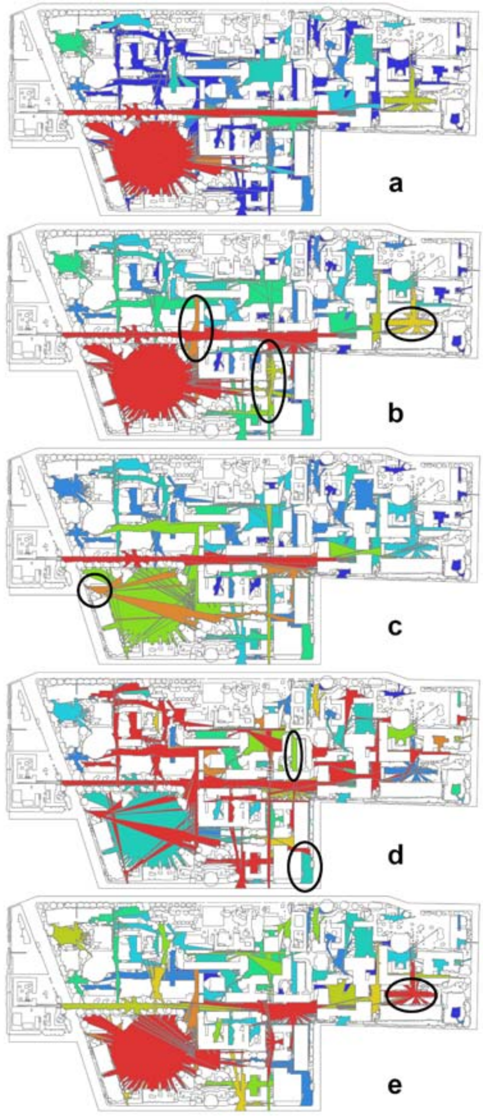

Figure 4: a) Isovist area; b) Perimeter; c) Maximum radials; d) Isovist area/convex area; e) fractal dimension. See text for explanation of circled areas.

The fractal dimension map in Figure 4e represents a synthetic indicator of the spatial complexity of visibility - the particular combination of near and distant views, independent of the *content* of the view. For example, the car park isovist (circled) is spatially complex, but in contrast to the other red shaded high D_i areas the views are very ordinary.

Compactness and occlusivity were also assessed, but are not shown in Figure 4. Visually compact spaces include both functional service/delivery areas and more 'habitable' courtyards. The occlusivity map represents the relative proportion of occluding surfaces, which terminate views from a given vantage point and thus closely resembles the perimeter map, which represents the *overall* boundary of each isovist.

4.3. Fractal analysis of hemispherical images

Skyline traces were unobtainable for 10 images due to the density of overhead foliage. The fractal dimensions of the traces for the remaining 80 images ranged between 1 and 1.246. There was a clear association between skyline fractal dimension and the amount of visible vegetation, the diversity of heights and rooflines of surrounding buildings, and also the *dominance* of built form (a function of both the height and the distance of built elements to the image origin). Fractal dimensions of surrounding environmental surfaces (90 spaces) ranged from 1.567 to 1.849, comparable to the values obtained for 50o field of view vista images obtained for the UNSW campus and other Sydney sites. As well as reflecting the presence of vegetation, high D_{surf} values were associated with the degree and scale of contrast between elements (structures and surfaces) in the surrounding built form [Figure 5].

Figure 5: Left - hemispherical image of convex space #90; centre - image converted to binary for fractal analysis of surrounding surfaces (D_{surf} = 1.684); right - skyline trace of the image (D_{sky}= 1.195).

5. Statistical analysis of the dataset

Isovist and/or skyline fractal dimension data were unobtainable for 19 convex spaces due to vegetation density, giving a final set of 71 spaces with data for all variables:

- Convex metrics: Area; Connectivity; Integration R*n* and R3; Control; Controllability.
- Isovist metrics: Area; Perimeter; Maximum radials; Compactness; Isovist area/convex area; Fractal dimension. Occlusivity was discarded in view of its high correlation with p_i (Pearson's r = .993).
- Fractal metrics: Skyline *D*; Surface *D*.

Multivariate statistics offers a variety of tools to investigate complex datasets. In this case *hierarchical cluster analysis* was used to disaggregate the convex spaces, based on similarities/dissimilarities in values across the range of variables, and *factor analysis* was used to identify the underlying structure in the variable set. Both methods are seen as exploratory; a heuristic, not a definitive explanation. SPSS v15 was employed for the analysis.

5.1 Cluster analysis of the convex spaces

Figure 6 shows the output of a hierarchical cluster analysis of the convex spaces, and Figure 7 maps the clusters onto the campus plan. Ward's method was used to maximise cluster homogeneity by minimising the sum of squared deviations of observations from their cluster means at each step of the analysis (Everitt, 1980). Squared Euclidean distance was selected as the interval measure to give greater weight to significant differences between clusters, and a z-score transformation was applied to standardise the variables.

The analysis identified 15 primary clusters, with one to 13 members. The first major division is between clusters 1-12 and 13-15. The latter represent the largest convex spaces of the dataset; isovist area, perimeter and maximum radials values are about seven, five, and three times higher respectively than the dataset mean. Connectivity and control values are more than twice the mean, but isovist compactness is only 15% of the mean. Spaces belonging to clusters 13-15 are highly integrated globally and locally, support expansive views and extensive connections, and comprise the University's main movement and activity spaces.

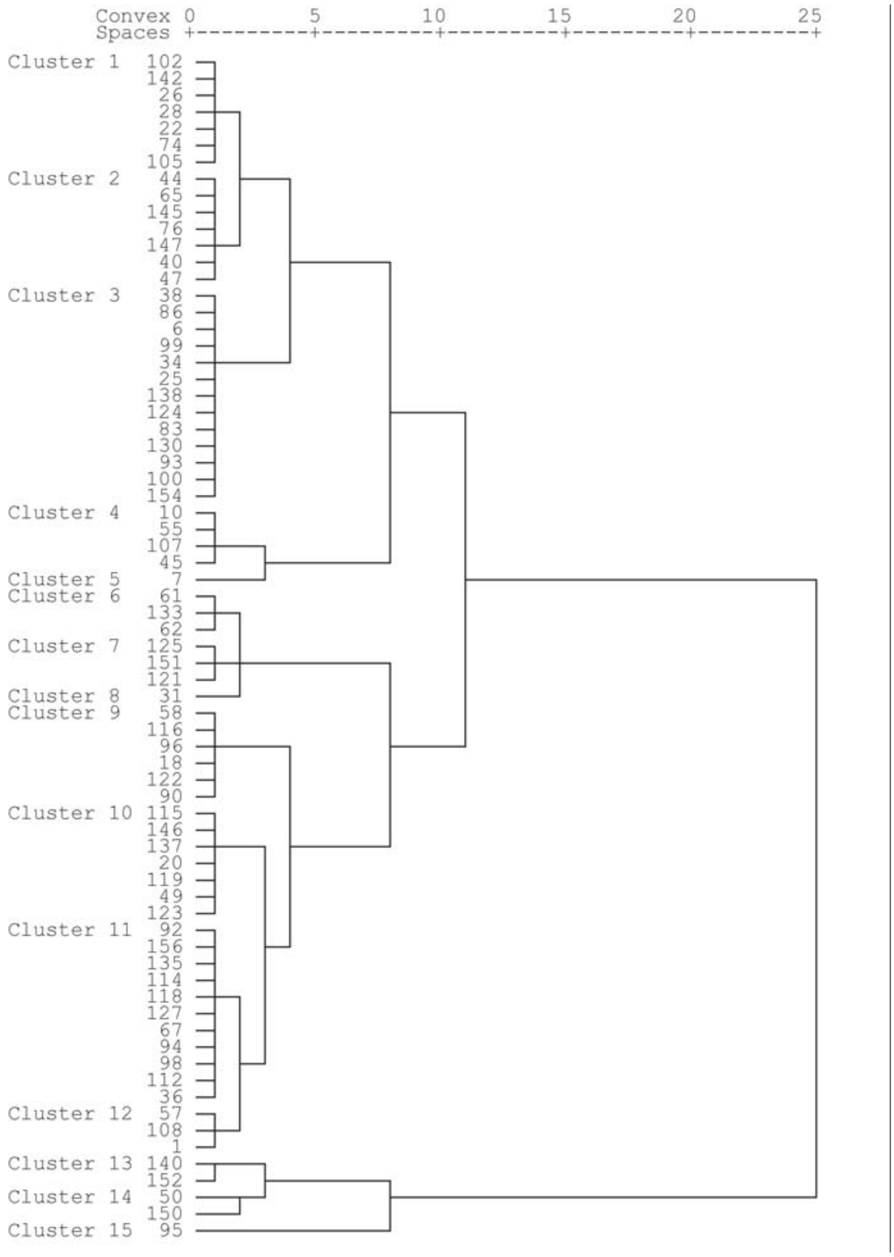

Figure 6: Dendrogram of UNSW convex space proximities based on the selected variables.

The second major division is between clusters 1-5 and 6-12. Key differences include area: spaces belonging to the former group are on average half the size of those comprising the latter. Mean values for isovist area, perimeter and maximum radials for clusters 1-5 (32 spaces) are also about half those for clusters 6-12 (34 spaces). Convex spaces in clusters 6-12 are generally better connected and integrated, more controlling and controllable and convex area/isovist area is significantly higher, suggesting greater access to visual information. Despite lower than average connectivity and integration, the spaces comprising clusters 1-5 are more likely to be places to move through rather than stay in. Clusters 6-12 include a number of transitional spaces, but also a significant proportion of destination spaces. Table 2 examines clusters 1-12 in more detail.

Figure 7: Mapping of convex space clusters to the UNSW urban structural unit.

No.	Key attributes of clusters	Typical examples
1	Isovist compactness nearly twice the dataset mean; maximum radials value less than half the mean; local integration significantly lower than average.	Semi-enclosed transitional spaces (minor routes, delivery areas).
2	As above, spaces generally smaller, R*n* and R3 lower.	As above.
3	Generally larger, more connected and integrated and contain more extensive isovists than 1 and 2; above average skyline and surface *D* values.	Includes several courtyard destinations' as well as movement corridors; significant vegetation.
4	High *D*; integration significantly lower than average.	Vegetated courtyards / culs-de-sac.
5	Highest isovist compactness and lowest d_i^{max} and integration for the dataset; a_i/a_c ratio close to one (i.e. complete intervisibility).	Single space (#7), a spatially isolated although well used courtyard.
6	a_i/a_c values about three times the dataset mean; isovist compactness very low; d_i^{max} twice the mean; isovist, skyline and surface *D* well above average.	Spaces located between buildings, i.e. movement corridor 'pinch points'; complex views
7	As above, but smaller spaces and lower d_i^{max}.	As above.
8	As above, but poorly integrated, and particularly high surface *D*.	As above (single space, #31)
9	High connectivity and control (twice the mean); relatively high controllability and integration; average $a_i/a_c < 1$ (internal views obscured by vegetation); *D* > average.	Existing (#18 & 96) and potential passive recreation spaces (#90, abutting student housing and #122, currently a car park).
10	Convex and isovist measures close to average; all three *D* values below average; d_i^{max} and a_i/a_c relatively high.	Small / transitional spaces, relatively extensive views.
11	Slightly higher than average connectivity, R*n*, R3, controllability, and isovist compactness; slightly lower values for isovist area, perimeter and d_i^{max}.	Includes main quadrangle (#94), Library lawn (#36) and other key campus "people places" (#67, 98, 135).
12	Slightly below average values for convex metrics and isovist compactness; lowest values of the dataset for a_i/a_c; D_i and skyline *D* quite high.	Vegetated spaces; diverse functions – car park (#1); cafeteria forecourt (#108); landscaped building entry (#57).

Table 2: Attributes and examples of spaces comprising clusters 1-12 of the campus USU.

5.2 Factor analysis of the variables

A principal axis factor analysis was conducted to investigate the relationships among the 14 variables. This method is commonly employed where the objective is interpretation of the factors rather than simple data reduction. Rotation of the factor axes accentuates differences between factor loadings by redistributing the variance, which increases interpretability. Oblique rotation provides information about the extent to which the factors themselves are correlated and is regarded as better suited to obtaining theoretically meaningful factors (Hair *et al*., 2006). A direct oblimin rotation, considered the standard method for non-orthogonal solutions (Darlington, 2004), was applied to the initial factor matrix. The SPSS default delta setting of zero (most oblique) provided the clearest solution in terms of factor loadings. The first four factors explain 75% of variance, 66% after rotation. Factor loadings on the variables > 0.75 are regarded as strong, 0.6-0.74 as moderate and 0.45-0.59 as weak.

Factor 1 loads strongly on convex area, isovist area and isovist perimeter, moderately on isovist *D* and weakly on d_i^{max}. It may be interpreted as a composite measure of the size of a convex space, how much can be seen from its centroid with respect to surrounding surfaces and the mix of near and distant views.

Factor 2 loads moderately on a_i/a_c, with a weak negative loading on convex area and weak positive loading on d_i^{max}. This factor is difficult to interpret, but may reflect the degree to which views are restricted within a given convex space or extend beyond that space.

Factor 3 loads strongly on control, and moderately on convex connectivity, controllability and integration R3. Recalling the role of control and controllability in terms of the spaces a given space can 'see', and that connectivity by definition measures how well convex spaces are linked, Factor 3 may tentatively be interpreted as a synthetic indicator of *configurational* (as distinct from *informational*, or content-related) legibility.

Factor 4 loads strongly on skyline *D* and weakly on surface *D*, and can be interpreted as a measure of the three-dimensional diversity of the view from the convex space centroid.

The factor analysis suggests that for this sample of convex spaces, the area of the space and the dimensions of the isovist associated with its centroid (including fractal dimension), and convex connectivity, control and controllability are the most significant variables in differentiating the convex spaces. Convex integration and fractal dimension are less significant for this dataset, and the presence of vegetation appears to be the main determinant of both skyline and surface *D*. These results are obviously site-specific, and analysis of the results from a diverse range of USUs is required to justify any general conclusions.

6. Discussion

The number of convex spaces in a system is by definition equal to or greater than the number of axial lines, and normally will be significantly greater (in this research the ratio is about 1.77). The campus convex analysis suggests that this larger number of entities reveals more of the fine structure of the open space network *at USU scale* than axial analysis, where the value of a given axial line is effectively the average of the values of the convex spaces through which it passes. Convex analysis appears to identify real distinctions between spaces, from the perspective of the occupant inhabiting and moving between them. For example the role of the main quadrangle as a global integration hub or the local differentiation between sections of the University Mall are not apparent from the axial representation described in a previous study (Osmond, 2007). Hanson (2000) suggests that convex analysis is linked to the inhabitant's view of a space whereas axial analysis relates more to the visitor's view, which is consistent with the above findings. Similarly, Cutini's study of Tuscan settlements (2003) suggests that the intrinsic visual connectivity *within* a convex space provides the configurational basis for potential human co-presence and interaction at that specific scale.

The overall ambience of an urban structural unit depends on the interaction of many properties, both quantitative and qualitative. Convex analysis enables the comparative evaluation of physical permeability, or efficiency of movement. The distribution of convex space areas provides a signature of configurational diversity, the extent to which the campus layout offers spaces of varying extent to accommodate diverse types of interaction. In addition, factor analysis suggests that convex connectivity, control and controllability in combination may reflect the configurational legibility of the USU.

A central proposition of this paper is that convex decomposition provides a framework to apply a variety of methods *additional* to convex analysis. Point isovist analysis as adapted here measures the amount of space and surfaces, the distance, intervisibility and complexity of views seen from the convex space centroid. In general, the distributions of these metrics reflect the visual diversity of the campus USU as a function of its layout. In particular, isovist fractal dimension appears to afford a convenient indicator of this property at a fine grain. Visual permeability is clearly associated with isovist maximum radial values, and visual *stimulance*, in the sense of exposure to new information inherent in the surrounding environment - Salingaros' (1999) *information field* may be evaluated in terms of isovist area and perimeter.

The fractal dimensions of fisheye images of skylines and surfaces give separate indicators of visual diversity: the former with respect to the heights and outlines of surrounding buildings and vegetation; and the latter with respect to the complexity of foreground and surface elements. A more visually diverse environment - without verging on the chaotic - is generally regarded as more legible (e.g. Bentley *et al.*, 1985) and more intrinsically stimulating and information-rich than one in which all views are similar. So the fractal dimension, particularly of surrounding surfaces, may also capture aspects of *informational* (as distinct from configurational) legibility and visual stimulance. The capacity to disentangle these properties is dubious; *D* is best understood as a composite metric, which reflects several interrelated qualities, of which visual diversity appears dominant. It must also be emphasised that the *D* value of a digital image is contingent on the choices made in processing and analysis. Fractal analysis is predicated on *comparison* - the numerical values thus obtained are relative, and meaningful only within a consistent methodological frame of reference.

7. Conclusions

The objective of the present research was to test the idea that convex decomposition of a defined urban area - an urban structural unit - offers a viable basis for a variety of methods relevant to investigating the physical and psychological qualities of the urban environment. The case study USU is a densely built university campus, which represents a particular type of urban environment, but as noted in the introduction the intent of the USU framework is to enable transferability of analytical methods. These can include methods additional to those of space syntax; thus convex decomposition can provide a common spatial denominator - the convex space - to connect, separate but complement research frameworks for extracting information from the built environment. Just as the *plot* represents the basic unit of urban form for a range of studies in urban planning and design, land economics etc, the convex space may be utilised as the basic unit or 'atom' of analysis to support investigation of various aspects of urban ambience.

Application of three methods relevant to this objective - convex, isovist and fractal analysis - provides useful insights into physical and visual permeability, configurational and informational (or visual content-related) legibility, visual diversity and stimulance (exposure to new information) associated with the case study site. Further, selection of the convex space as the starting point for analysis, as distinct from subjectively or randomly selected locations, enables specific instantiations of the above properties to be associated with specific convex spaces. This in turn enables the characterisation of an urban environment in terms of the properties of its constituent convex spaces. The present research indicates that at urban structural unit (roughly, 'neighbourhood') scale, application of these methods appears to identify real distinctions among convex spaces from the perspective of the occupant inhabiting and moving between them. Identification of the convex space as the basic evaluative unit should also facilitate comparison *between* USUs.

It should also be noted that the three methods applied here represent just a fraction of the potential utility of the convex space, both in relation to space syntax (e.g. Hanson's exploration of urban morphological transformations over the past century, 2000) and in fields as apparently remote from space syntax as urban climatology, which considers *physical* ambience (Osmond, 2009).

This research concludes that convex decomposition at neighbourhood scale offers a viable basis for comparative evaluation of a variety of significant urban ambience properties. Behavioural observation shows that in the case of the study site, convex spaces, which score highly against measures of visual diversity, permeability, legibility etc tend to function well as 'people places', which encourage social encounter and/or efficient movement. Conversely, convex spaces which score poorly tend to be avoided. On the other hand, there are high scoring spaces which are also avoided, generally because they have been given over to low-quality uses such as loading areas or car parking. Evaluation thus, informs opportunities to match uses to spaces through planning and design intervention.

Finally, the research presented in this paper is essentially exploratory, and like any exploration, it generates as many questions as answers. The emphasis has been on quantitative metrics, which limit evaluation of urban ambience to those aspects to which a number can be attached. The overall ambience of an urban environment is a synthesis of many properties, both quantitative and qualitative. Identification of numerical values for properties, which depend on human perception and cognition is suggestive, but intrinsically insufficient, and ultimately dependent on correlation with the outcomes of qualitative environment-behaviour research.

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