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Measuring the homogeneity of urban fabric using 2D geometry data

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Abstract

To preserve the urban fabric or characteristics in specific quarters, there is often a need to either strengthen or lessen the homogeneity of the urban fabric when inserting new buildings. Evaluating the form of urban fabric is fundamentally important for urban design practice and relevant policy making. However, the quantitative methods and attempts are rare due to the lack of available methods. To address this deficiency, this article presents a GIS-based method to measure the homogeneity of urban fabric by extracting attributes directly from the geometry of 2D building footprints, including the angles between buildings, areas of building footprints, and distances between buildings. These attributes are calculated for separate overlaid grids in the open space between buildings, where each grid holds the measured values for one attribute. We test the method on a prototype, which we applied on four real sites using OpenStreetMap data. The results show how to categorize different kinds of urban fabric based on the new measure

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of homogeneity. The method can be used to interactively inform urban planners how new design proposals would affect the homogeneity of a neighborhood. Furthermore, the measure can be used to synthesize new design variants with a defined homogeneity.

Keywords
Spatial analysis, homogeneity, urban design, geographical information systems

Introduction

The urban fabric, commonly represented as a plan of the urban form seen from above, has been an important research subject for many decades in urban design and other architecture-related disciplines (Caniggia and Maffei, 2001; Conzen, 1960). Studies of urban fabric became more important as modern cities began to suffer from fragmentation caused by arbitrary building types, interruptions to pedestrian flow, and leftover spaces, both inside and outside the city (Trancik, 1986). Modern cities are losing the order that was kept over centuries in ancient traditional cities (Alexander et al., 1987), where individual parts would fit the overall pattern, and order emerged because every component, although distinct, was compatible with the whole. All the parts served a common purpose and growth was symbiotic (Alexander, 2002). Rowe and Koetter (1984) criticized modern city planning that sacrificed organic urban fabric in favor of modern buildings that stood out ostentatiously as objects rather than melding into the background of a city. In addition, the visual qualities of urban space—its building types, open spaces, street scenery, and so on—likewise distinguish cities and quarters from one another (Proshansky et al., 1983). This suggests that it could be possible to devise a quantitative method to study urban fabric through its size, shape, form, and relative allocation as a whole (Nasar, 1990). When proposing new schemes, designers need to address these and other requirements to harmonize with the existing building fabric. However, the complex formal relationships within the urban fabric are not easy to understand, due to a lack of suitable tools (Ratti and Richens, 2004).

This article provides a GIS-based technique that is capable of determining the homogeneity of urban fabric. The method presented employs GIS raster analysis techniques and open source data (OpenStreetMap, 2014) to help urban designers analyze the degree of homogeneity of existing urban configurations. Moreover, this method can help designers interactively determine how a new design proposal would affect the homogeneity of the surrounding urban configuration in the early design stages. The area affected by the introduction of a new building geometry could be automatically detected using this method, and homogeneity variations could be shown.

To describe the development of our method of measuring homogeneity, we begin by presenting an overview of the state of the art of urban homogeneity and the theoretical basis for our method. We then introduce a general concept for measuring the homogeneity of urban fabric and follow this up with an explanation of its implementation in GIS. We implement this method in a case study, and present an evaluation of the results. Finally, we discuss possible improvements and further future areas of application.

State of the art

The concept of homogeneity was discussed by Lynch (1960), who studied how observers experience the configuration of their city. He listed five visual elements: paths, edge, landmarks, nodes, and districts. From his point of view, these are easily identifiable elements that people use to create a mental map of a city and a cognitive image of its configuration. He called these qualities legibility and imageability. To test this idea, Lynch took three exemplary cities (Boston, Jersey City, and Los Angeles) as case studies. Lynch defined imageability as a quality of the physical environment that evokes a strong image to an observer: "*It is that shape, color, arrangement which facilitates a kind of vividly identified powerfully structured, highly useful mental images of the environment*." Among these five visual elements, a district is defined as a part of the city, which presents some common visual and functional characteristics. They are defined by Lynch as "*relatively large sections of the city distinguished by some identity or character that one can mentally enter, and which can be recognized internally and perhaps also used as an external reference*." For Lynch, homogeneity is considered as one of the important traits that distinguish districts from one another. A highly imaginable city or district is well formed and is instantly recognizable to people who have visited or lived there.

For Alexander et al. (1982), the quality of urban space has a strong influence on how people sense the urban environment in daily life. He considered homogeneity as an important measure of urban space quality and a key factor for achieving organic order. His intention was to keep a certain degree of continuity in the urban configuration while avoiding too homogenous structures where everything looks the same. He developed 15 properties to describe organic order, some of which are directly or indirectly related to the concept of homogeneity, such as levels of scale, alternating repetition, graded variation, and not-separateness (Alexander, 2002). To achieve these principles, a balanced range of sizes of entities with small-scale jumps between adjacent ones are required. Some degree of variation was held to enhance the richness of a neighborhood, but it should stay within a certain range. Exceptions may exist as important buildings or landmarks, but they should be intentionally placed and well integrated into their surroundings. Alexander's concept is predominantly descriptive, and he proposed neither a precise definition of homogeneity nor quantitative methods for its measurement.

The concept of homogeneity was also discussed by social scientists as an important issue for social well-being to help people relate themselves to specific places (Omer, 2007; Skjaeveland and Garling, 1997). Omer (2007) argues that when people experience homogeneity in their neighborhood, they have a positive connection that can help to maintain a sense of attachment. The physical (built-up) environmental properties, such as land use, street pattern, house type, and identifiable boundaries, play a key role in contributing to the identity of a neighborhood (Golledge and Stimson, 1990).

All of the above indicate that homogeneity has frequently featured in the qualitative description of urban form, alongside aesthetics, visual identity, or imageability. Nevertheless, there have been few attempts to translate this concept into quantitative measures. One such exploratory experiment was conducted by Choay (1985) who investigated whether the homogeneity of the urban fabric can be identified by the repeatability of the geometric forms it contains, and used building facades for investigation. Maïzia (1999) argued that cities are distinguished by a certain morphological homogeneity, and attempted to develop a method of measuring the homogeneity of building facades without tapping into the homogeneity of building layouts. Another attempt was conducted by Dalton and Bafna (2003), who used spatial notations such as axial lines to try and detect Lynch's five visual elements in Boston. Later on, other quantitative measures of Isovists and Isovist properties were used (Batty, 2001; Benedikt, 1979) to simulate the impact of building layout on people's movements and behaviors (Peponis et al., 2003). Morello and Ratti (2009) introduced a method using DEMs (Digital Elevation Models) to interpret the visual elements defined by Kevin Lynch. While the main idea was also based on calculating Isovist properties, it was not expressly concerned with the notion of differentiating homogeneity or deviation within a study area.

According to Ratti and Richens (2004), the reason for this situation is a lack of tools for analyzing 2D urban configurations with respect to the resulting spatial quality. They argue that apart from Hillier's (Hillier, 1996; Hillier and Hanson, 1984) Space Syntax method for investigating urban configurations, most other tools have been developed either to assist individual building analysis, or to simulate environmental forces such as wind, heat, light, or sound. The application of such methods for building compositions and their influence on the urban fabric are comparatively rare.

In recent years, as a result of the advancement in computational technologies such as geographic information systems (GIS) and spatial analysis, the idea of quantifying the qualities of urban space has become more realizable (Ewing and Handy, 2009; Franz and Wiener, 2008; Gil, 2012; Golledge and Stimson, 1990; Singh, 1999). GIS provides tools used to retrieve and explore the spatial relationship of urban structure inherent in space (Singh, 1999). Ratti and Richens (2004) use GIS raster analysis to measure geometric parameters and predict several aspects such as shadow casting and sky view factors. Their results show the possibility of using a raster-based urban model to inform planning and design. Llobera (2003) uses raster analysis to develop a visual scape concept. In this method, he extended the traditional GIS viewshed (Isovist) analysis to provide a better description of the structure of visual space using two parameters: prominence and exposure. As a data source, OpenStreetMap provides worldwide maps with various levels of detail and rich attributes assigned to the different urban features (Curtis et al., 2014). In this context, a feature is an element like a street, plot, or building used for the representation of urban structures in GIS.

Concept

The simplest representation of urban fabric is a 2D plan of building footprints. The building footprint provides an immediate and intuitive gestalt of the urban fabric. Formulated by psychologists during the 1920s (Wertheimer, 1924), the Gestalt principles of perception offer a series of rules that explain how the world is perceived in terms of coherent objects and forms rather than just as a series of unrelated items. For instance, according to the 'figure-ground' concept of the Gestalt principles, a patch of one color or texture in the middle of another color or texture, tends to be perceived as an 'object' and is afforded greater significance than its surroundings. In simple terms, it is often felt to stand out. Following this principle, the building footprint size along with the distance between buildings exerts an influence on the formation of the Gestalt of urban fabric. Using 2D building footprints from OpenStreetMap Haklay (2010), we could therefore view the urban fabric as collective building patches in abstraction. The outline and size of building footprints can easily be distinguished from one another. To normalize different shapes of building footprints, we split the outline into independent edges. According to some psychological studies (Bülthoff and Edelman, 1992), differences can be captured uniquely by identifying sequences of angles (Kimia et al., 1995; Mi et al., 2009). In the following proposal, we therefore introduce the three measures, *the angle between buildings*, *building footprint size*, and *the distance between buildings* as three means to measure the homogeneity of urban fabric.

Angle between buildings

Building orientation affects the overall configuration of a district. A building's orientation is defined by its bounding edges. There are three prototypes for building angular edges as shown in Figure 1, which are (a) parallel (0), (b) perpendicular (90), and (c) any other angle between 0° and 90° (the angle of each edge is measured counterclockwise starting

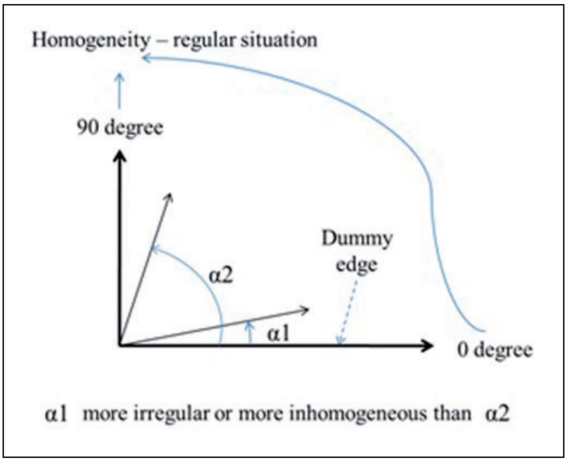

Figure 1. Building edges orientation and homogeneity status.

from the east of the standard coordinate system). For illustration purposes, it is assumed that there is a dummy building edge at 0° angle. If the angle between the building's edge and dummy edge is exactly 0° or 90°, a configuration is considered the most regular or most homogeneous situation, because it is closest to the regular condition, which is either parallel or perpendicular. On the other hand, if the angle between them is slightly larger than zero, this case is considered to be more inhomogeneous ($\alpha 1$) than ($\alpha 2$) in Figure 1. For the sake of simplicity, all measured angle edges should be between 0 and 90. Consequently, the actual measured angle was adjusted to lie within this range, i.e. by subtracting 90° from angles between 90° and 180°, or subtracting 180° from angles between 180° and 270°, or subtracting 270° from angles between 270° and 360°. The prototype assumes that there is high homogeneity at angle between building's edges that equal 0°, but that when the angle between edges is slightly larger than zero, the situation changes from highly homogeneous to highly inhomogeneous. As the edge angle increases, the degree of inhomogeneity decreases until it reaches the highest homogeneous case again at an angle of 90°. In the following test, we implement this principle for building edges rather than for a single building to calculate angular homogeneity. Although it seems that the angle index considers the angle of each edge on its own, it is able to indirectly consider the relationship between the angles of one edge to another. This is described in detail in the workflow section.

Building footprint size

For a given district, the building footprint is an important indicator of the degree to which buildings occupy the space of an urban configuration. Intuitively, the larger the footprint size of a building, the greater its mass in the urban fabric, and the greater its influence on its surrounding spaces, and accordingly in reverse for smaller footprints.

Distance between buildings

The distance between buildings indicates how far away each building is from its neighbors. This measurement is used to indicate the overall distribution of the buildings' relative locations in a group. For example, shorter distances usually indicate higher density and closer relationships between buildings, while higher distances denote greater spatial dispersion.

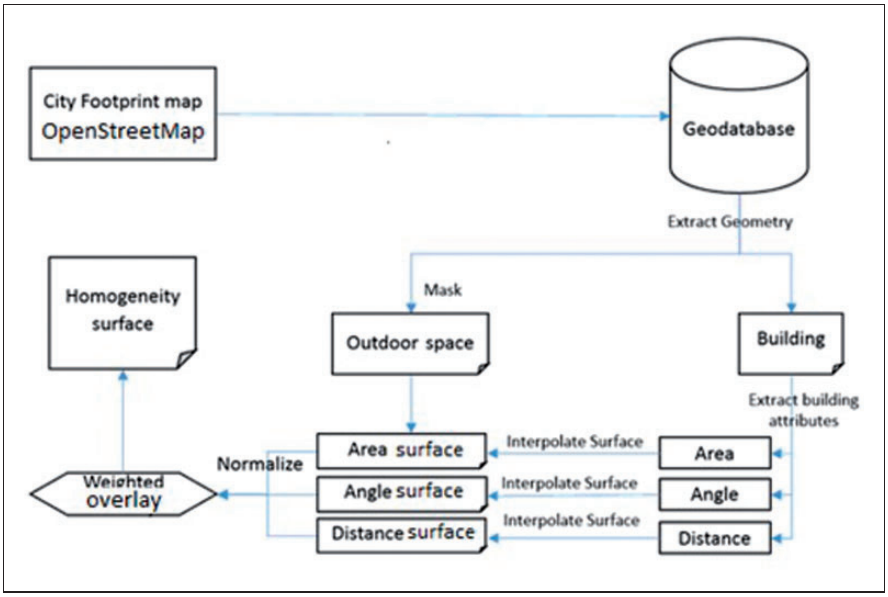

Figure 2. The overall workflow diagram.

Methodology

The schema in Figure 2 shows an overview of the whole process for measuring homogeneity. A step-by-step description of data extraction and analysis follows below. In the following section, we test our method using a simple prototype case of urban fabric.

Workflow

The methodology for detecting the homogeneity of spatial configurations employs raster analysis. The formal logic of raster analysis is known as Map Algebra (De Smith et al., 2007) and treats a spatial configuration as a continuous surface with a specific value at each location. The analytical steps are combined into an automated procedure. In the following, we present a detailed description of the procedure:

Step 1: Extract the attributes Angle, Area, *and* Distance

Angle. The Angle attribute is calculated for each line representing the edge of a building, as described above. The Angle is then normalized, so that the resulting values are in the range 0 to 1, where 0 represents the most regular case (0°, i.e. parallel or 90°, i.e. perpendicular) and 1 represents the most irregular case (slightly larger than 0°). The resulting values are used to interpolate a surface that represents the effect of the orientation of different building edges on the surrounding open spaces. The formula below is used to calculate the normalized *Angle* value:

$$Angle_{index} = \left(1 - \frac{Ang}{90}\right) \times \beta \tag{1}$$

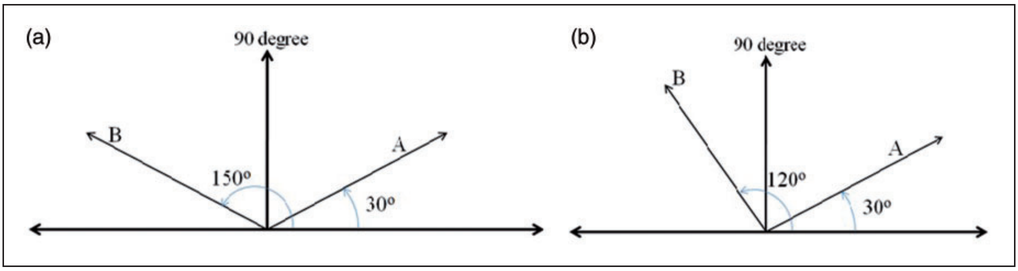

Figure 3. Indirect consideration of the relation between the angles of two edges (a) when the angle between edges is not 90° and (b) when the angle between edges is 90°.

$$\beta = \begin{cases} 0 \ \mathit{if} \ Ang = 0, \ 90 \\ 1 \ \mathit{if} \ Ang = \ else \end{cases} \tag{2}$$

Ang: is a specific edge angle (counter-clockwise) $0 \rightarrow 90$

$$\begin{aligned} &\mathit{If}\ 90 < Ang < 180, \quad then\ Ang = Ang - 90 \\ &\mathit{If}\ 180 < Ang < 270, \quad then\ Ang = Ang - 180 \\ &\mathit{If}\ 270 < Ang < 360, \quad then\ Ang = Ang - 270 \end{aligned} \tag{3}$$

$Angle_{index}$: represents the angle index value for each edge

Although the angle index considers just the angle of one edge, it is of particular interest to indirectly consider the relation between the angles of one edge to another by converting all angles to become between (0° and 90°). As shown in Figure 3(a), the angle index of edge A with 30° inclination (where east is 0°) is 0.666, and the angle index of edge B with 150°inclination (from 0°) is 0.333. The angle between the two edges A and B is 120°, which is deemed irregular based on the pre-specified prototypes. After conducting interpolation, focal statics and deviation calculations, the result at the end of the process indicates that the situation is inhomogeneous. Figure 3(b), on the other hand, shows an angle between edges A and B as 90°, which is deemed a regular case. Since the angle index of the two edges A and B are identical and equal to 0.666, the result at the end of the process, after conducting interpolation, focal statistics, and deviation calculations, is a deviation of 0, which indicates a homogeneous situation.

Footprint area. Area values are calculated for each building and assigned to the respective building's footprint as an attribute. The building footprint area values are also assigned to the building edges. The values are used to interpolate a surface representing the effect of building footprints on the surrounding open spaces.

Distance. We determine the impact of distance from each building edge to all its surrounding edges using the following procedure:

(1) Calculate the Euclidean distance from all points in the open space between buildings to their closest building edges. The Euclidean distance is the "ordinary" distance between two points that one can measure with a ruler. The distance functions describe each

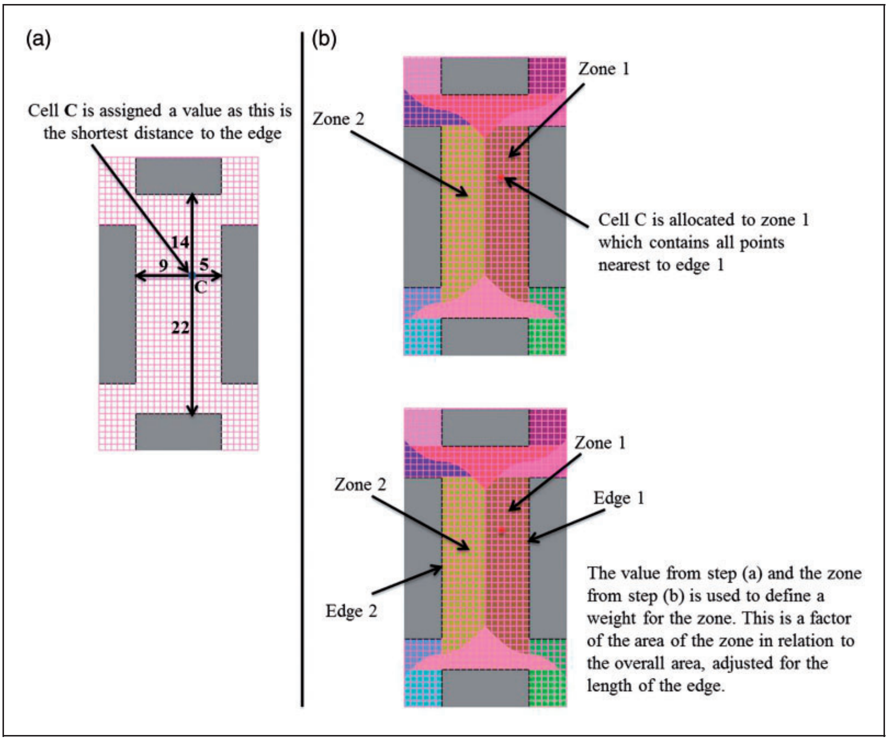

Figure 4. Distance attribute extraction process: (a) Euclidean distance function and (b) Euclidean allocation function.

location's relationship to a building edge. The distance output raster contains the measured distance from every cell to the nearest edge of the surrounding buildings (Figure 4(a)).

(2) Determine the zone for each building edge (Euclidean allocation). Here, the aim is to determine the open area closest to a given edge. A generated raster surface between buildings is divided into zones that describe the areas closest to the respective bounding building edges. Each of these zones is assigned a distinct zone ID and all cells within that zone are coded accordingly with the same value (Figure 4(b)).

(3) The area of each zone surface determined in the previous step is calculated and divided by the multiplication of the total area of the open space in the study area and the length of the building edge for that zone. The aim is to generate a weight value for each zone that describes the impact of distances between buildings enclosing an open space: the larger the weight of the zone, the greater the distance of the edge of the corresponding building from other building edges (equation (4)). The zone weight value is assigned to the edge of the corresponding building (Figure 4). The length of building edges is used to increase the impact of short edges and decrease the impact of long edges when conducting interpolation.

$$\text{Distance}_{\text{index}} = \frac{\text{Area of zone}_{\text{i}}}{\text{Edge length} * \text{Total zones area}} \tag{4}$$

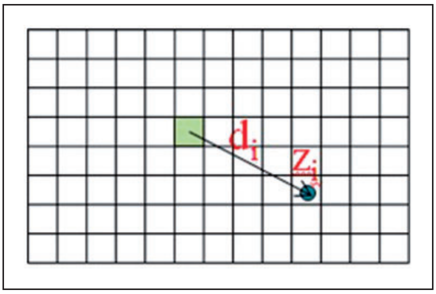

Figure 5. Inverse distance weighting (IDW) interpolation process.

Step 2: Create a surface representing the interpolated values

The potential impact of a building's edge angle, footprint size, and distance on the open space between buildings for each unknown cell can be estimated using interpolation techniques based on the principle that spatially distributed elements are spatially correlated. One of the techniques we used in this research is inverse distance weighting (IDW). To ensure the best cell estimated values are determined and that the results are reliable, the maximum number of points are used and their distribution within the site space considered. The average of the interpolated sample points is computed to estimate the unknown cell values as shown in equation (5). IDW assumes that each interpolation point has an influence that diminishes with distance. The closer the vicinity of a sampled point to the unknown cell being estimated, the more influence it has in determining the average as shown in equation (6). It is obvious from this equation that the diminishing in weight (influence of sampled point) will be greater in remote points rather than those in the vicinity as power value increases. Therefore, when the cell is too close to the edges with highest value, the effect at that cell will be high compared with those located far away from these edges. Figure 5 illustrates the equations (5) and (6) utilized for the interpolation process.

$$Z_k = \frac{\sum_{i=1}^{m} z_i w_{dik}}{\sum_{i=1}^{m} w_{dik}} \tag{5}$$

$$w_{dik} = \frac{1}{d_{ik}^{p}} \tag{6}$$

where Z_k is the estimated potential effect of *Angle*, *Footprint area, or Distance* for each unknown cell (k); z_i is the value of sample interpolated point (i); w_{dik} is the weight or influence of point (i) during averaging process; d_{ik} is the distance between the sample interpolated point (i) and the unknown cell(k) required to be estimated; p is the power value to be adopted, $p \geq 1$, it is used to be equal 2; m is the number of entire known points within the site under consideration that are used to estimate the unknown cell(k).

Step 3. Identify the deviation of the interpolated values for the surface created in step 2, from the mean values of the cell neighbors to determine the measure of homogeneity

To measure the extent to which the interpolated values at different locations are similar to their surroundings, we undertake a statistical measurement (called Focal Statistics ESRI

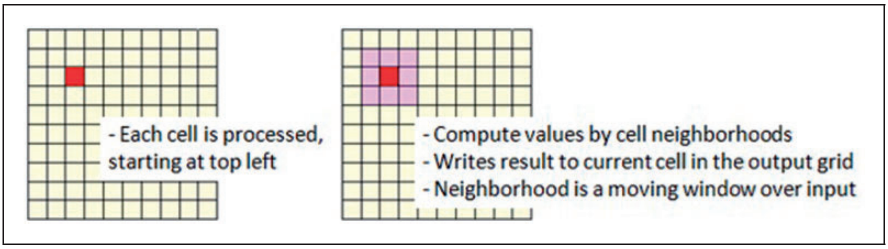

Figure 6. Focal statistics.

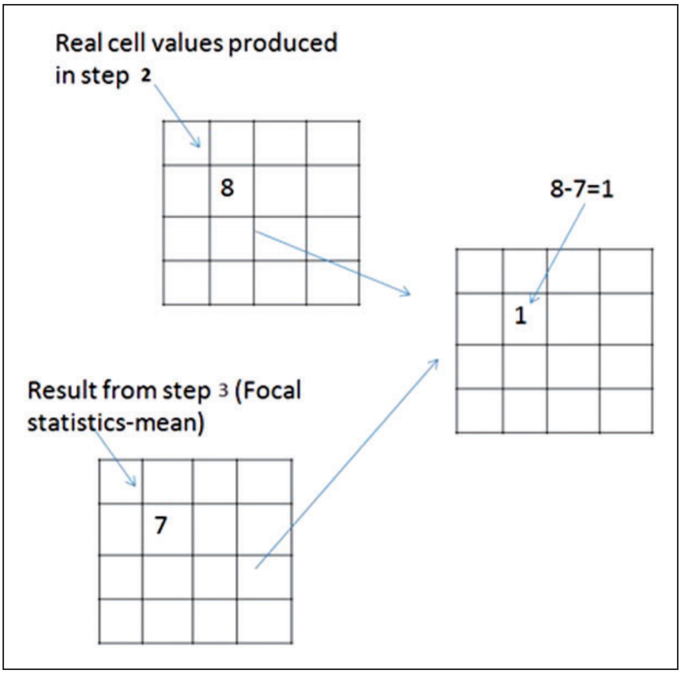

Figure 7. Detecting the deviation of cell values from the mean.

(2014), see Figure 6), to calculate the cell data based on the values of neighboring cells, and the mean of the values within a specified surrounding neighborhood for each cell location. The neighborhoods can overlap, so that cells in one neighborhood may also be included in the neighborhood of another considered cell. This results in a raster grid where each cell has the mean value of the neighboring cells.

To measure the absolute values of the respective cell's deviation from the mean, we subtract the mean value from real cell value (the raster surface produced in step 2) at every cell location (produced earlier in this step using the focal statistics function), resulting in a raster surface that expresses the deviation of every cell from its neighboring cells. The lower the result of the subtraction in each cell, the more homogenous that cell is with respect to its neighborhood (Figure 7).

To obtain a more general picture, we use block statistics to perform a neighborhood operation that calculates the sum value for cells within a fixed set of non-overlapping

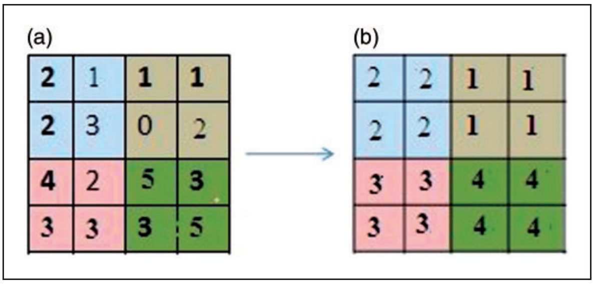

Figure 8. Block statistics: (a) input and (b) output after block statistics—sum.

areas or block. The resulting value for an individual neighborhood or block is assigned to all cells contained in the block. The block statistics method gives us a more generalized picture of value deviation in specific areas and consequently makes it easier to see the overall pattern of homogeneity across a district (Figure 8).

Step 4: Normalize the three surfaces for Angle, Footprint area, *and* Distance

To compare the resulting three surfaces for *Angle*, *Footprint area*, and *Distance*, we normalize them using equation (7). The aim is to obtain a coefficient that provides a meaningful relative value of homogeneity and in turn makes it possible to compare the degree of homogeneity of different urban configurations.

$$Normalized\ value = \frac{value_i - value_{min}}{value_{max} - value_{min}} \tag{7}$$

Testing the method

To test the method, we started with a simple very homogenous spatial configuration with respect to the three geometry parameters *Angle*, *Footprint area,* and *Distance*. We then intentionally made changes to the configuration to test the effectiveness of the method. Figure 9 shows the various test configurations. The background indicates the degree of homogeneity: dark green areas are very homogenous while red areas are very inhomogeneous. Figure 9(c) shows the result of the distance analysis. It is obvious that, although there are some biased values caused by the edges at the borders of the test configuration that have infinite distance, the result still represents the change in distance inside the prototype.

Case study

To demonstrate homogeneity detection, a real case study situation consisting of four different locations in the city of Zurich was analyzed (Figure 10). The data were obtained from OpenStreetMap (www.openstreetmap.org) and we selected sites with very clear edges that separate them from their surroundings. In sites 1 and 2 in Figure 10, the neighborhoods are separated by a railroad and main roads, whereas in sites 3 and 4 in Figure 10, the edges are formed by a river and highways. We intentionally selected sites with obvious discrepancies in their spatial configurations, because they make it possible to test our

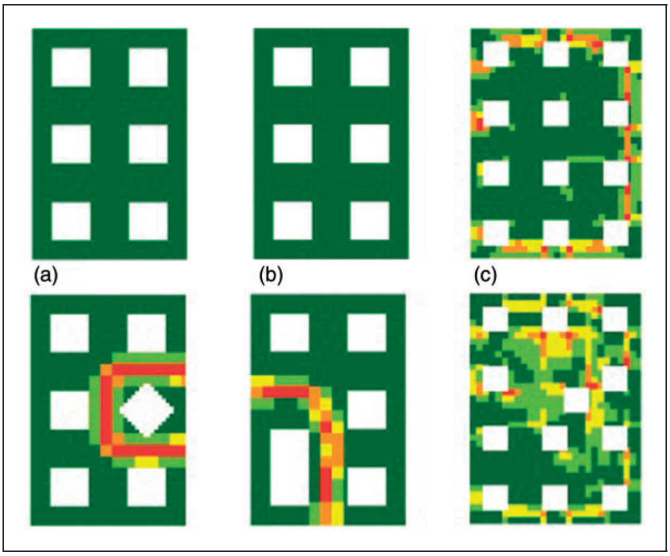

Figure 9. Prototype for testing the homogeneity analysis: (a) Angle, (b) footprint area, and (c) distance. The first row represents a homogeneous configuration and the second row represents an inhomogeneous configuration.

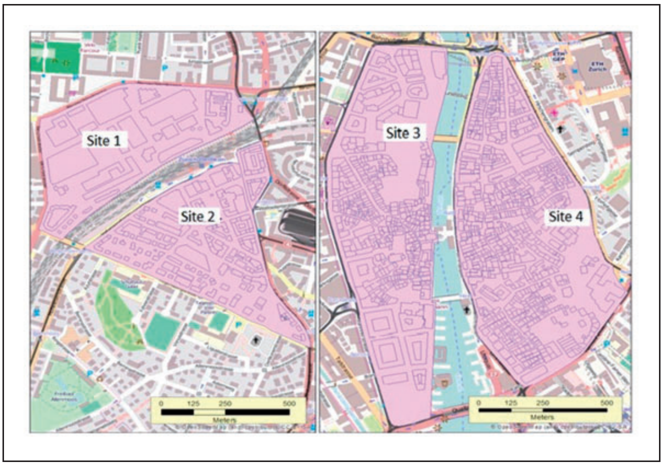

Figure 10. The study area sites in Zurich, Switzerland, sites 1 and 2 are in Oerlikon, sites 3 and 4 are in the old historic part of the city. The building footprints were obtained directly from OpenStreetMap and the site boundary was manually digitized.

homogeneity measurement method. Sites 1 and 2 are newly developed areas located in the Oerlikon district of Zurich, while sites 3 and 4 are located in the historic part of Zurich.

Evaluation

The homogeneity maps' results (Figures 12, 15, and 17) are represented as a raster surface with values for each cell. The value of cell shows, how much it differs from its neighboring

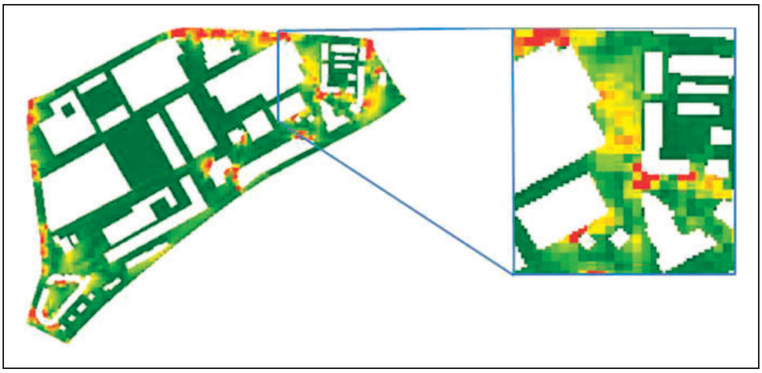

Figure 11. Angle homogeneity map. Interpolated map of edge angle values and detail showing section with significant changes (orthogonally arranged spaces are dark green).

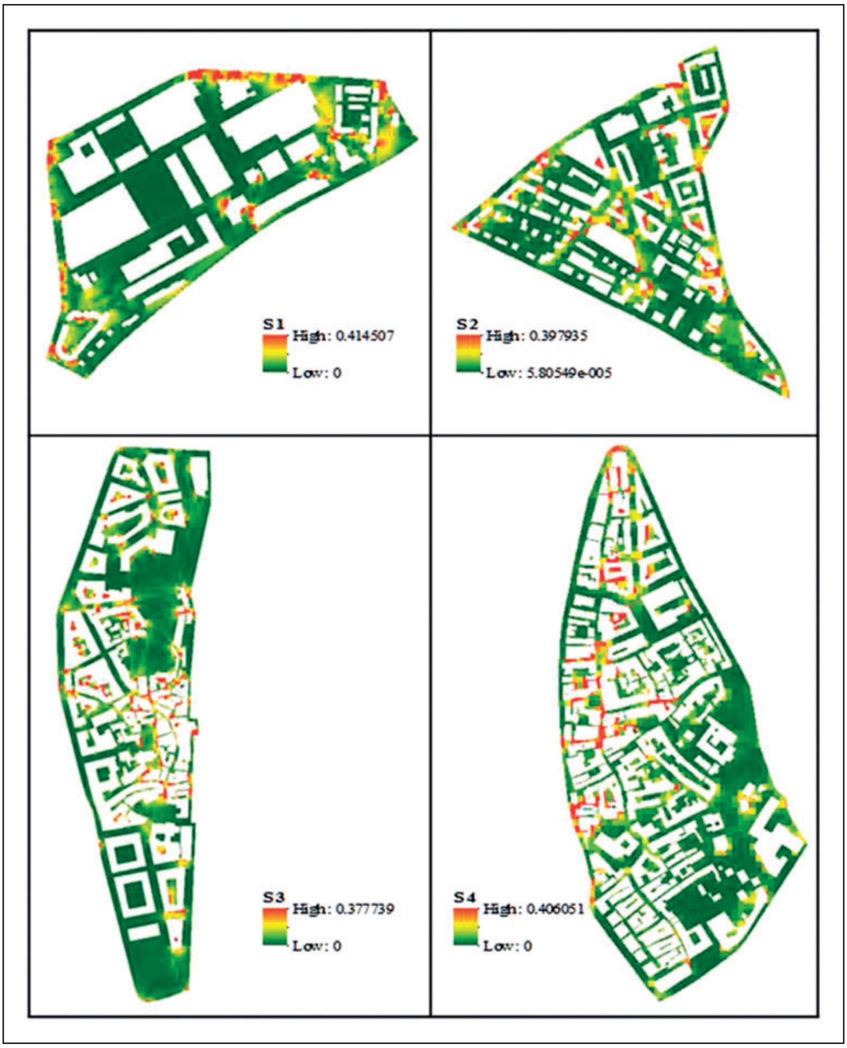

Figure 12. Angle analysis and the resulting analysis grid.

cells, in terms of the influence of the three predefined parameters: *Angles* of the building edge, building *Footprint* area, and *Distance* relation to other edges. Using the frequency chart and a boxplot, we were able to compare different sites to acquire a more general and extensive understanding.

The following part of the evaluation is a more generalized comparison of the four sites. The frequency charts (Figures 13(b), 16(b), and 18(b)) show the global distribution of values across the whole area and provide an indication of the existence and extent of inhomogeneous areas. The high existence of low cell values designates that most of cells have approximately similar values to their surroundings. The boxplot chart (Figures 13(a), 16(a), and 18(a)) is used to acquire a more precise comparison, since the median values provide an overall picture of the relative intensity and Inter Quartile Range (IQR) indicates the variance of inhomogeneity. Because the frequency charts are skewed to the right, the normal distribution has not been applied here. The variance is better represented using IQR values (Burt et al., 2009), as it provides us with variance values that are not biased by outliers. A higher IQR represents more dispersed values. The median values provide an overall picture of the relative intensity in cases where two comparison sites have similar IQR. The individual data sets could be visualized as boxplots arranged side by side on a common scale for better at-a-glance comparison. This can make even subtle differences apparent for further analysis.

Angle homogeneity measurement

Using the method introduced above, we can detect the distribution and intensity of differences, among spatial configurations in a given area. For the building edge angle, the map shows how much a space is influenced by its surrounding edge angles.

When the space is surrounded by building edges that are either parallel or perpendicular to each other, we call it an orthogonal arrangement—or homogeneous. When the space is surrounded by buildings that are not parallel or perpendicular to each other, we call it an oblique arrangement—or inhomogeneous. The angle homogeneity map (Figure 12) shows the degree to which a space corresponds to either a relatively orthogonal or oblique arrangement. Figure 12 shows the pattern in which cells deviate from their neighbors. For instance, cells with green colors indicate that they are surrounded by edges sharing similar angular index values (perpendicular or parallel), whereas cells with red colors indicate that they are surrounded by edges sharing different angular index values.

Looking at site 1 (Figure 11), we can obviously see and identify where there are building edges with significant changing angles. Figure 11 reveals the significance of the overall changing angle. If the surrounding angles are orthogonally arranged, the corresponding locations are shown dark green. Because of the IDW interpolation used to generate the angle map, even if the cell may be within oblique arrangement, some areas can be still homogeneous because they are very close to a certain edge and are primarily under its dominance, with little deviation for its angular index (marked as a red shape in Figure 11).

In Figure 12, site 1 presents large green areas with a high degree of homogeneity, while sites 3 and 4, by contrast, indicate a broad distribution of less homogeneous areas. According to the statistical results shown in Figure 13, the ascendant arrangement of the four analyzed sites based on the median value of angle inhomogeneity intensity is sites 1, 2, 3, and 4 (Figure 13(a)), and the ascendant arrangement of sites based on IQR of angle inhomogeneity is sites 1–4 (Figure 13(a)). The result also shows that the average intensity of obliquely arranged angles is low in sites 1 and 2, where buildings in these areas tend to have parallel or perpendicular facing edges. Low IQR indicates a higher concentration of cell

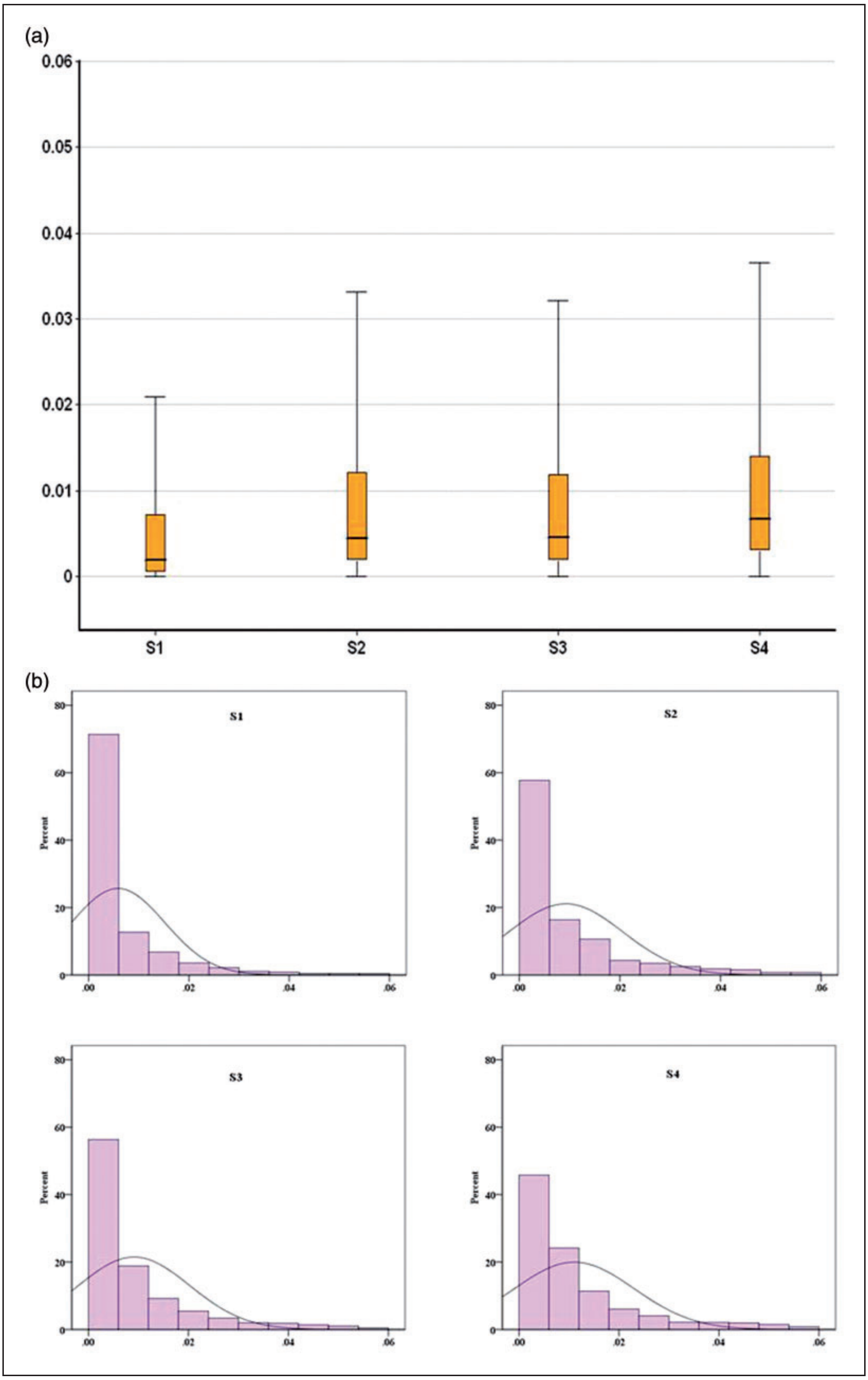

Figure 13. (a) Boxplot for the sites values and (b) the frequency of the angle values.

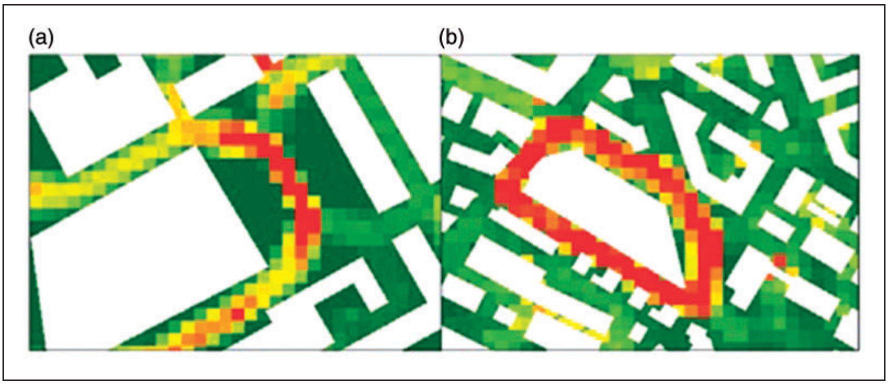

Figure 14. Influence of different building footprint sizes: (a) influence of big masses and (b) big mass difference and narrow open space.

value distribution. Moreover, the results display the average intensity of angular inhomogeneity for sites 3 and 4 (Figure 13(b)), which is higher than that for sites 1 and 2 (Figure 13(b)). So for sites 3 and 4, the sense of inhomogeneity caused by obliquely arranged angles seem more dispersed and deviated when walking in these areas.

Building footprint area homogeneity measurement (area homogeneity)

The area homogeneity map (Figure 15) can be used to detect both where and to what extent locations are surrounded by buildings with different footprints areas. Usually highly inhomogeneous areas can be found in the middle of spaces where buildings have different footprint sizes. In the homogeneity map, cells with high values are marked red in Figure 14(a) and (b), which indicated that the area has low homogeneity for the property footprint area. It shows significant differences within site 1, because most major spaces are filled high cell values (Figure 15). For site 2, some inhomogeneous cells appear in the middle and the upper part of this area. For sites 3 and 4, some of the bottom and upper parts of the spaces have inhomogeneous cells, especially in their core areas and nearby alleys, and only a few spaces around the monumental buildings exhibit high contrast cells. If the space around a location is large enough to contain some homogeneous areas alongside inhomogeneous area (as shown in the left in Figure 14(a)), low values are very close to a certain mass and are primarily within its dominance. But if the space is small or narrow, it means there is not enough room to show the differences (Figure 14(b)), so the space will be mostly covered by an inhomogeneous area.

The boxplot and histogram of site 1 confirm its conspicuous difference from other sites (Figure 16(a) and (b)). For site 1, the median value and IQR are much higher than other three sites, whereas site 2 has the lowest median value and IQR. Site 3 has slightly higher median value and IQR than site 2 (Figure 16(a)). The result also shows that the average intensity in site 1 is most significant since buildings with different footprint sizes correspond to each other. The difference in footprint size is less dispersed in sites 2 and 3, slightly ascendant in site 4, and most apparent in site 1. Therefore, the internal distribution of difference is most spread out in site 1, indicating a high potential contrast in the spatial distribution of low values to high values (high median and IQR). Figure 16(a) indicates that

Figure 15. Footprint area analysis and the resulting analysis grid.

sites 3 and 4 have a relatively similar degree of homogeneity, because small-scale houses account for the majority in these areas. For area homogeneity, site 2 seems to be most homogenous, both in terms of intensity and dispersion, as the result does not correspond to our initial expectation, where we supposed site 2 would be more similar to site 1, since both sites are newly developed areas. In site 1, business buildings, offices, and other complex buildings are mixed throughout the majority of this area, and have neither unified intentions nor similar footprint sizes. Instead, the pattern changes very incoherently to satisfy their own functions and needs. Generally speaking, historical areas tend to be homogenous for the building footprint size, and only some dominant buildings, such as a cathedral, library, or city hall, contrast with their surroundings, while the remaining buildings are regular in

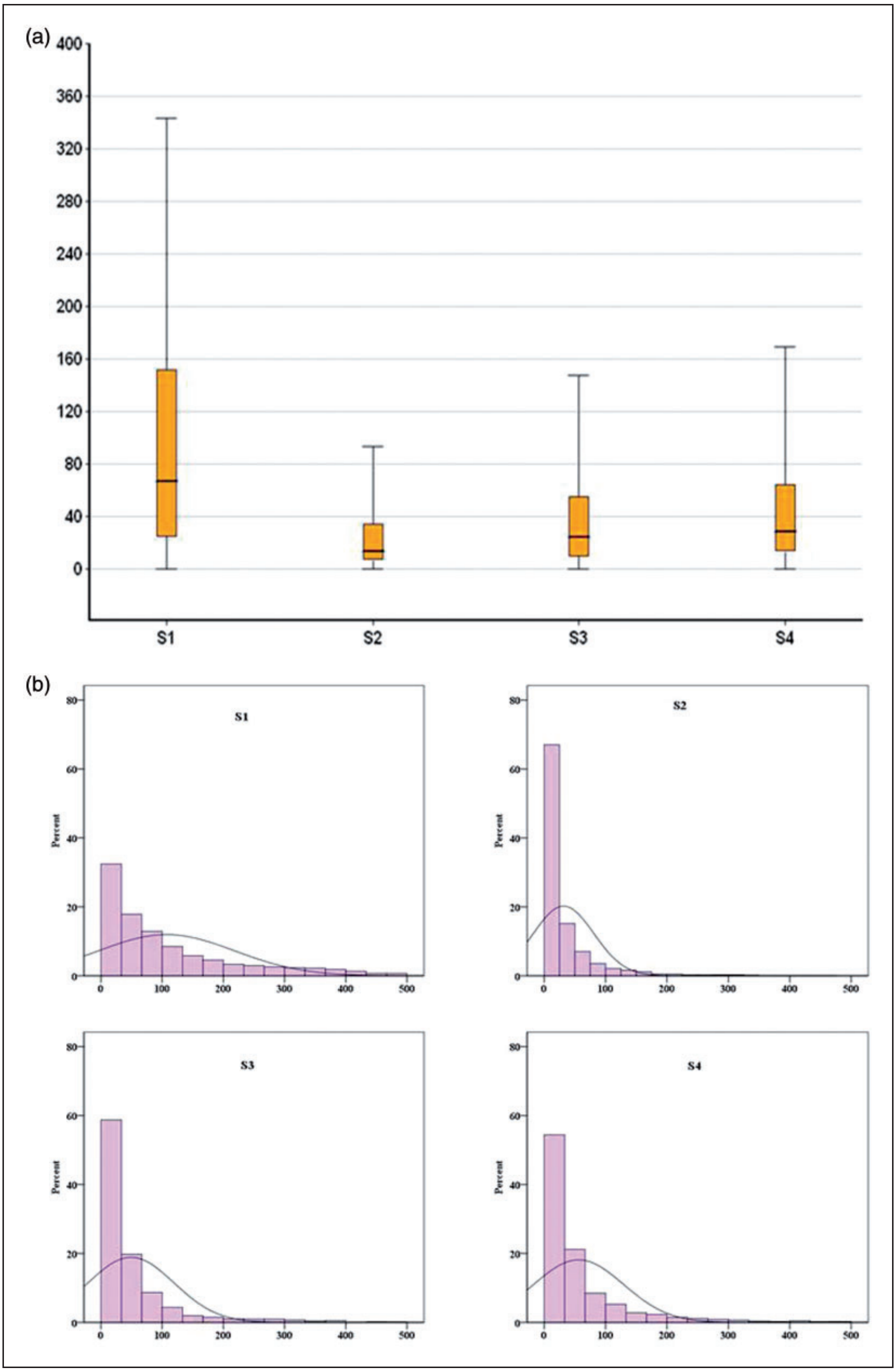

Figure 16. (a) Boxplot for the sites values and (b) the frequency of the footprint area values.

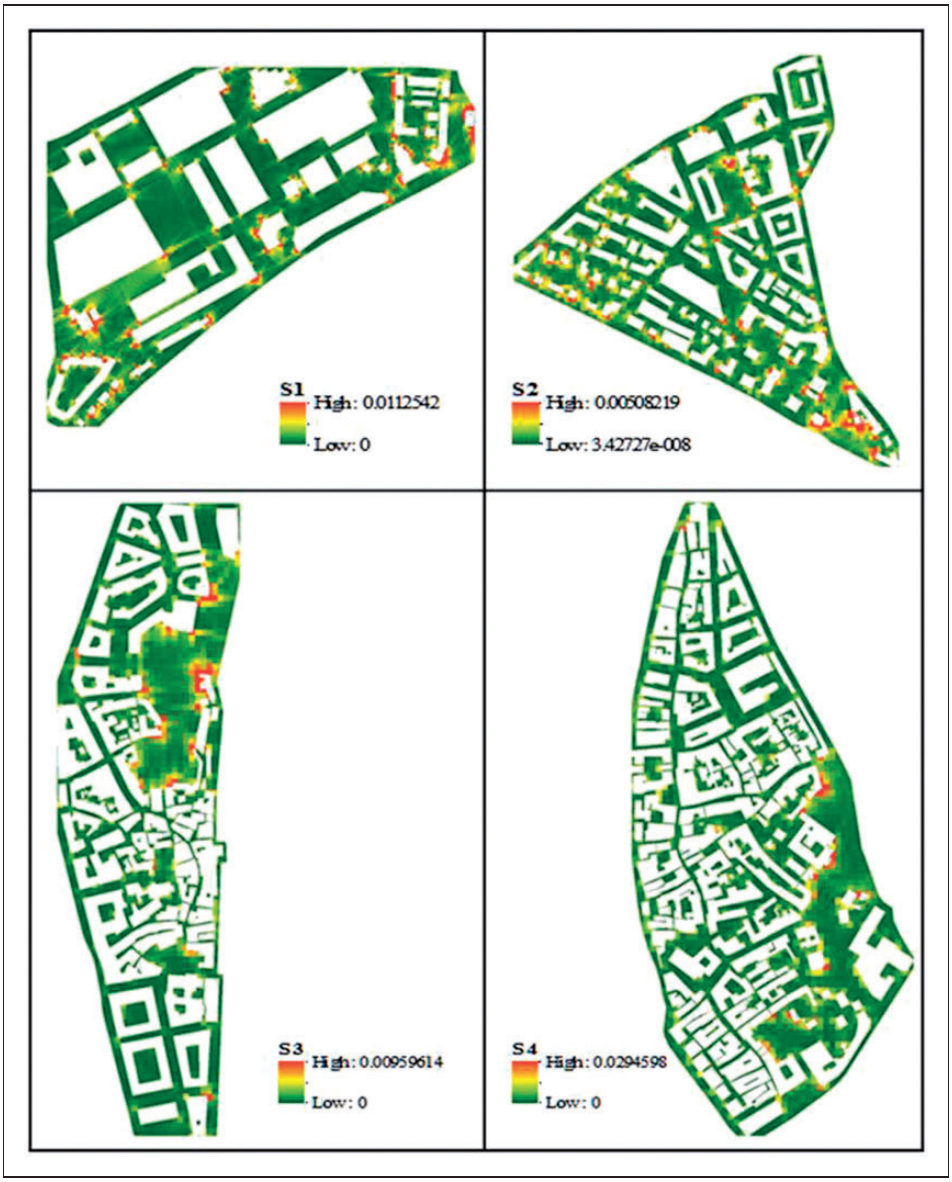

Figure 17. Distance analysis and the resulting analysis grid.

arrangement and coexist homogeneously with each other. They are not completely constrained by their function, but adapted to highly diverse functions such as shopping stores, restaurants, markets, and housing.

Distance homogeneity measurement

The *Distance* homogeneity map (Figure 17) is used to detect where and how the distances to surrounding building edges change. Cells with warm colors indicate that these spots have very varying distances to surrounding edges, while cold colors indicate that these spots have

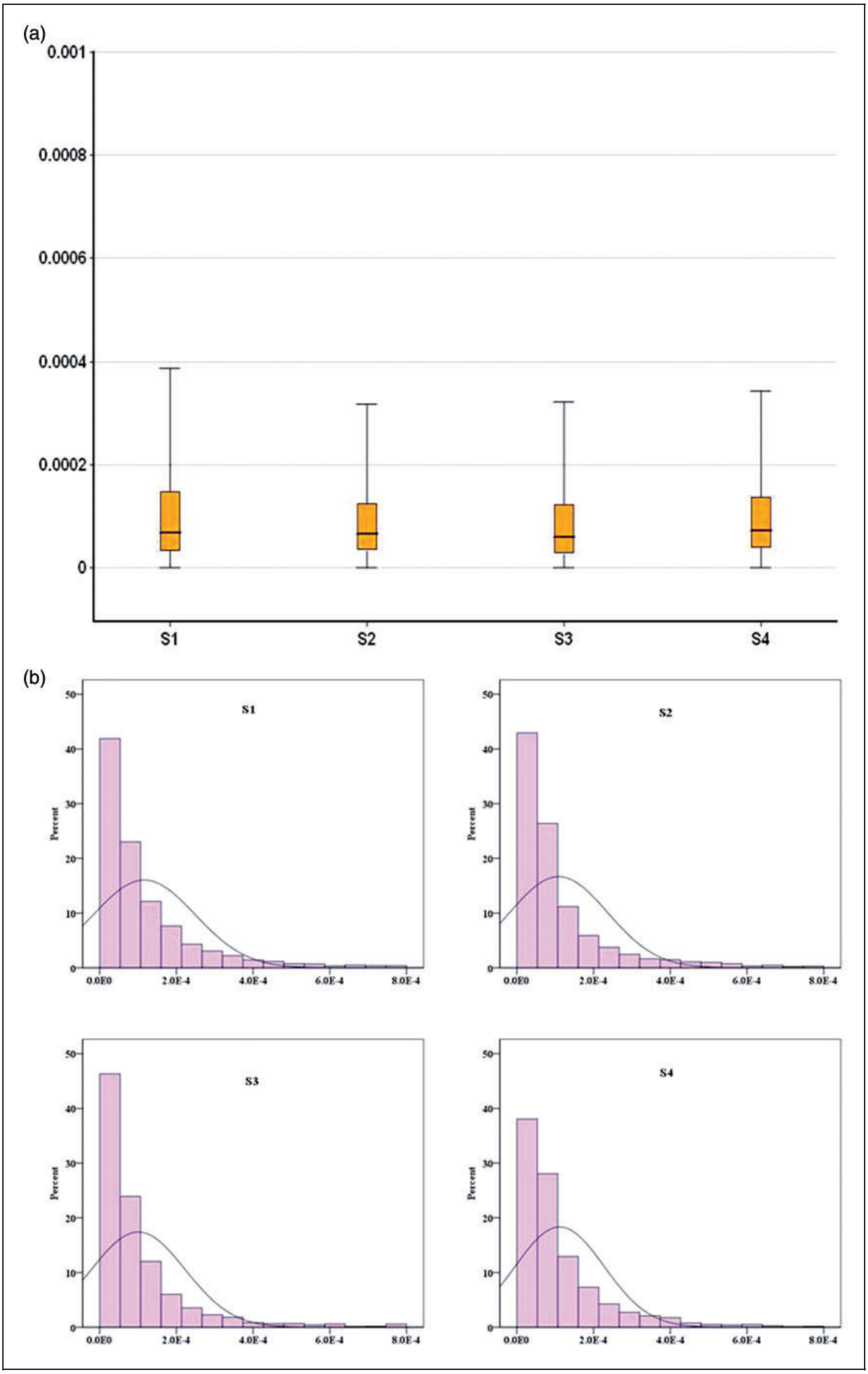

Figure 18. (a) Boxplot for the sites values and (b) the frequency of the distance values.

very similar distances to surrounding edges. We can tell intuitively that sites 1 and 2 are filled with more inhomogeneous cells. For sites 3 and 4, most alleys and internal streets are homogeneous except for inhomogeneous spots at the corners of site boundaries or around amorphous spaces that are poorly defined.

The histogram chart designates that there is a similar tendency of skewed distribution for the values (Figure 18(b)). From the boxplot chart, the median values of four sites are arranged ascendant from sites 3, 2, 4, and 1 (Figure 18(a)). Therefore, it seems that sites 1, 2, and 4 are slightly less homogeneous than site 3 for the distance metric. Site 1 is the most inhomogeneous area in this metric, since it has higher values for the median and third quartile than the other three sites. Site 3 is the most homogeneous one, with the lowest values for median and third quartile. Also, we can tell that sites 2, 3, and 4 have similar IQR values, and is more concentrated than site 1, indicating that the changes in the values are less pronounced and more continuous for sites 2, 3, and 4. As described in the previous section, site 1 mostly contains business buildings, offices, and other complex buildings with larger open spaces between them, either for environmental reasons or to facilitate public circulation. The resulting pattern of loosely organized shapes of different sizes is therefore more inhomogeneous for the building distance as well. While in sites 3 and 4, small buildings account for the majority of the area, they tend to adjoin each other. Both in terms of their size and spatial proximity, the spaces between them tend to form linear pathways of similar width, and the buildings also tend to wind along these paths as continuous shapes. Both buildings and spaces define each other simultaneously, and only a few open spaces are not well defined and cause a small degree of inhomogeneity as indicated by red or yellow colors in Figure 17.

Discussion and conclusion

In this article, a new GIS-based method is introduced and examined to assess homogeneity. Three predefined geometrical properties have been selected for this study as being suitable for representing the spatial configuration and potential identity of a district. By applying this method to four sites in the city of Zurich, we were able to visualize the intensity and distribution of specific homogeneity patterns that are a product of their spatial layouts. The results indicate that historical quarters with denser and smaller buildings tend to have more organic urban fabric with winding street systems. The angular homogeneity is therefore relatively low, but the area homogeneity and the distance homogeneity are influenced not only by the historical quarters but also by the function of the buildings. Finer urban fabrics tend to present uniform and continuous building-space interfaces in historical areas. This result could help to explain why people tend to perceive historical quarters as being richer without feeling disturbed by the fluctuating scale of the buildings and spaces in-between. On the contrary, in newly urbanized districts, the layout tends to be orthogonal with lots of leftover spaces dispersed throughout the city.

The results also show that the inhomogeneity values within all the four study areas are significantly skewed to the left when looking at the frequency charts, i.e. low values account for the majority rather than high values, indicating that similar values are more commonly seen in all the sites than different values. The result also indicates that people more or less follow certain rules when building cities as artificial works of human creation. This does not necessarily mean that the value of homogeneity should always be as high as possible to create better urban environments. In extreme cases, where every building in a neighborhood looks the same and has very similar spatial characteristics, it is more likely to result in monotonous rigidity rather than organic order. This suggests that in addition to exhibiting a certain level of homogeneity, attractive neighborhoods will nevertheless exhibit a certain spread of homogeneity values—i.e. enough to present a coherent impression without being rigidly monotonous.

The method we present can be employed as a procedure for architects to interactively evaluate new constructions or interventions in the existing urban context in the early design stages. Furthermore, this method could be trained to analyze historical quarters and learn from past examples about how to achieve or preserve the organic arrangement of the urban fabric. This measure can also be used as a goal function for a computational synthesis method, as presented by Schneider and Koenig (2012), to automatically create new spatial configurations with a defined level of homogeneity. In this article, we also present how to work with a small amount of data, requiring only 2D geometry obtained from open source data sources such as OpenStreetMap. It is therefore possible to undertake the study on a wider scale to provide more insight into homogeneity issues in different cities around the world. The emerging spatial big data technology will facilitate this for future research. Moreover, in future work, this method can be used to incorporate other defining parameters of the built environment for homogeneity measurement and not just geometrical parameters. We can, for example, compare physical and non-physical characteristics to obtain a better understanding of the nature of districts. The presented method could be developed further to detect and classify different sites and to analyze correlations between people's emotional responses to urban environments with the measured homogeneity levels of the corresponding spatial configuration.

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