SPATIAL DISCONTINUITY IN THE MULTI-SCALED AREA STRUCTURES OF THE CENTRAL HISTORIC DISTRICTS OF LONDON AND BEIJING

TAO YANG; BILL HILLIER

ABSTRACT

Why are those historic central districts divided into different named areas? Is there any spatial mechanism of defining and/or generating those areas as the parts of the cities? this paper explores what kind of geometric and spatial mechanism might account for the formation of the area structure represented by the periodic patchwork pattern (if their relationship is verified in the second phase), and make the first step towards understanding the part-whole problem discussed in the book of Space is the Machine. This will allow us to explore the spatial laws causing partitioning of the urban network into different parts. On these grounds, it finally seeks to propose a new heuristic model of area boundary – embodied by spatial discontinuity - in relation to the change rate of street density.

KEYWORDS
Named areas; Peak; Trough; Space Syntax

1. INTRODUCTION

As many writers (Clout and Wood, 1986; Hall, 1989; Morris, 1994; Kostof, 1999; Hebbert, 1998) argued, Central London always resisted a grand overall design, and evolved in a rather more piecemeal fashion throughout history. It has been often characterised as a collection of villages or distinct places highlighted by a set of area names1. In contrast, many researchers (Liang, 1952; Liu, 1980; Hou, 1998; Fu, 1998; Liang 2005) pointed out that the Inner City of Beijing was originally planned and constructed according to a grand scheme2 based on a regular grid, and the current named areas are closely related to the original gated quarters3, in spite of having experienced incremental reconstruction, adjustment and modification throughout its long history. Why are those historic central districts divided into different named areas? Is there any spatial mechanism of defining and/or generating those areas as the parts of the cities? The previous studies revealed that the power law can be applied to describe those named areas with regarding to their contextual structures with an increase of radius (Yang & Hillier, 2007). Based on which, this paper explores what kind of geometric and spatial mechanism might account for the formation of the area structure represented by the periodic patchwork pattern (if their relationship is verified in the second phase), and make the first step towards understanding the part-whole problem discussed in the book of Space is the Machine. This will allow us to explore the spatial laws causing partitioning of the urban network into different parts. On these grounds, it finally seeks to propose a new heuristic model of area boundary in relation to the change rate of street density.

2 A conceptual plan of capital city, elaborated in the Confucian etiquette framework in the Zhou Dynasty (1027 - 256 BC), was used to guide the construction of the Inner City of Beijing, which has been reviewed in Appendix C1. Or, see Liu Dun Zhen (1980) Chinese Architecture History, China Architecture and Building Press (in Chinese).
3 During the Yuan Dynasty (1271 - 1368), the city Dadu (current Beijing) was divided into 50 gated quarters - called Fangs – physically defined by the main roads and the archways called Paifangs. And most main roads enveloping those gated quarters have not been dramatically changed, and some quarter names still have survived today.
2. THE NAMED AREAS SELECTED IN THE TWO HISTORIC DISTRICTS

The district of Central London studied in this paper, illustrated in Fig. 1a, is the same as the congestion zone of London (implemented on 19 February 2007)\(^4\), broadly bounded by Marylebone Road, Euston Road and Pentonville Road to the North, City Road, Commercial Street and Bishopsgate to the East, Tower Bridge Road, New Kent Road and Kennington Lane to the South and Vauxhall Bridge Road, Grosvenor Place and Park Lane to the West. This district approximately corresponds to the central district of London defined in Abercrombie’s London Plan of 1944\(^5\). This paper focuses on the areas to the north of the Thames River, called the central district of London. It comprises three parts: the City of London (the financial and business centre), Westminster (the political and cultural centre), and the West End (the commercial and entertainment centre)\(^6\). They form the vital historical core of London being made up of many distinct named places, such as Mayfair, Soho, Bloomsbury etc (Clout and Wood, 1986; Sheppard, 1998; Mills, 2010). According to the area boundaries informally defined in The London Gazetteer (Willey, 2007), nine named areas in this central district are selected as the study areas, the City\(^7\), Westminster\(^8\), Marylebone\(^9\), Mayfair\(^10\), Soho\(^11\), Bloomsbury\(^12\), Covent Garden\(^13\), Holborn\(^14\) and St. James’\(^15\), all of which are shown in Fig. 1a.

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\(^{5}\) For the description of the central district of London in the Abercrombie’s London Plan, see Forshaw and Abercrombie, 1943, p22.
\(^{6}\) For description of those three parts, see footnote 6.
\(^{8}\) Ibid, P546-57.
\(^{9}\) Ibid, P316-17.
\(^{10}\) Ibid, P317-18.
\(^{11}\) Ibid, P446-47.
\(^{12}\) Ibid, P48.
\(^{13}\) Ibid, P119-20.
\(^{14}\) Ibid, P243.
\(^{15}\) Ibid, P423.
Proceedings of the 12th Space Syntax Symposium

a The Boundary of Central London and the Locations of Nine Named Areas Studied in This Paper. Thick red lines denote the boundary of Central London.

The Boundary of the Inner City of Beijing and the Locations of Nine Named Areas Examined in This Paper.

Fig. 1 The Selected Named Areas in The Two Cases. Thick red lines denote the boundary of Central District.
Beijing Inner City, a 38 sq km district, is encircled by the Second Ring Road to the north, west and east, as well as Chang'an Avenue\textsuperscript{16}, the ten-lane road bypassing Tian'an Men Square, to the south (Fig. 1b). We call it \textit{the central district of Beijing} in this paper. Like the central district of London, this district is also the historic core of the capital city, and comprises the current political, cultural, commercial and financial centres. According to the boundaries of named areas highlighted in the Beijing Administrative Map Collection (BCAB and BSMI, 2005), we selected nine named areas: Wangfujing\textsuperscript{17}, Dongdan\textsuperscript{18}, Dongsi\textsuperscript{19}, Xintaicang\textsuperscript{20}, Nanluogu\textsuperscript{21}, Zhonggulou (Bell Tower and Drum Tower)\textsuperscript{22}, Shichahai\textsuperscript{23}, White Pagoda\textsuperscript{24} and Fengsheng\textsuperscript{25}.

3. THE PEAK-TRough PATTERNS OF THE NAMED AREAS

We sought to investigate how geometric and metric properties of those named areas influence, or even determine, the spatial formation of those areas in the two cities. The previous studies showed that the periodic patchwork patterns created by MMD can be transformed into the peak-trough patterns by using the technique of the mountain scattergram (plotting MMD at any fixed radius against MMD at the infinite radius) (Hillier et al, 2010), and this provides a method for investigating the metric integration pattern of any named area at a local radius, in relation to the metric integration pattern of the whole network.

For example, the segments comprising the City of London were selected using DepthMap\textsuperscript{26}, see points highlighted in yellow (Fig.2a). We continued to create a series of mountain scattergrams by plotting the MMD $R_n$, on the x-axis, against the negative of MMD at the radius of $k$ (MMD $R_k$), from low to high, on the y-axis. At 1600m (on the y-axis), a peak (coloured in yellow) appeared for first time in the window of the scattergram (Fig.2b). Then, we coloured the segments of the City (bounded by dotted lines in Fig. 2c) in terms of MMD at 1600m; and meanwhile we adjusted the colour range to highlight the location of the most integrated segments within this area (because the summit of the peak denotes the lowest MMD segments, or the most metrically integrated segments). Blue indicates high MMD $R_{1600m}$ and red denotes low values. As Fig. 2c show, the MMD $R_{1600m}$ values increase from a small group of metrically integrated segments (more or less located at the geometric

\textsuperscript{16} Both the Second Ring Road and Chang'an Avenue were built along the former city wall of the Inner City after the 1960s. See Appendix C.

\textsuperscript{17} See BCAB and BSMI (Beijing Civil Affair Bureau and Beijing Surveying and Mapping Institute) (2005), Beijing Administrative Map Collection, Hunan Map Publisher. (in Chinese) p8.

\textsuperscript{18} Ibid, p13.

\textsuperscript{19} Ibid, p12.

\textsuperscript{20} Ibid, p11.

\textsuperscript{21} Ibid, p10.

\textsuperscript{22} Ibid, p10.

\textsuperscript{23} Ibid, p20.

\textsuperscript{24} Ibid, p19.

\textsuperscript{25} Ibid, p19.

\textsuperscript{26} For details, see A Researcher’s handbook of DepthMap (Turner, 2004). http://www.vr.ucl.ac.uk/depthmap/handbook.html
centre of the City) to their surroundings, and the City itself is also surrounded by the relatively colder segments. It suggests that the City, by and large, has a metrically integrated centre gradually merged into the less integrated contexts at the radius of 1600m.

Fig. 2 The Mountain Scattergram and the MMD R1600 Pattern of the City.

The above method was then applied to all other areas of London (Fig. 3a - f). In contrast to the City, Bloomsbury is represented as a trough at 1600m, corresponding to the MMD R1600 pattern where a small group of metrically segregated segments (coloured in blue) located at its geometric centre (Fig. 3a); and meanwhile, Bloomsbury itself seems to be surrounded by the relatively more metrically integrated segments (coloured in orange, yellow and green). This suggests that Bloomsbury, compared to the City, has no metrically integrated centre, but has more integrated edges. Holborn, Marylebone, Mayfair and Westminster are more or less denoted by troughs at 1800m, 2200m, 1600m and 2200m, respectively (Fig. 3b, c, d and e). However, they have different spatial patterns coloured according to the MMD Rk values. In Holborn, the most metrically segregated segments are located near the geometric centre, but other segregated segments focus on its south-east corner; and Holborn itself is surrounded by metrically integrated segments only to the east, north and west. As for Marylebone, the highest MMD R2200m values diminish from the geometric centre of its eastern part.
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(coloured in light blue) to its western part (mainly coloured in yellow) and its surrounding areas. This indicates that the most segregated spaces of Marylebone concentrate on its eastern part rather than its own geometric centre. As for Mayfair, the most segregated segments (coloured in dark blue) are located on the northern edge and the more integrated segments (coloured in yellow) are situated at the south west corner; and Mayfair itself is bounded by more integrated spaces (coloured in orange and yellow) to the east and west. As for Westminster, the most segregated segments are found at the eastern edge (that is, the edge of Thames River), and the whole area is surrounded by more integrated segments to the other three directions (south, west and north). The above analysis suggests that the most segregated segments of those areas (denoted by the bottom end of those troughs) are not all located at the geometric centre of those areas, but they are surrounded by more integrated segments situated within or outside those areas.

a. Bloomsbury

b. Holborn

c. Marylebone
d. Mayfair

Fig. 3 a-e The Mountain Scattergrams (Left) and the MMD Rk Patterns (Right) of Bloomsbury, Holborn, Marylebone, Mayfair and Westminster (Each image to the right has a slightly different colour range in order to clearly show the segments with the highest or the lowest MMD Rk values within each area, because those segments with the extreme values are surrounded by many segments with slightly lower or higher values).

And meanwhile, as with the City, the other three areas, namely Soho, St. James’s and Covent Garden, are roughly represented as peaks (Fig. 3 f-h). However, the most metrically integrated segments (coloured in red or orange) of these three areas, compared to the City, are located at/near the edges. As for Soho, the lowest MMD R1800 values increase from the southern edge to the northern part; as for St. James’s, the lowest MMD R1500 values rise up from the north east edge to the south west part; as for Covent Garden, the lowest MMD R1500 values increase from the south west edge to the north east part. This shows that they have more metrically integrated centres located on/near the edge rather than at the geometric centre. By and large, the above analysis suggests that the centres – in terms of metric accessibility from any places to any others – of the named areas are not necessarily arranged at their geometric centres.
Left: Yellow indicates the named areas

Right: the segment map coloured according to MMD Rk. Red denotes low value and blue indicates high value

Fig. 3 f-h The Mountain Scattergrams (Left) and the MMD Rk Patterns (Right) of Soho, St. James’s and Covent Garden

We moved to examine the Beijing areas (Fig. 4). Dongdan and Nanluogu are represented as troughs at 1100m and 1000m, respectively (Fig. 4 a and b). In Dongdan, the most metrically segregated
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segments (coloured in blue) are located at its geometric centre; and this area is surrounded by more metrically integrated segments to the east and the south. However, in Nanluogu, the most metrically segregated segments are situated at the south east corner; and this area is bounded by more integrated segments to the south, west and north.

The other Beijing areas are more or less denoted as peaks, but their MMD Rk patterns are not the same (Fig. 4 c-g). As for Dongxi and Xingtaicang, a small group of the most metrically integrated segments are situated at their geometric centres, and the MMD Rk values increase from the centre to the edge (Fig. 4 c and d). As for Whitepagoda, the most metrically integrated segments are, however, found near the western edge; and meanwhile this area is surrounded by more metrically segregated segments (Fig. 4 e). As for Wangfujing, Fengsheng and Zhonggulou, the most metrically integrated are also situated on one of their edges, and the MMD Rk values increase from their metrically integrated centres to the surroundings (Fig. 4 f, g and h). As for Shichahai, the most metrically integrated segments are located at the geometric centre of its north east part, and its south west part is dominated by the metrically segregated segments (Fig. 4 i). The above analysis shows the possibility that the metrically integrated centres of those areas, represented as the summit of the peaks, can be located at the different parts of those areas; however the MMD Rk values would always increase from the metrically integrated centres to the surroundings.
c. Dongsi

d. Xingtaicang

e. Whitepagoda

f. Wangfujing
In general, it can be demonstrated that the named areas in London and Beijing can be classified into two types of areas according to their representations in the mountain scattergrams. Roughly speaking, the peak suggests that the corresponding area has a metrically integrated centre (though not
necessarily located at the geometric centre of internal layout); but the trough implies that the corresponding area, without a strong metrically integrated centre, is surrounded by the metrically integrated edge. This might relate to the spatial formation of the named areas. Some named areas, such as the City of London, are formed around a strong geometric centre; but some named areas, such as Bloomsbury, are surrounded by more intensively developed surrounding areas.

4. THE PATCHES AND THEIR SURROUNDINGS

The interpretation of the peak-trough pattern relates to Hillier’s theory of grid intensification\(^\text{27}\), which proposes the phenomenon of city growth leading to a reduction of block size so as to reduce average metric distance from all points to all others in an urban network. We then sought to investigate whether the peak-trough patterns generated in the above cases have any empirical relationship with the grid intensification. When an area is occupied by smaller sized blocks, the segment map of the area in general has a larger number of shorter segments; and vice versa. And therefore, we compared the average segment length of the created patches, associated with peaks or troughs, with that of their surrounding segments involved in producing those patches, in order to explore the extent to which the created patches are intensified regarding their surroundings.

An example of a red patch of London was used to elucidate the method of making the above comparison. As Fig. 5a shows, we selected the segments making up R1 as the root area, and then highlighted the surrounding segments located up to 1400m away from the selected patch of R1. Since R1 (denoted by black segments in Fig. 5a) was created at 1400m, the surrounding segments within 1400m (represented by grey segments) contributed to the formation of R1. The average segment length of R1 and that of the surroundings were \textit{visually} and \textit{numerically} compared to achieve a better understanding of the creation of R1.

Proceedings of the 12th Space Syntax Symposium

a. The red patches (associated with peaks) as well as their surroundings in London

b. The blue patches (associated with troughs) as well as their surroundings in London

Fig. 5 The Patches Created at 1400m and Their Surroundings for the London Case. Black denotes the created patches and grey represents their surrounding segments within 1400m.

Fig. 5 shows the red and blue patches of London as well as their surrounding segments within 1400m. At first sight, it is difficult to tell whether these created patches are more intensified than their surroundings or not, although some red patches, such as R5 and R6, seem more intensified than some parts of their surroundings (e.g. parks), and some blue patches, such as B1 and B3, seem less intensified than some parts of their surroundings. However, the quantitative analysis (Table 1) indicates that all the red patches (associated with peaks) have shorter segments than their surroundings, and all the blue patches (related to troughs) have longer segments than their surroundings. Compared to the surrounding segments involved in the generation of the patches, the red patches are more intensified but the blue patches less intensified. In particular, both the most intensified patch R1 and the least intensified patch B1 are more geometrically different from their contexts regarding segment length, because R1 has the lowest ratio of 0.674 and B1 has the highest ratio of 1.591.
Table 1 A Comparison of the Segment Length of the Created Patches and that of Their Surroundings in the London Case (Ref.: Reference Number; Avg Seg Length: Average Segment Length; Avg R: Average Values of Red Patches; Avg B: Average Values of Blue Patches)

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Avg Seg Length</th>
<th>Patch (Black) m</th>
<th>Surrounding (grey) m</th>
<th>Ratio (Black/Grey)</th>
</tr>
</thead>
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<tr>
<td>R1</td>
<td></td>
<td>31.75</td>
<td>47.14</td>
<td>0.674</td>
</tr>
<tr>
<td>R2</td>
<td></td>
<td>38.00</td>
<td>51.02</td>
<td>0.745</td>
</tr>
<tr>
<td>R3</td>
<td></td>
<td>38.36</td>
<td>48.02</td>
<td>0.799</td>
</tr>
<tr>
<td>R4</td>
<td></td>
<td>59.58</td>
<td>61.66</td>
<td>0.966</td>
</tr>
<tr>
<td>R5</td>
<td></td>
<td>53.85</td>
<td>56.34</td>
<td>0.956</td>
</tr>
<tr>
<td>R6</td>
<td></td>
<td>63.21</td>
<td>66.91</td>
<td>0.945</td>
</tr>
<tr>
<td>Avg R</td>
<td></td>
<td>47.46</td>
<td>55.18</td>
<td>0.847</td>
</tr>
<tr>
<td>B1</td>
<td></td>
<td>79.74</td>
<td>50.12</td>
<td>1.591</td>
</tr>
<tr>
<td>B2</td>
<td></td>
<td>68.31</td>
<td>52.45</td>
<td>1.302</td>
</tr>
<tr>
<td>B3</td>
<td></td>
<td>57.80</td>
<td>44.58</td>
<td>1.297</td>
</tr>
<tr>
<td>B4</td>
<td></td>
<td>48.28</td>
<td>37.88</td>
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</tr>
<tr>
<td>B5</td>
<td></td>
<td>56.00</td>
<td>42.67</td>
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</tr>
<tr>
<td>Avg B</td>
<td></td>
<td>62.03</td>
<td>45.54</td>
<td>1.355</td>
</tr>
</tbody>
</table>

Then we moved to investigate the created patches (shown in Fig. 10 and 11) in the Beijing case. Fig. 6a shows the red patches created at 1700m as well as their surrounding segments within 1700m; and Fig. 6b displays the blue patches generated at 1700m as well as their surrounding segments within 1700m. The patches are denoted by black segments and the surroundings are represented by grey segments. At first sight, R3 seems more intensified than its surrounding, and B5 appears sparser than its surroundings. However, it is not easy to draw the conclusion that one patch on average is more or less intensified than its surroundings. For example, R1 is obviously more intensified than the western context, but it seems not more intensified than the eastern and southern contexts. This also suggests that the geometric difference between the created patches and their surroundings in Beijing cannot easily distinguished by visual examination.
Proceedings of the 12th Space Syntax Symposium

Fig. 6 The Patches Created at 1700m and Their Surroundings for the Beijing Case. Black denotes the created patches and grey represents their surrounding segments within 1700m.

However, the quantitative analysis of the Beijing case (Table 2) shows that all the red patches on average have shorter segments than their surrounding areas, and all the blue patches on average have longer segments than their contextual areas. In spite of the fact that the Beijing patches (either the red or the blue patches) on average have longer segments (red: 63.69m; blue: 104.86m) than the London patches (red: 47.46m; blue: 62.03m; shown in Tables 1), the same relationship between the created patches and their surroundings is also found in the Beijing case. The red patches are more intensified than their surroundings, and the blue patches are less intensified than their contexts.

Table 2 A Comparison of the Segment Length of the Created Patches and that of Their Surroundings in the Beijing Case (Ref.: Reference Number; Avg Seg Length: Average Segment Length; Avg R: Average Values of Red Patches; Avg B: Average Values of Blue Patches)

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Avg Seg Length</th>
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<td></td>
<td></td>
</tr>
</tbody>
</table>
As the red and blue patches emerge side by side to form a kind of periodic structure, the red patches would act as the surroundings of the blue patches and vice versa. The above analysis therefore implies that more intensified sub-grids are surrounded by, and meanwhile envelope, less intensified sub-grids across the entire historic districts at a constricted radius. The peak-trough pattern in fact captures this kind of periodicity. The peak, associated with red patch, denotes a metrically integrated and intensified centre surrounded by less intensified spaces, called the centre-to-edge motif in the previous paper; and meanwhile, the trough, related to the blue patch, represents relatively less intensified central area enclosed by metrically integrated and intensified edges, called the edge-to-centre motif in the previous paper. By and large, it can be proposed that the periodic patchwork (or peak-trough) pattern might arise from the unevenly intensified grid as a whole system.

When we investigated the variation between two differently intensified parts, we in fact treated one part as the internal, and another part as the external. The internal can be considered as each root area (or even segment) and the external as the contextual areas (or a group of segments) encountered up to a radius. And meanwhile, radius itself is a tool for defining the contextual areas. Then, how does the generation of each patch as the internal relate to the extension of the contexts as the external, how does the degree of intensification vary with an increase of radius, and how does this account for the formation of the patches?
5. THE CHANGE RATE OF SEGMENT DENSITY

In order to tackle the above questions, we turned to focus on the idea of *segment density*, meaning the number of the segments encountered within a relatively small radius *as a unit*, because the degree of intensification also can be approximately assessed by segment density. Based on the segment maps of London and Beijing, we first visualised the distribution patterns of segment density (approximated by node count at a small radius of k, denoted NC Rk), aiming to make the first step towards investigating whether and how the created patches are influenced by grid intensification.

For example, **Fig. 7a and b** illustrate the NC R1400 pattern of London, as well as the NC R1700 pattern of Beijing, as a way of showing the distribution pattern of segment density in the two cities. At first sight, they show two different concentric patterns. In the London case (**Fig. 7a**), its geometric centre is most intensified, and segment density roughly decreases from the centre to the edge. In contrast, the geometric centre of Beijing (occupied by the Forbidden City) is less intensified, and enveloped by the most intensified grids within the Second Ring Road; and then segment density diminishes outwards (**Fig. 7b**).

![Two Different Patterns of Segment Density of London and Beijing](image)

**Fig. 7 Two Different Patterns of Segment Density of London and Beijing** (approximated by NC at low radius). Red denotes high segment densities and blue indicates low values.

However, both images (**Fig. 7a and b**) do not show anything resembling the periodic patchwork patterns. In those periodic patchwork patterns, the same coloured patches (either red or blue) emerge across the whole maps of London and Beijing. Thus, the distribution patterns of segment density (**Fig. 6a and b**) in fact suggest that the *same* coloured patches have *different* segment densities. In general, the patches located at the central districts of London and Beijing (except for the Forbidden City) are more intensified than those situated at the outside of the central districts. This might be due to a simple fact that the historic central districts in the two cities have been intensively developed. To a large extent, however, it also implies that the variable of segment density *itself* does not account for the patchwork patterns.
Furthermore, when we carefully observed the above two images (Fig. 6a and b), some orange and yellow clusters can be found within the red parts, and meanwhile, some cyan clusters can be found within the blue parts. Perhaps this demonstrates that segment densities slightly vary within the central districts or the outside. Does this imply that small variations of segment densities relate to the formation of the patchwork patterns?

As segment density can be approximated by NC Rk (if k is small), we then focused on how the NC Rk of the individual segments of the same coloured patches varies with respect to the change of radius. For example, in the London patchwork pattern created by MMD R1400, three segments were randomly selected from the different red patches, because there are only three red patches generated at 1400m in the central district of London; and three segments randomly chosen from three different orange patches, and three segments randomly picked out from three different blue patches. In the Beijing patchwork pattern generated at 1700m, nine segments were also randomly selected in the same way we carried out for the London case. The segment reference numbers are displayed in these two images.

We sought to investigate the variation of segment density - starting from each selected segment – with an increase of radius, and this can be approximated by the metric embeddedness trajectories within the range of 100m to the radius at which the patchwork patterns were generated (1400m for the London case and 1700m for the Beijing case). The metric embeddedness trajectories of all those individual segments were illustrated by plotting NC Rk against Rk. Fig. 8 a and b illustrate these embeddedness trajectories in London and Beijing respectively (see Appendix for full tables). At first sight, the segments selected from the different coloured patches (in either case) seem to have different shapes of the trajectories; and at least the blue segments have more curved trajectories than the red and orange segments. This possibly suggests that the contexts of the different coloured segments can be intensified in different ways.

![Red segments](overlay_plot_red.png)  ![Orange segments](overlay_plot_orange.png)  ![Blue segments](overlay_plot_blue.png)

a. The embeddedness trajectories of the nine segments in London.
b. The embeddedness trajectories of the nine segments in Beijing

**Fig. 8 The Metric Embeddedness Trajectories of the Individual Segments Selected from the Different Patches in London and Beijing.**

The non-linear regression analysis numerically demonstrates that all the above embeddedness trajectories (Fig.8) are approximately governed by power laws. This suggests that the way in which those segments are metrically embedded into the surroundings is controlled by scale parameter (H) and exponent parameter (α) of the power-law relation between node count and radius (expressed by the equation of $NC_k = H \times k^\alpha$). Tables 1 and 2 summarise these two parameters (H and α), together with basic values, such as segment reference numbers (denoted by Depthmap Ref, which corresponds to reference number), MMD and NC – at certain radius – of each selected segment in London and Beijing respectively.

**Table 3 The Relationship Among MMD, NC and Power-law Exponents of the Nine Segments Selected from the Different Patches Created by MMD in London.**

(MMD_R1400: mean metric depth at 1400m; NC_R1400: node count at 1400m; H: scale parameter of the power-law relation between node count and radius; α: the exponent of the power-law relation between node count and radius.)

<table>
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<th>Seg610</th>
<th>Seg1477</th>
<th>Seg339</th>
<th>Seg3678</th>
<th>Seg1407</th>
<th>Seg4736</th>
<th>Seg7111</th>
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<td>Orange</td>
<td>Orange</td>
<td>Blue</td>
<td>Blue</td>
<td>Blue</td>
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<td>MMD_R1400</td>
<td>818.2</td>
<td>817.7</td>
<td>818.5</td>
<td>863.4</td>
<td>865.7</td>
<td>863.6</td>
<td>1004.4</td>
<td>1004.3</td>
<td>1005.2</td>
</tr>
<tr>
<td>NC_R1400</td>
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<td>2159</td>
<td>3248</td>
<td>1125</td>
<td>1523</td>
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<td>H</td>
<td>1.71</td>
<td>3.52</td>
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<td>α</td>
<td>1.544</td>
<td>1.523</td>
<td>1.528</td>
<td>1.786</td>
<td>1.779</td>
<td>1.748</td>
<td>2.795</td>
<td>2.745</td>
<td>2.743</td>
</tr>
</tbody>
</table>
Table 4 The Relationship Among MMD, NC and Power-law Exponents of the Nine Segments Selected from the Different Patches Created by MMD in Beijing.

(MMD_R1700: mean metric depth at 1700m; NC_R1700: node count at 1700m; H: scale parameter of the power-law relation between node count and radius; α: the exponent of the power-law relation between node count and radius.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Seg 34898</th>
<th>Seg 15641</th>
<th>Seg 16618</th>
<th>Seg 1165</th>
<th>Seg 29644</th>
<th>Seg 34999</th>
<th>Seg 34822</th>
<th>Seg 10557</th>
<th>Seg 34670</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patch Colour</td>
<td>Red</td>
<td>Red</td>
<td>Red</td>
<td>Orange</td>
<td>Orange</td>
<td>Orange</td>
<td>Blue</td>
<td>Blue</td>
<td>Blue</td>
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<td>997.5</td>
<td>999.4</td>
<td>1033.7</td>
<td>1036.2</td>
<td>1035.9</td>
<td>1205.6</td>
<td>1206.8</td>
<td>1206.7</td>
</tr>
<tr>
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<td>568</td>
<td>781</td>
<td>1531</td>
<td>618</td>
<td>991</td>
<td>1538</td>
<td>437</td>
<td>842</td>
<td>1159</td>
</tr>
<tr>
<td>H</td>
<td>E-03</td>
<td>7.05</td>
<td>1.43</td>
<td>1.81</td>
<td>2.26</td>
<td>5.6</td>
<td>8.44</td>
<td>2.55</td>
<td>3.2</td>
</tr>
<tr>
<td>α</td>
<td>1.54</td>
<td>1.56</td>
<td>1.56</td>
<td>1.714</td>
<td>1.75</td>
<td>1.684</td>
<td>2.688</td>
<td>2.635</td>
<td>2.649</td>
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</tbody>
</table>

As for the London case, we then compared MMD R1400 with NC R1400. The same coloured segments (red, orange or blue) have very similar MMD R1400 values, but they do not necessarily have similar NC R1400 values. For example, Segment 610 (selected from a red patch co-inciding with the City, see Fig. 5) has 2.7 times the NC R1400 than Segment 19191 (chosen from another red patch roughly corresponding to Pimlico, see Fig. 5); but these two segments have almost the same MMD R1400 values (818.5 and 818.2, respectively). Since NC R1400 approximates to segment density, it indicates that the City and Pimlico, both of which are identified as the red patches (Fig.8), have different segment densities. This demonstrates that the same coloured patches, even located at the central district of London, are differently intensified. When we examined the segments in the Beijing case, we also found that the same coloured segments (shaded in the same colour in Table 1) have almost the same MMD R1700, but have significantly different NC R1700. This also indicates that the same coloured patches in the central district of Beijing are differently intensified. The above analysis numerically confirms that the spatial discontinuities within the two central districts are not produced by the variable of segment density itself.

Then, how about the power-law exponents? The segments selected from the same coloured patches (red, orange or blue) in each case have similar values of power-law exponent α (Tables 1 and 2) As discussed in the previous paper, the power-law exponent mathematically approximates the change rate of node count, and so at relatively small radius, the power-law exponent roughly reflects the change rate of segment density. Tables 1 and 2 therefore demonstrate that the same coloured patches in each
case have similar rates of change in segment density. This suggests that the patchwork patterns arise from the change rate of segment density, rather than segment density itself.

Or, the above analysis further implies that the transition between the intensified sub-grids and the sparse sub-grids produces the patchwork patterns. For example, the red segments have small exponents, the orange segments have moderate exponents, and the blue segments have high exponents, as Tables 1 and 2 show. This numerically demonstrates that the red segments encounter less intensified contexts – with increasing radius – than the blue segments. To some extent, this can supports the previous finding that the red patches of the two central districts have more intensified centres, but the blue patches have more intensified edges. This will be theoretically discussed in paper seven.

In addition, we further statistically verified the power law relationship between NC and radius for all the individual segments, as well as their relationships between the MMD Rk and the power law exponents, in order to confirm whether the change rate of segment density matters in a more generalised sense. Here we still sought to study the MMD R1400 for London and the MMD R1700 for Beijing. However, we respectively investigated the relationship between NC and radius, within the range of 400m to 1700m for London and within the range of 400m to 2000m for Beijing, with an interval of 100m. As the endpoint of the radius range is larger than the radius at which the MMD Rk values were calculated, this enables us to explore whether the change rate of segment density beyond the radius of 1400m (for London) and of 1700m (for Beijing), representing the contexts, empirically affect the values of MMD Rk, roughly denoting the internal structures.

The result shows that 95% segments in the London case have a power law relationship between NC and radius, with the R-square above 0.9, within the range of 400m to 1700m, and 95% segments in Beijing have a power law relationship with the R-square above 0.9 within the range of 400m to 2000m. And it demonstrates that a strong non-linear relationship between the power law exponents and the MMD R1400 values, with the R-square of 0.813, was found in the London case, and a strong non-linear relationship with the R-square of 0.900 identified in the Beijing case. In fact, this suggests that the patchwork patterns generated by the MMD at the radius of k, in these two cases, are statistically influenced by the change rates of segment density beyond the radius of k.

Morphologically speaking, it can be implied that the density change rate between the internal and the contexts, in the cases of London and Beijing, has significant impact on the formation of the patchwork patterns. Such change in segment density possibly infers a spatial discontinuity between generated patches in these two urban networks.


The empirical analysis further suggested two kinds of morphological motifs (respectively associated with two types of created patches): the centre-to-edge motif, meaning the sub-grid in which smaller blocks are placed at the centre and bigger blocks at the edge; the edge-to-centre motif, indicating the
sub-grid in which smaller blocks are situated at the edge and bigger blocks at the centre. For example, in each case of Central London and Central Beijing, red patches were surrounded by blue patches, and vice versa. By and large, this suggested that these two types of morphological motifs appeared alternatively across the urban network as a whole. It can be therefore inferred that more intensified sub-grids tend to be placed side by side with less intensified sub-grids.

Moreover, red patches produced at a fixed radius on average had shorter segments than the surrounding segments involved in creating that red patch; and meanwhile, blue patches on average had longer segments than the contextual segments involved in creating that blue patch - although the segment structures of both the red and blue patches in the London Docklands morphologically extended out in several constricted directions rather than all directions, in contrast to the patches in Central London and Central Beijing. Since shorter segments and/or smaller blocks mean more intensified parts, and longer segments and/or larger blocks indicate less intensified parts, the above analysis suggests that the transition between different degrees of intensified parts, expressed by the change rate of segment density, were involved in producing the periodic patchwork patterns in the empirical studies of Central London and Central Beijing.

However, the patches – either in red or in blue – located at the edge of the whole city were less intensified than the patches situated at the centre, which was empirically demonstrated in Paper Five. By examining notional examples (Fig.19), we seek to further clarify the morphological mechanism of generating the same coloured patches at both the centre and the edge of a city as a whole system, and then to explore a theoretical relationship between segment density and radius.

Fig. 9 a and b display two centre-to-edge sub-grids picked out by the same fixed radius from the root segment (marked by black dot). The former theoretically represents a less intensified sub-grid found at the edge of a larger system, and the latter shows a more intensified one located at the centre of the larger system. We respectively calculated the change rate of node count (metric embeddedness) and MMD of the root segment. The root segments of these two sub-grids have similar metric embeddedness (1.56 and 1.59, respectively) and MMD (9.03 and 9.07, respectively) at the level of the sub-grid. This suggests that metric embeddedness or MMD at the local scale captures the locally defined feature that the block size of these two sub-grids reduces, in a consistent way, from the centre to the edge.
Proceedings of the 12th Space Syntax Symposium

Fig. 9 Four Notional Sub-grids Selected From A Larger Grid. Each sub-grid has the same fixed radius of 14 from its root segment (highlighted by black dot) to its edge segment; and each of them is coloured with regard to the depth from its root segment. (Red denotes the segments closing to the root segment, and blue indicates the segment far from the root segment)

Moreover, Fig. 9 c and d demonstrate two edge-to-centre sub-grids defined by the same fixed radius from the root segment (highlighted by black dot). Again, the former represents a less intensified sub-grid found at the edge of a larger system, and the latter shows a more intensified one located at the centre of the larger system. The root segments of these two sub-grids have similar metric embeddedness (2.14 and 2.15, respectively) and MMD (10.1 and 10.0, respectively) at the level of the sub-grid. This indicates that metric embeddedness or MMD calculated at the local scale reflects a kind of local property that the block size of these two sub-grids increases, in a consistent way, from the centre to the edge, although they have different degrees of intensification.

In general, it can be suggested that the patches (created by metric embeddedness or MMD at a fixed radius) manifest the geometrical arrangement that all the blocks of each sub-grid (defined by the local radius) geometrically vary from the centre to the edge. As the whole system is not evenly intensified, the different sub-grids have the different geometrical arrangements of blocks and segments at local scales, which perhaps generate the differently coloured patches. For example, the centre-to-edge sub-grids relate to red patches, and the edge-to-centre sub-grids are associated with blue patches. In this
sense, it can be argued that the geometrical arrangement of blocks taking place at local scales result in the periodic patchwork patterns.

More accurately, the idea of geometrical arrangement involves two variables, namely segment density and the change in radius. Segment density basically measures the number of segments encountered within a fixed radius as a unit. And this reflects a static geometric feature of grid intensification, in which the reduction in block size would reduce MMD from all segments to all others. And as reviewed in Paper Three, radius can be treated as a tool for selecting a group of segments up to a fixed metric distance away from root segment, and this suggests the concept of catchment area from the root segment. The change in radius therefore captures the variation of catchment areas, and this indicates dynamic view of observing catchment areas. Thus, the combination of segment density and the change in radius, to a large extent, suggests a kind of local geometric dynamics, meaning the variations of block size and/or segment length in relation to a sequence of different sized catchment areas representing the view fields starting from root segment. To large extent, this implies that the dynamic variations of local geometric features, if we observe from all the segments at a series of local radii, are essentially involved in the creation of the periodic patchwork patterns.

Considering that the original idea of embeddedness trajectory (Yang & Hillier, 2012) - on which each segment is spatially embedded into the contexts, regarding to its distances to them, with an increase of radius - also shows the variation of catchment areas, the local geometrics dynamics seems to relate to the embeddedness trajectory. By numerically examining the log-log relationship between node count and radius for individual sample segments (conducted in Papers Five and Six), each empirical case study demonstrated that the segments selected from the red patches had similar power-law exponent of smaller than 2, but the segments chosen from the blue patches had similar exponent of larger than 2 (Tables 1, 2). In contrast, any a segment selected from an evenly intensified grid – without taking account of edge effect – theoretically have a power-law relationship, with the approximated exponent of 2, between node count and radius. Since urban grid is theoretically embedded into a two-dimensional surface, the power-law exponent of 2 in fact suggests the way of evenly intensifying the urban grid. As a result, red patches with the exponent of smaller than 2 indicates that these red patches encountered less intensified sub-grids with an increase of radius; and blue patches with the exponent of larger than 2 demonstrates that these blue patches met more intensified sub-grids with an increase of radius. This suggests the kind of dimensional distortion of urban grid in which red patch, with the dimensions of smaller than 2, is interpreted as the centre-to-edge motif, and blue patch, with the dimensions of larger than 2, is treated as the edge-to-centre motif. As Paper Four suggested that power-law exponent is associated with the variable of MMD at a fixed radius, do different dimensions of the sub-grids imply the optimisation of MMD of those sub-grids at local scales? Or, why is urban grid unevenly intensified?

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28 For a theory of grid intensification, see Hillier (1999, 2007, 2010). This was reviewed in Paper Four.
29 For details, see Section 3.23.
7. THE MULTI-SCALE GRID INTENSIFICATION

Then, we conducted a notional experiment in order to explore whether a sub-grid – selected from a large grid – seeks to optimise its MMD values at low and medium radii by taking the unevenly intensified form. We started by examining a 700m×700m regular grid, with each cell constituted by 10 one-metre-segments at each side, called Grid A (Fig. 10). Then, a 300m×300m sub-grid, located at the centre and highlighted by red lines, was selected to calculate MMD at the radius of 20m to 200m, with an interval of 20m. It is called sub-grid A. As the distance from the edge of this sub-grid to the edge of the grid is 200m, the radius of smaller than 200m - at which the central sub-grid was studied - would help us to avoid the edge effect of the whole grid.

![Grid A](image1)

![Grid B](image2)

![Grid B1](image3)

![Grid B2](image4)

![Grid C](image5)

![Grid C1](image6)

![Grid C2](image7)

**Fig. 10 Five Notional Grids with The Central Sub-grids.** Grid A is a 700m×700m regular grid, with each cell constituted by 10 one-metre-segments at each side; Sub-grid A is a 300m×300m sub-grid located at the centre and highlighted by red lines. The 300m×300m sub-grid is transformed into the centre-to-edge subgrids with the different degrees of intensification, and this is represented by Grids B, B1 and B2, respectively. And the 300m×300m sub-grid is also transformed into the edge-to-
centre subgrids with the different degrees of intensification, and this is represented by Grids C, C1 and C2.

On one hand, the 300m×300m sub-grid was intensified at the centre to produce three sub-grids representing the centre-to-edge motif (Fig. 10). Sub-grid B1 is less intensified at the centre than Sub-grid B, but more intensified at the centre than Sub-grid B2. On the other hand, the 300m×300m sub-grid was intensified at the edge to generate three sub-grids representing the edge-to-centre motif. Sub-grid C1 is less intensified at the edge than Sub-grid C, but more intensified than Sub-grid C2. The MMD values at the radius of 20m to 200m were calculated for these six sub-grids respectively.

Table 5 shows that Sub-grid A, the evenly intensified sub-grid, is not the most metrically integrated across all the non-global radii, comparable to all the other intensified sub-grids. At the radius of 20m and 40m, Sub-grids C and B, respectively representing the edge-to-centre and the centre-to-edge motifs, are most integrated; at the radius of 60m and 80m, Sub-grids C2 and B2 are most integrated, but Grids B most segregated; at the radius of 100m to 160m, Sub-grid C2, an edge-to-centre motif, is most integrated, but Sub-grid B most segregated (except 160m); at the radius of 180m and 200m, Sub-grid B is most integrated but Sub-grid A most segregated. This suggests two points. First, if a sub-grid selected from an evenly intensified grid was transformed into the sub-grids more intensified at either the centre or the edge, it would become more metrically integrated at relatively lower or medium radii (without the edge effect). Second, the sub-grid taking the form of the centre-to-edge motif is more integrated at higher radii and the lowest radii, but the sub-grid taking the form of the edge-to-centre

<table>
<thead>
<tr>
<th></th>
<th>MM D_{R20}</th>
<th>MM D_{R40}</th>
<th>MM D_{R60}</th>
<th>MM D_{R80}</th>
<th>MM D_{R100}</th>
<th>MM D_{R120}</th>
<th>MM D_{R140}</th>
<th>MM D_{R160}</th>
<th>MM D_{R180}</th>
<th>MM D_{R200}</th>
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<td>39.8</td>
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<td>106.4</td>
<td>119.7</td>
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<td>55.9</td>
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<td>82.1</td>
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<td>106.0</td>
<td>117.8</td>
<td>129.6</td>
<td>361.7</td>
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<td>40.1</td>
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<td>79.7</td>
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<td>131.4</td>
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<td>79.7</td>
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<td>106.1</td>
<td>119.3</td>
<td>132.4</td>
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<td>79.4</td>
<td>92.6</td>
<td>106.0</td>
<td>119.4</td>
<td>132.9</td>
<td>376.9</td>
</tr>
</tbody>
</table>
motif is more integrated at lower and medium radii. It can be suggested that the unevenly intensified sub-grids, located at the centre of the whole grid, are more metrically integrated than the evenly intensified sub-grids across scales.

Table 6 The Metric Mean Depth (MMD) at Local and Global Radii of Seven Larger Grids.

Light red denotes low values and dark red indicates high values; MMD_{R20} means metric mean depth at 20m, and MMD_n indicates metric mean depth at the infinite radius.

<table>
<thead>
<tr>
<th></th>
<th>MM_D_{R20}</th>
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<th>MM_D_{R60}</th>
<th>MM_D_{R80}</th>
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<th>MM_D_{R140}</th>
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<td>78.3</td>
<td>91.0</td>
<td>103.7</td>
<td>116.3</td>
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<tr>
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<td>467.8</td>
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<td>39.4</td>
<td>52.4</td>
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<td>471.0</td>
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</tbody>
</table>

Then, we further examined whether the larger grid in which the central sub-grid is embedded would become more integrated or segregated across radii. As Fig. 6 shows, Grids B and C are more integrated at the radius of 20m and 40m; Grids B2 and C2 seem to become more integrated at the radius of 60m, 80m and 100m; Grids B1 and C1 intend to become more segregated at the radius of 100m to 140m; Grid B is most integrated at the radius of 160m to 200m. Roughly speaking, at the radius of smaller than 140m, the central sub-grid corresponding to either the centre-to-edge motif or the edge-to-centre motif helps to reduce the MMD Rk of the whole system; at the radius of not smaller than 140m, the sub-grid B, associated with the centre-to-edge motif, makes the whole system more integrated. This suggests that the unevenly intensification of the sub-grids also contribute to the optimisation of metric integration of the whole grid into which those sub-grids are embedded. In other words, when a sub-grid is intensified either at the centre or at the edge of the sub-grid, the whole system into which it is embedded will also become more metrically integrated at a series of relatively local radii and the global radius.

In theory, a city as a whole seeks to take the form of the centre-to-edge motif, with an attempt to maximise MMD at the level of the whole system, as discussed in Paper Three. Fig. 6 also demonstrates that even the central sub-grid taking the centre-to-edge motif results in the reduction of MMD at global scale for the whole system. Thus, it can be theoretically argued that urban grid results
from a combination of different layers of multi-scaled grid intensification, namely a single centre-to-edge grid in which the centre part of urban grid as a whole on average is more intensified than the edge part, as well as the periodic patchwork patterns in which the centre-to-edge motifs are mixed with the edge-to-centre motifs identified at a series of relatively local radii. For the urban grid, some patches at the edge of the whole system, albeit less intensified at the global scale, would have almost the same degrees of local-scale metric integration as those at the centre of the whole system. This aims to optimise, rather than maximise, metric integration of the whole system at those local/medium scales. In this sense, cities seek to simultaneously intensify their grids and/or sub-grids at both global and local scales, in order to balance the optimisation of global metric integration with that of local metric integration. We call it the multi-scale grid intensification, which might facilitates inter-accessibility between all the streets at the radius ranging from the global to the local.

Then, it can be argued that the periodic patchwork patterns - in which red patches emerge side by side with blue patches at a series of local radii - roughly manifest the layers of the grid intensification taking place at local scales, rather than the global scale of the whole system, in order to optimise metric mean depth of the whole system at the non-global scales.

8. DISCUSSION
Based on a theoretical concept that area discontinuities arise from the spatial discontinuities in urban grid is proposed, and this casts new light on the spatial definition of urban areas. In contrast to the conventional idea that a city as a whole is considered as a collection of territorially bounded units with either clear or soft boundaries, analogous to cell walls, supporting socio-economic, cultural and functional activities within each unit, this paper argues that urban areas emerge from the way in which individual spaces are structured internally and how this relates to the spatial structuring in the contexts found at different scales. As a result, the area boundaries, in general, are fuzzy in the sense that they are the manifestations of the spatial discontinuities (where the configurational relationships change significantly) varying at different scales, but do not depend on the area being either self-contained, geometrically differentiated, or having clear spatial limits.

On this ground, a conceptual model can be proposed to explain the spatial mechanism of generating area structures represented by the periodic patchwork patterns produced at different radii. It comprises two parts. First, a city is unevenly intensified at both global and local scales, usually shown by the centre-to-edge grid at global scale, as well as the centre-to-edge and edge-to-centre motifs alternatively found at a series of non-global or local radii, in order to optimise metric integration at both global and local scales, rather than maximise metric integration at a fixed scale. Perhaps this might result from small-scale economic activity process (Hillier, 1999) that aims to maximise interaccessibility from all places to all the others at both global and local scales, in that people need to reduce travel distance across different levels of areas, ranging from street to quarter, neighbourhood, district, city and even region. In this sense, it might be the multi-scale microeconomic process that serves as an essential tool of spatially aggregating urban parts into a whole.
Second, the different parts of the urban grid then obtain the different rates of change in street density (approximated by segment density), as the urban grid has been unevenly intensified. At non-global scale, each of the streets making up an area is also spatially embedded into the multi-scale contextual structures at different rates. This can be numerically described by the embeddedness trajectories with the discontinuities where the embeddedness rates change dramatically. The fuzzy boundaries of urban areas then arise from, and vary with, their relations with the multi-scale external structures involved in generating those areas at different radii.

It can be suggested that this conceptual model provides a new way of defining urban areas with regard to spatial configuration. The fuzzy boundaries of urban areas, it has been argued, are at least as much more influenced by the contexts as by the internal structure itself, in that the previous three papers empirically and theoretically showed a kind of remote effect through which the spatial structuring in the larger – even much larger-context interacts with the local – and even the non-local – spatial properties of an area, and creates the fuzzy boundary effect, which becomes a main factor in the definition of the areas represented at the non-global level.

This paper has suggested that urban areas pre-defined in terms of other socio-economic variables, such as named areas and the newly developed areas, can be characterised and differentiated according to the way they are spatially embedded into the surroundings. However, it just made an initial step towards investigating functional meaning of the created patches, and focused on the spatial rather than the socio-economic. The latest space syntax researches suggested that the street itself was a place for community interaction, with varying degrees of mixing across social groupings (Vaughan, 2018: 215). The empirical studies also implied that urban spatial configuration might play a key role in socio-economic differentiation (Omer, Goldblatt, 2012; Law, 2017; Major, 2018). It might be conjectured that the created patches, arising from the spatial interaction between the internal and the external, might sustain social differentiations and/or groupings. Movements along the streets between the patches and the contexts play a fundamental role in generating those patches. A more systematical, detailed and in-depth comparison between socio-economic data and created patches is required to help understand the social or economic significance of the periodic patchwork patterns.

References


