

Geographical Characterisation of British Urban Form and Function using the Spatial Signatures Framework

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ABSTRACT

The spatial arrangement of the building blocks that make up cities matters to understand the rules directing their dynamics. Our study outlines the development of the national open-source classification of space according to its form and function into a single typology. We create a bespoke granular spatial unit, the enclosed tessellation, and measure characters capturing its form and function within a relevant spatial context. Using K-Means clustering of individual enclosed tessellation cells, we generate a classification of space for the whole of Great Britain. Contiguous enclosed tessellation cells belonging to the same class are merged forming spatial signature geometries and their typology. We identify 16 distinct types of spatial signatures stretching from wild countryside, through various kinds of suburbia to types denoting urban centres according to their regional importance. The open data product presented here has the potential to serve as boundary delineation for other researchers interested in urban environments and policymakers looking for a unique perspective on cities and their structure.

Background & Summary

How the building blocks that make up cities are spatially arranged is worth quantifying and understanding. By "building blocks", we mean both the activities and agents that inhabit cities, as well as the (infra)structure that supports them. The former can be conceptualised as *urban function*, while the latter falls under the study of *urban form*. Understanding urban form and function is important for two main reasons. First, the combination of both *encodes* rich information about the history, character and evolution of cities. For example, the shape and properties of the street network encode the technology of the time (e.g., automobile); while the degree of mix in land uses can reflect cultural values. Second, the spatial pattern of urban form and function also acts as a frame that *influences* a variety of outcomes, from economic productivity to socio-economic cohesion to environmental sustainability.

In this paper, we use the Spatial Signatures framework^{1,2}, which develops a "characterisation of space based on form and function designed to understand urban environments"¹. Spatial signatures are theory-informed, data-driven computable classes that describe the form and function of a consistent patch of geography. Figure 1 presents an overview of the development of a spatial signature classification. We build a series of enclosures that we combine with building footprints to further subdivide geographical space into what we call enclosed tessellation cells (ETCs). We then attach form and function characters to each of these subdivisions, and use those to group them into consistent and differentiated classes we call signatures. Each phase is expanded in detail in the next section.

We introduce an open data product (ODP³) containing a classification of spatial signatures for Great Britain (illustrated in a figure 2). In doing so, we provide an analysis-ready layer that brings together urban form and function consistently, in detail, and at national scale. To the best of our knowledge, this is the first dataset capturing urban form and function published both with a degree of detail and scale as ours. Our results are based on the analysis of more than 14 million of ETCs, to each of which we attach more than 300 characters capturing a wide range of aspects relating to urban form and function. We provide access to both granular geographical boundaries of the delineated spatial signatures as well as measurements for each character at the signature level. The ODP also includes a web map that allows exploration without any technical requirement other than a web browser, and we have open sourced all the code, including details on the computational backend. The uniqueness of our ODP makes it challenging to set up a technical validation as a comparison with existing datasets. Nevertheless, we relate our signatures to a few well-established data products that capture each a subset of the form and function dimensions we consider. Our results are encouraging in that they show broad agreement in expected areas, but also highlight aspects that can only be discovered when considering form and function in tandem.

The approach and outputs presented bring several benefits to a range of stakeholders interested in cities. This spatial signatures ODP provides insight generated from detailed, comprehensive and computationally intensive data analysis and presents it in a way that is easy to access, work with and integrate into larger projects. Together with the importance of form and function discussed above, we anticipate the output will be relevant to both academic researchers as well as policymakers and practitioners. As a framework, the spatial signatures provide a flexible yet generalisable way to understand, characterise and quantify urban form and function. One way to understand our results is as an application to Great Britain of a more general approach to quantitatively characterise the spatial dimension of cities. As such, our conceptual approach can be applied in many more local contexts and regions beyond Great Britain. It is true that Great Britain currently represents an unusual case in that it is specially “data dense”, with a large variety of open data that may not be readily available in other parts of the world. However, given form and function reinforce each other, spatial signatures are designed to be robust to variations in the specific data sources used, and two different classifications do not need to be based on exactly the same data to be useful. At the same time, we note that the combination of volunteered geographic information (e.g., OpenStreetMap) and technologies such as modern satellites and artificial intelligence are filling many of these gaps very rapidly, and we anticipate near-future developments that will make the implementation of classifications such as the one presented here possible in almost any (urban) area of the planet. In this sense, our ODP (data, code, and methodology) can be a useful illustration for researchers and practitioners who, even if not specifically interested in the British use case, would like to implement a similar approach on their own.

As illustration of potential applications, we provide two. The spatial signatures may be used to delineate types of (origin and destination) locations in mobility analysis, that could unveil patterns of commuting or migration in situations like the COVID-19 pandemic. A second application may focus directly on supporting policy on inequalities. For example the spatial signatures can underpin analysis on equality of access to services and amenities within the UKs Levelling Up agenda⁴, using them to target areas based on their signature type, since they will share key structural components. It is important to note we do not expect signatures to focus on a single aspect of urban environment as, for example, Local Climate Zones⁵ do with climate, but instead on a wider range of uses due to their inclusion of both form and function and a data driven nature reflecting the specific place rather than abstract conceptual classes. In this respect, we hope the present paper serves not only to document our own work but to inspire future efforts aimed at urban form and function.

Methods

The method of identification of spatial signatures consists of three top-level steps. First, we delineate a spatial unit of analysis that reflects the structure of urban phenomena on a very granular level. Then we characterise each of them according to form and function, capturing the nature of each unit and its spatial context. Finally, we use cluster analysis to derive a typology of our spatial units that, once combined into contiguous areas, forms a typology of spatial signatures.

Spatial unit

The first major methodological decision relates to the definition of the spatial unit. An ideal candidate needs to reflect space in a granular manner, and we argue it should fulfil three conditions. First, it should be *indivisible*, meaning that any subdivision would result in a unit that is incapable of capturing the nature of urban form and function. Second, it needs to be *internally consistent* - it should always reflect only a single signature type. Last, it should be geographically *exhaustive*, covering the entirety of the study area.

Spatial units used in literature can be split into three groups. One is using administrative boundaries like city regions⁶, wards or census output areas⁷, that are convenient to obtain and can be easily linked to auxiliary data. However, those rarely reflect the morphological composition of urban space and, in some cases, may even “obscure morphologic reality”⁸. At the same time, most of them are divisible, and larger units are not always internally consistent. Another group is based on arbitrary uniform grids linked either to spatial indexing methods like H3⁹ or Ordnance Survey National Grid, or to ancillary data of remote sensing or other origins like a WorldPop grid¹⁰. Grids however cannot be considered internally consistent as they do not consider the underlying structure of the landscape. Finally, urban morphology studies tend to use morphological elements as street segments¹¹, blocks¹², buildings¹³ or plots¹⁴ as units of analysis. Some of those could be seen as indivisible and internally consistent, but since they are largely based on built-up fabric, they are not exhaustive. For example, in areas without any building or street, there is no spatial unit to work with. Plots could be theoretically considered as exhaustive, consistent and indivisible, but there is no accepted conceptual definition and unified geometric representation¹⁵.

We are, therefore, proposing an application of an alternative spatial unit called *enclosed tessellation cell* (ETC), defined as “the portion of space that results from growing a morphological tessellation within an enclosure delineated by a series of natural or built barriers identified from the literature on urban form, function and perception”¹. ETCs follow the morphological tradition in that it is based on the physical elements of an environment but overcome the drawbacks of conventionally used units. Its geometry is generated in the three steps illustrated in a Figure 3. First, a set of features representing physical barriers subdividing space, in our case composed of the street network, railways, rivers and a coastline, is combined, generating a layer

of boundaries (3 A). These then partition space into smaller enclosed geometries called *enclosures* (3 B), which can be very granular or very coarse depending on the geographic context. In dense city centres where a single enclosure represents a single block is a high frequency of small enclosures. At the same time, in the countryside, this approach leads to very few large enclosures as their delimiters are far away from each other. Enclosures are then combined with building footprints (3 B), which act as anchors in space and potentially subdivide enclosures into enclosed tessellation cells using the morphological tessellation algorithm¹⁶ (3 D), a polygon-based adaptation of Voronoi tessellation. The resulting geometries are indivisible as they contain, at most, a single anchor building, internally consistent due to their granularity and link to morphological elements composing urban fabric, and geographically exhaustive as they cover an entire area limited by specified boundaries.

In our ODP for Great Britain, street networks are extracted from OS Open Roads datasets¹⁷ representing simplified road centrelines cleaned of underground road segments. Railways are retrieved from OS OpenMap - Local¹⁸ ("RailwayTrack" layer) which captures surface railway tracks. Rivers are extracted from OS OpenRivers¹⁹ representing river network of GB as centrelines, and a coastline is retrieved from OS Strategi®²⁰, capturing coastline as a continuous line geometry. Building geometry is extracted, again, from OS OpenMap - Local ("Building" layer) and represents generalised building footprint polygons.¹

Characterisation of space

Spatial signatures capture the character of the built and unbuilt environment based on two components - form and function. Each of them is quantified at the level of individual ETCs using methods appropriate for each specific dataset. While form is described using urban morphometrics (i.e. quantitative analysis of urban form)²¹, function is a composite of a variety of data inputs. We outline each component with a bit more detail below.

Form

Morphometric characterisation of urban form is based on the numerical description of four elements capturing the built environment - buildings, streets, ETCs, and enclosures - and reflects their patterns based on six categories of characters: dimensions, shapes, spatial distribution, intensity, connectivity and diversity²². Each element is considered across different scales, from the measurement of individual geometries, to relations of neighbouring geometries, to a graph-based analysis of the street network. The combination of elements, categories and scales results in a set of 59 individual morphometric characters listed in the table 1. The selection builds on the principles outlined by²¹ and later explored by²³, both following the rules derived by²⁴. The gist is to include as many characters present in literature as is feasible, while minimising potential collinearity and limiting redundancy of information. That can be caused by capturing the same phenomena, like a specific aspect of a shape of a building, using multiple characters. Note that the characters that are statistically correlated but capture different concepts are kept as such information is reflective of a nature of urban form and increases the robustness of the method.

However, measuring individual characters is not enough to understand the predominant spatial patterns. For some types of urban environment, high heterogeneity is not uncommon. This means that using, for example, areas of building footprints would, in most cases, result in largely discontinuous clusters that do not capture the pattern within an area. Therefore, we represent each of the morphometric characters using three summary variables reflecting statistical distributions of measured data within a spatial context of each ETC. Context is defined as tenth order of contiguity computed across the mesh composed of contiguous ETCs as illustrated in figure 4. Furthermore, each value is weighted by the inverse distance between so-called poles of inaccessibility (defined as a centre of a maximum inscribed circle) of each ETC. Three proxy variables then capture the first, the second and the third quartile of the resulting weighted distribution. Such a characterisation can capture the contextual tendency of each morphometric character and hence identify contiguous clusters in both homogenous and heterogeneous urban tissues. These contextual values are then used as an input for cluster analysis while the original non-contextualised versions are left out, making the final form component composed of 177 contextual characters.

Function

Characterisation of the function component uses a different approach. While data describing urban form are not generally available in a processed format, forcing us to employ morphometric approaches, different aspects of function are often available as open data products. We guide the compilation of functional characters following three main principles: first, we identify from the literature on urban function key areas to be represented; second, we translate those abstract areas into measurable features; and third, we select open data available in for Great Britain that allows for the redistribution of derivative products. With a list of function characters selected, the main goal of our characterisation of ETCs based on function is to develop appropriate transfer methods to link data published as grids or linked to administrative boundaries to ETCs.

In this work, we are using five different transfer methods: Areal interpolation, Building-based dasymetric areal interpolation²⁵ using building footprint area, Network-constrained accessibility, Euclidean accessibility, and Zonal statistics. Areal

¹Note that the dataset does not distinguish between individual buildings when they are adjacent (e.g. perimeter block composed of multiple buildings is represented by a single polygon).

interpolation is used when the functional data covers the entirety of space in the form of polygon geometry and when there is no assumption that the phenomena it captures are linked directly to the human population, such as land cover data. When there is an assumption of relation to the population, building-based dasymetric areal interpolation is used instead. The main difference is that instead of ETC polygons, building footprint polygons linked to individual ETCs are used as a target of interpolation. That ensures that data like population estimates are linked to ETCs proportionally to their ability to house population rather than by their area. Network-constrained accessibility is used when the input data represents points of interest like locations of supermarkets. Points are then snapped to the nearest node on the street network and linked to the ETCs through the count of observations accessible from the cell within 15 minutes of walk (1200m on the street network) and a distance to the nearest point. In some cases, Euclidean (as-crow-flies) accessibility is measured instead to accommodate for phenomena that are often outside the reach of a drivable network like water bodies. Zonal statistics are used to transfer data originally stored in a raster format to ETCs as the mean value of raster pixels intersecting each polygon geometry. Finally, characters based on interpolation and zonal statistics are expressed using their contextual versions following the method used for form characters to, again, reflect the contextual pattern of measured values. As in the case of morphometric characters, only contextual versions are then used in the cluster analysis. The selection of datasets and the chosen transfer method are listed in the table 2.

Cluster analysis

When combined, contextual summaries of form and function characters (or characters themselves when they are reflecting the context by definition) compose a dataset describing each ETC by 331-328 variables (177 contextual characters representing 59 initial characters for form and 154-151 for function composed of 144 contextual characters representing 48 characters that do not capture context by design and 10 accessibility-based characters that do). Assigning equal weight to each variable, we standardize them applying Z-score normalization, and use them as input for K-Means cluster analysis. Although collinearity is likely to be present between several of them, we do not view this as a problem: we select each character not from a purely statistical point of view (i.e., which ones will be more effective at segmenting the dataset), but instead from a conceptual one. Each variable has been identified by the literature on urban form and function as a relevant aspect that contributes to collectively characterising these two more abstract concepts. We thus see this situation as a way of adding robustness to the measurement of more conceptual notions which are ultimately our aim. We opt for K-Means because we consider it strikes a compromise in the trade-off between performance and scalability. K-Means is widely used in the literature on unsupervised learning, and in much of that concerning the clustering of geographic entities²⁶. To select the algorithm, we experimented with a random subset of our dataset, comparing K-Means with alternatives such as Gaussian Mixture Models (GMM) or Self-Organising Maps (SOM). We found results from the latter two were not notably better in terms of cluster compactness and qualitative examination of the geographic clusters, but were significantly slower in computation runtime, posing serious challenges to be run at scale. Although K-Means does not consider space explicitly, our approach incorporates information about the geographic context of each observation through the operation described above and illustrated in Figure 4. We prefer this over a spatially-constrained algorithm (e.g., SKATER²⁷) that restricts the clustering only among spatially contiguous observations because we are not interested in areas that are spatially contiguous unless they are sufficiently similar to each other on the attribute space. Our contextual approach is more similar to spatially-encouraged algorithms such as the GeoSOM²⁸ or spatially-encouraged spectral clustering²⁹ that incorporate geographic proximity when clustering but do not restrict. Our choice in this case was led by its scalability over other such algorithms. Nevertheless, we consider this a fruitful avenue for future research.

Due to the nature of the selected K-Means clustering, the step preceding the final analysis is the selection of an optimal number of clusters. We use the clustergram exploratory method³⁰, reflecting the behaviour of different options, the relationship between clustering solutions regarding the allocation of individual observations to classes, and the separation between the clusters within each tested solution (figure 5). Clustergram is further accompanied by measures of internal validation measures - the Silhouette score diagram, Calinski-Harabasz index³¹ and Davies-Bouldin index³². The optimal number of classes is selected based on the interpretation of clustergram supported by additional measures aiming at a balance between cluster separation and an appropriate detail of resulting classification. We use mini batch K-Means with a batch size of 1,000,000 and 100 initialisations to create the clustergram and test number of clusters between 2 and 25. The results indicate 10 clusters as an optimal solution. The final clustering solution is generated using mini batch K-Means with a batch size of 1,000,000 and 1,000 initialisations to ensure the stability of the outcome.

The results of the clustering capture the first group of a national signature classification composed of ten clusters. However, since the classified ETCs cover the entirety of space, from vast natural open spaces to dense city centres, it may result in only a few classes representing urban areas. While that is caused by the variable heterogeneity of our dataset in combination with K-Means clustering, the measured characters have the ability to further distinguish classes of already identified clusters. As spatial signatures are focused on the urban environment, we further subdivide those clusters covering a substantial portion of urban areas using another iteration of K-Means clustering (one class into nine and another into three clusters). Both subdivisions were created using standard K-Means (single batch) using 1,000 initialisations. The resulting classification then provide

provides classification capturing the typology of spatial signatures with a detailed focus on urban development.
Finally, individual spatial signature geometries are generated as a combination of adjacent ETCs belonging to the same signature class. To describe each geometry and each signature type, we measure mean values of the original, non-contextualised characters, and release it as additional descriptive tables. The resulting numerical profile of each signature type is available as table 3. Table 4 contains pen portraits derived from these numerical profiles.

Data Records

The data product described in this article is available through the Consumer Data Research Centre Open Data repository available at <https://data.cdrc.ac.uk/dataset/spatial-signatures-great-britain> under the Open Government Licence v3.0 license and archived at <https://doi.org/10.6084/m9.figshare.16691575.v1>. The dataset stored in the repository contains a GeoPackage with a signature geometry (OSGB36 / British National Grid (EPSG: 27700) CRS) and related signature type, plain-text pen portraits describing individual signature types, a series of CSV files describing individual signatures and signature types, and a CSV files linking signature types to the Output Area and Lower Super Output Area geometry. An online interactive map of spatial signatures for the whole of Great Britain is available on the project website (<https://urbangrammarai.xyz/great-britain>). The underlying data used to create the ODP are available in a dedicated GitHub repository available from (https://github.com/urbangrammarai/signatures_gb).

Composition and comparison

Character importance

The characters used in the cluster analysis have each different importance in distinguish between signature types. Those characters which spatial distribution most closely matches the distribution of signatures can be seen as more important than those that are seemingly random or mostly invariant (as some of the land cover classes are). Unpacking the importance of individual characters from K-Means clustering cannot be done directly, ~~but a useful method is to~~. However, we can use F-test to assess the significance of the relationship between the characters and signature types or train a supervised model, in our case Random Forest, designed to predict individual signature types from input data. Such a model then The former unpacks whether all the characters play a role in the delineation of clusters while the latter provides a feature importance - a relative measure of a strength of each character in distinguishing between the types. Out of 328 characters, 18 are invariant² and 5 insignificant³ (all derived from land cover) according to the F-test results. The results of this the Random Forest-based feature importance approach are shown in a table 5. As you can see, form-based characters dominate the top 10 characters, but it is worth noting that these top 10 characters together bear only 0.196 of the overall importance.

A similar exercise can be done on a level of individual clusters, with a binary Random Forest model trained to distinguish that particular class from the other. Resulting relative importance of top 10 characters for each signature type is presented in a table 6. While it is clear that form-based characters still dominate the prediction, the more urban signature types are, the higher the importance of function seems to be. Complete tables with all characters are available as online tables 1 and 2.

Comparison

Spatial signatures are unique as a classification method, limiting the potential validation. Therefore, we rather present a comparison of signatures and ancillary datasets capturing conceptually similar aspects of the environment. We compare the signatures with four of such datasets, each focusing on a different classification perspective, but all related to our classification to a degree when we can assume there will be a measurable level of association between the two:

- WorldPop settlement patterns of building footprints (2021)¹⁰
- Classification of Multidimensional Open Data of Urban Morphology (MODUM) (2015)⁷
- Copernicus Urban Atlas (2018)³³
- Local Climate Zones (2019)³⁴

²Land cover [Airports] Q1, Land cover [Mineral extraction sites] Q1, Land cover [Road and rail networks and associated land] Q1, Land cover [Water bodies] Q1, Land cover [Inland marshes] Q1, Land cover [Dump sites] Q1, Land cover [Water courses] Q2, Land cover [Burnt areas] Q2, Land cover [Water courses] Q1, Land cover [Burnt areas] Q1, Land cover [Agro-forestry areas] Q3, Land cover [Coastal lagoons] Q2, Land cover [Burnt areas] Q3, Land cover [Agro-forestry areas] Q1, Land cover [Agro-forestry areas] Q2, Land cover [Dump sites] Q2, Land cover [Coastal lagoons] Q1, Land cover [Coastal lagoons] Q3³

³Land cover [Green urban areas] Q1, Land cover [Road and rail networks and associated land] Q2, Land cover [Water bodies] Q2, Land cover [Transitional woodland-shrub] Q1, Land cover [Coniferous forest] Q1

238 Comparison approach

239 All datasets, spatial signatures and those selected for a comparison contain a categorical classification of space linked to their
240 unique geometry. The first requirement to be able to compare data products is to transfer their information to the same geometry.
241 We take two approaches for this step, depending on the dataset we are comparing the signatures with: an interpolation of
242 one set of polygon-based data to another (input to ETCs); or the conversion of spatial signatures to the raster representation
243 matching an input raster, which is computationally more efficient when one of the layers is already a raster. The second step is a
244 statistical comparison of two sets of classification labels, one representing spatial signature typology and the other comparison
245 classes. We use contingency tables and Pearson's χ^2 test to determine whether the frequencies of observed (signature types) and
246 expected (comparison types) labels significantly differ in one or more categories. Furthermore, we use Cramér's V statistics³⁵
247 to assess the strength of the association.

248 WorldPop settlement patterns of building footprints

249 WorldPop settlement patterns of building footprints dataset aims to derive a typology of morphological patterns based on a
250 gridded approach with cells of 100x100m, and building footprints. Authors measure six morphometric characters linked to the
251 grid cells and use them as input for an unsupervised clustering algorithm leading to a six-class typology. As the classification is
252 dependent on building footprints, grid cells that do not contain any information on the building-based pattern are treated as
253 missing in the final data product. For the comparison, this *missing* category is treated as a single class. It is assumed that the
254 top-level large scale patterns detected by the WorldPop method and spatial signatures will provide similar results. However,
255 there will be differences caused by the inclusion of function in spatial signatures, higher granularity of both initial spatial units
256 and the resulting classification (6 vs 19 classes).

257 Signature typology is rasterized and linked to the WorldPop grid. The resulting contingency table is shown in Figure 6.
258 There is a significant relationship between two typologies, $\chi^2(114, N = 22993921) = 13341832, p < .001$. The strength of
259 association measured as Cramér's V is 0.311, indicating moderate association. The contingency table shows that WorldPop
260 classes tend to be linked to groups of signature types of a similarly degree of urbanity. A WorldPop class 15 is "undefined"
261 due to the lack of building footprints in the area, therefore overlapping a large portion of signatures. The difference between
262 classifications is likely driven by two main aspects - one is the different number of classes. We can see that WorldPop classes
263 tend to cluster ~~wihtin~~ within a limited number of signature types and vice versa. The only exception is allocation of signature
264 types into classes 4 and 6, which seems to heavily overlap. That is possibly caused by the second aspect - inclusion of function.
265 Both classes 4 and 6 tend to be outside of city centres but still within urban areas. While it is the footprint-based form that is
266 driving the difference between them, signatures in the same area are often ~~disntinguished~~ distinguished by function and varies
267 access to amenities and services.

268 MODUM

269 Multidimensional Open Data Urban Morphology (MODUM) classification describes a typology of neighbourhoods derived
270 from 18 indicators capturing built environment as streets, railways or parks, linked to the Census Output Area geometry. The
271 classification identifies 8 types of neighbourhoods. Compared to the WorldPop classification, MODUM takes into account
272 more features of the built environment than building footprints, which makes it conceptually closer to the spatial signatures.
273 However, it is still focusing predominantly on the form component, although there are some indicators that would be classified
274 as function within the signatures framework (e.g. population). The MODUM method uses a different way of capturing context
275 compared to the signatures, which leads to some classes being determined predominantly by a single character. For example,
276 the *Railway Buzz* type forms a narrow strip around the railway network, which is an effect signatures avoid. MODUM typology
277 is available only for England and Wales. Therefore, the comparison takes into account only ETCs covering the same area.
278 The classification is linked to the ETC geometry is based on the proportion (the type covering the largest portion of ETC is
279 assigned). The resulting contingency table is shown in Figure 7. There is a significant relationship between two typologies,
280 $\chi^2(152, N = 13067584) = 13938867, p < .001$. The strength of association measured as Cramér's V is 0.300, indicating
281 moderate association of very similar levels we have seen above. The contingency table indicates similar relationships, where a
282 single MODUM class overlaps a group of signature types. However, the groups tend to be well defined and formed based on
283 the similarity of types. Signature types are minimally present in MODUM classes driven by a single character (*Railway Buzz*,
284 *Waterside Settings*, *High Street and Promenades*), suggesting the more balanced weight of characters.

285 Copernicus Urban Atlas

286 Copernicus Urban Atlas is the least similar of the comparison datasets. It is a high-resolution land use classification of functional
287 urban areas derived primarily from Earth Observation data enriched by other reference data as OpenStreetMap or topographic
288 maps. Its smallest spatial unit in urban areas is 0.25 ha and 1 ha in rural areas, defined primarily by physical barriers. It
289 identifies 27 predefined classes using the supervised method. The majority of urban areas is classified as urban fabric further
290 distinguished based on continuity and density resulting in six classes of the urban fabric. The classification does not consider

the type of the pattern or any other aspect. Furthermore, it does not take into account what signatures call *context* as each spatial unit is classified independently, which in some cases leads to the high heterogeneity of classification within a small portion of land. Signatures take a different approach. Consequently, it is expected that the similarity between the two will be limited. Urban Atlas is available only for functional urban areas (FUA), leaving rural areas unclassified. Comparison then applies to FUAs only. The classification is linked to the ETC geometry based on the proportion (the type covering the largest portion of ETC is assigned). The resulting contingency table is shown in Figure 8. There is a significant relationship between two typologies, $\chi^2(450, N = 8396642) = 5229900, p < .001$. The strength of association measured as Cramér's *V* is 0.186, indicating a weak association. The contingency table shows the difference in the aim of spatial signatures and that of Urban Atlas with a majority of signatures being linked to a few of Urban Atlas classes. Within relevant classes, we see a tendency of signature types to cluster within Urban Atlas classes based on the level of urbanity, albeit not as strong as in the previous two cases. The main reason behind such a large difference are the aims of both classifications. While the Copernicus Urban Atlas ~~attempts~~ attempts to capture land cover, resulting in a large number of non-urban classes, spatial signatures are aimed at urban environment with 13 out of 16 classes covering primarily urbanised areas.

Local Climate Zones

Local climate zones (LCZ) are conceptual classes originally designed to support study of urban climate as temperature. It consists of 17 classes of which 10 can be classified as urban and 7 and natural ones. In the context of Great Britain, the dataset used in this study does not contain 2 of them, *Lightweight low-rise* and *Compact highrise* as they are not present in the British landscape. The datasets produced by³⁴ released LCZs in a 100 meters grid based on the 2016 data. As the LCZs are remotely sensed in this case, authors report overall average accuracy of 80 %. As a conceptual classification aimed to cover all possible types of ~~primarily~~ primarily urban climate zones globally, LCZs may not be optimal when looking into a single country with specific history of urban development. This is ~~further~~ further indicated by classes that are missing. It is therefore likely that large parts of British cities will fall into only a few of LCZ classes, while being ~~represented~~ represented by a much larger number of signature types.

Signature typology is rasterized and linked to the LCZ grid. The resulting contingency table is shown in Figure 9. There is a significant relationship between two typologies, $\chi^2(225, N = 1620338) = 18467242, p < .001$. The strength of association measured as Cramér's *V* is 0.276, indicating a modest to weak association, close to values we've seen in first two cases. As expected, urban signature types are clustered primarily within *Compact midrise* and *Open lowrise* LCZs, while non-urban signatures mostly fall into the *Low plants* LCZ.

The difference between signatures and LCZs can be accounted to two aspects. One, as we've seen before is the inclusion of function in spatial signatures, differentiating e.g. LCZ's *Open lowrise* into many signature types. The other is data-driven nature of signatures compared to conceptual LCZs, where differences in signature types are below the resolution capability of simple matrix composed of density and compactness levels. On the other, it is encouraging to see that most of signature types fall predominantly in a single LCZ class, suggesting that while both classifications are built differently, they are able to capture similar large-scale patterns in cities.

Summary

None of the comparisons shows more than a moderate association, but since none of the comparison datasets is aiming to capture the same conceptualization of space as spatial signatures do, such a result is expected. The moderate association with both WorldPop settlements patterns and MODUM is reassuring as both are conceptually closer to signatures than the Urban Atlas (especially in their unsupervised design). Urban Atlas, though very different in its aims and methods, still shows a measurable association, which we interpret as sign that the key structural aspects forming cities are captured by both. The comparison exercise suggests that general patterns forming cities are shared among signatures and existing typologies. Signature types tend to form groups when we look at their relation to comparison classes and it is not uncommon that a single signature type is present in multiple groups linked to different classes. However, all these groups tend to be formed based on the similarity and illustrate the granularity of the presented classification compared to existing datasets, allowing us to distinguish, for example, five types of signature types forming town ~~an~~ and city centres.

Usage Notes

The released data product follows widespread standards for geographic data storage and should be easy to integrate with other data and methods by researchers wanting to reuse it. However, due to the density of signature geometry (resulting from the detailed ETCs), it may be needed to simplify the geometry for a smoother interactive experience on machines with limited resources.

Replication of the analysis optimally requires at least a single computational node with a large amount of RAM (+100GB) due to the size of the input data and detail on which signature ~~echaracterization~~ characterisation is computed. It is also

343 recommended to revisit revisiting the state of the development of related software packages, notably `momepy`³⁶, `libpysal`³⁷,
344 `tobler`²⁵ and `dask-geopandas` as they may soon offer more efficient drop-in replacements of the custom code used to
345 produce this dataset.

346 Code availability

347 The source code used to produce this dataset is openly available in a GitHub repository at
348 https://github.com/urbangrammarai/spatial_signatures and in the form of a website on <https://urbangrammarai.xyz>. Code is
349 organized in a series of Jupyter notebooks and have been executed within the `darribas:gds_dev:6.1`³⁸ Docker container,
350 unless specified otherwise in the individual notebooks.

351 References

- 352 1. Arribas-Bel, D. & Fleischmann, M. Spatial Signatures - Understanding (urban) spaces through form and function (2021).
353 Mimeo.
- 354 2. Fleischmann, M. & Arribas-Bel, D. Classifying urban form at national scale - The British morphosignatures (2021).
355 Proceedings of XXVIII International Seminar on Urban Form.
- 356 3. Arribas-Bel, D., Green, M., Rowe, F. & Singleton, A. Open Data Products: a framework for creating valuable analysis-ready
357 data. *J. Geogr. Syst.* (*forthcoming*).
- 358 4. HM Government. Levelling Up the United Kingdom. <https://www.gov.uk/government/publications/levelling-up-the-united-kingdom> (2022). London: The Stationery Office.
- 360 5. Stewart, I. D. & Oke, T. R. Local climate zones for urban temperature studies. *Bull. Am. Meteorol. Soc.* **93**, 1879–1900
361 (2012).
- 362 6. Angel, S., Arango Franco, S., Liu, Y. & Blei, A. M. The shape compactness of urban footprints. *Prog. Plan.* **139**, 100429,
363 [10/gg638j](#) (2020).
- 364 7. Alexiou, A., Singleton, A. & Longley, P. A. A Classification of Multidimensional Open Data for Urban Morphology. *Built
365 Environ.* **42**, 382–395, [10/gddwsn](#) (2016).
- 366 8. Taubenböck, H. *et al.* A new ranking of the world's largest cities—do administrative units obscure morphological realities?
367 *Remote. Sens. Environ.* **232**, 111353 (2019).
- 368 9. Brodsky, I. H3: Uber's hexagonal hierarchical spatial index. Available from Uber Eng. website: [https://eng.uber.com/h3/\[22 June 2019\]](https://eng.uber.com/h3/[22 June 2019]) (2018).
- 370 10. Jochem, W. C. & Tatem, A. J. Tools for mapping multi-scale settlement patterns of building footprints: An introduction to
371 the R package foot. *PLoS one* **16**, e0247535, [10/gh7sjr](#) (2021).
- 372 11. Araldi, A. & Fusco, G. From the street to the metropolitan region: Pedestrian perspective in urban fabric analysis:. *Environ.
373 Plan. B: Urban Anal. City Sci.* **46**, 1243–1263, [10.1177/2399808319832612](#) (2019).
- 374 12. Gil, J., Montenegro, N., Beirão, J. N. & Duarte, J. P. On the Discovery of Urban Typologies: Data Mining the Multi-
375 dimensional Character of Neighbourhoods. *Urban Morphol.* **16**, 27–40 (2012).
- 376 13. Hamaina, R., Leduc, T. & Moreau, G. Towards Urban Fabrics Characterization Based on Buildings Footprints. In *Bridging
377 the Geographic Information Sciences*, vol. 2, 327–346, [10.1007/978-3-642-29063-3_18](#) (Springer, Berlin, Heidelberg,
378 Berlin, Heidelberg, 2012).
- 379 14. Bobkova, E., Berghauer Pont, M. & Marcus, L. Towards analytical typologies of plot systems: Quantitative profile of five
380 European cities. *Environ. Plan. B: Urban Anal. City Sci.* [239980831988090](#), [10/ggbgsm](#) (2019).
- 381 15. Kropf, K. Plots, property and behaviour. *Urban Morphol.* **22**, 5–14 (2018).
- 382 16. Fleischmann, M., Feliciotti, A., Romice, O. & Porta, S. Morphological tessellation as a way of partitioning space:
383 Improving consistency in urban morphology at the plot scale. *Comput. Environ. Urban Syst.* **80**, 101441, [10.1016/j.comenvurbsys.2019.101441](#) (2020).
- 385 17. Ordnance Survey. OS Open Roads (2020).
- 386 18. Ordnance Survey. OS OpenMap - Local (2020).
- 387 19. Ordnance Survey. OS Open Rivers (2020).
- 388 20. Ordnance Survey. Strategi (2016).

- 389 21. Dibble, J. *et al.* On the origin of spaces: Morphometric foundations of urban form evolution. *Environ. Plan. B: Urban*
- 390 Anal. City Sci. **46**, 707–730 (2019).
- 391 22. Fleischmann, M., Romice, O. & Porta, S. Measuring urban form: Overcoming terminological inconsistencies for a
- 392 quantitative and comprehensive morphologic analysis of cities. *Environ. Plan. B: Urban Anal. City Sci.* 239980832091044,
- 393 [10/ggngw6](https://doi.org/10/ggngw6) (2020).
- 394 23. Fleischmann, M., Feliciotti, A., Romice, O. & Porta, S. Methodological foundation of a numerical taxonomy of urban
- 395 form. *Environ. Plan. B: Urban Anal. City Sci.* 23998083211059835 (2021).
- 396 24. Sneath, P. H., Sokal, R. R. *et al.* *Numerical taxonomy. The principles and practice of numerical classification.* (Freeman,
- 397 San Francisco, 1973).
- 398 25. eli knaap *et al.* pysal/tobler: Release v0.8.2, [10.5281/zenodo.5047613](https://doi.org/10.5281/zenodo.5047613) (2021).
- 399 26. Webber, R. & Burrows, R. *The predictive postcode: the geodemographic classification of British society* (Sage, 2018).
- 400 27. Lage, J. P., Assunção, R. M. & Reis, E. A. A minimal spanning tree algorithm applied to spatial cluster analysis. *Electron.*
- 401 *Notes Discret. Math.* **7**, 162–165 (2001).
- 402 28. Baçao, F., Lobo, V. & Painho, M. The self-organizing map, the geo-som, and relevant variants for geosciences. *Comput. &*
- 403 *geosciences* **31**, 155–163 (2005).
- 404 29. Wolf, L. J. Spatially–encouraged spectral clustering: a technique for blending map typologies and regionalization. *Int. J.*
- 405 *Geogr. Inf. Sci.* **35**, 2356–2373 (2021).
- 406 30. Schonlau, M. The clustergram: A graph for visualizing hierarchical and nonhierarchical cluster analyses. *The Stata J.* **2**,
- 407 391–402, [10.ghh97z](https://doi.org/10.ghh97z) (2002).
- 408 31. Caliński, T. & Harabasz, J. A dendrite method for cluster analysis. *Commun. Stat.* **3**, 1–27, [10.1080/03610927408827101](https://doi.org/10.1080/03610927408827101) (1974). <https://www.tandfonline.com/doi/pdf/10.1080/03610927408827101>.
- 409 32. Davies, D. L. & Bouldin, D. W. A cluster separation measure. *IEEE transactions on pattern analysis machine intelligence*
- 410 224–227 (1979).
- 412 33. European environment agency (EEA). *Urban Atlas* (2018).
- 413 34. Demuzere, M., Bechtel, B., Middel, A. & Mills, G. Mapping europe into local climate zones. *PloS one* **14**, e0214474
- 414 (2019).
- 415 35. Cramér, H. *Mathematical Methods of Statistics (PMS-9), Volume 9* (Princeton university press, 2016).
- 416 36. Fleischmann, M. momepy: Urban morphology measuring toolkit. *J. Open Source Softw.* **4**, 1807, [10.21105/joss.01807](https://doi.org/10.21105/joss.01807) (2019).
- 418 37. Rey, S. J. *et al.* The pysal ecosystem: Philosophy and implementation. *Geogr. Analysis* (2021).
- 419 38. Arribas-Bel, D. gds_env: A containerised platform for geographic data science, [10.5281/zenodo.4642516](https://doi.org/10.5281/zenodo.4642516).
- 420 39. Hallowell, G. D. & Baran, P. K. Suburban change: A time series approach to measuring form and spatial configuration. *The J. Space Syntax* **4**, 74–91 (2013).
- 422 40. Vanderhaegen, S. & Canters, F. Mapping urban form and function at city block level using spatial metrics. *Landsc. Urban*
- 423 *Plan.* **167**, 399–409, [10.1016/j.landurbplan.2017.05.023](https://doi.org/10.1016/j.landurbplan.2017.05.023) (2017).
- 424 41. Schirmer, P. M. & Axhausen, K. W. A multiscale classification of urban morphology. *J. Transp. Land Use* **9**, 101–130,
- 425 [10.5198/jtlu.2015.667](https://doi.org/10.5198/jtlu.2015.667) (2015).
- 426 42. Steiniger, S., Lange, T., Burghardt, D. & Weibel, R. An Approach for the Classification of Urban Building Structures
- 427 Based on Discriminant Analysis Techniques. *Transactions GIS* **12**, 31–59, [10.1111/j.1467-9671.2008.01085.x](https://doi.org/10.1111/j.1467-9671.2008.01085.x) (2008).
- 428 43. Basaraner, M. & Cetinkaya, S. Performance of shape indices and classification schemes for characterising perceptual shape
- 429 complexity of building footprints in GIS. *Int. J. Geogr. Inf. Sci.* **31**, 1952–1977, [10.1080/13658816.2017.1346257](https://doi.org/10.1080/13658816.2017.1346257) (2017).
- 430 44. Hamaina, R., Leduc, T. & Moreau, G. A New Method to Characterize Density Adapted to a Coarse City Model.
- 431 In *OpenStreetMap in GIScience*, 249–263, [10.1007/978-3-642-31833-7_16](https://doi.org/10.1007/978-3-642-31833-7_16) (Springer International Publishing, Berlin,
- 432 Heidelberg, 2013).
- 433 45. Hijazi, I. *et al.* Measuring the homogeneity of urban fabric using 2D geometry data. *Environ. Plan. B: Plan. Des.* 1–25,
- 434 [10.1177/0265813516659070](https://doi.org/10.1177/0265813516659070) (2016).
- 435 46. Boeing, G. A multi-scale analysis of 27,000 urban street networks: Every US city, town, urbanized area, and Zillow
- 436 neighborhood. *Environ. Plan. B: Urban Anal. City Sci.* **219**, 239980831878459, [10.1177/2399808318784595](https://doi.org/10.1177/2399808318784595) (2018).

- 437 47. Caruso, G., Hilal, M. & Thomas, I. Measuring urban forms from inter-building distances: Combining MST graphs with a
 438 Local Index of Spatial Association. *Landsc. Urban Plan.* **163**, 80–89, [10.1016/j.landurbplan.2017.03.003](https://doi.org/10.1016/j.landurbplan.2017.03.003) (2017).
- 439 48. Feliciotti, A. *RESILIENCE AND URBAN DESIGN: A SYSTEMS APPROACH TO THE STUDY OF RESILIENCE IN*
 440 *URBAN FORM*. Ph.D. thesis, University of Strathclyde, Glasgow (2018).
- 441 49. Lowry, J. H. & Lowry, M. B. Comparing spatial metrics that quantify urban form. *Comput. Environ. Urban Syst.* **44**,
 442 59–67, [10.1016/j.compenvurbsys.2013.11.005](https://doi.org/10.1016/j.compenvurbsys.2013.11.005) (2014).
- 443 50. Porta, S., Crucitti, P. & Latora, V. The network analysis of urban streets: A primal approach. *Environ. Plan. B: Plan. Des.*
 444 **33**, 705–725, [10.1068/b32045](https://doi.org/10.1068/b32045) (2006).

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449 Author contributions statement

450 M.F. and D.A. designed the method, M.F. conducted the experiments, M.F. and D.A. analysed the results. M.F. and D.A. wrote
 451 and reviewed the manuscript.

452 Competing interests

453 The authors declare no competing interests.

454 Figures & Tables

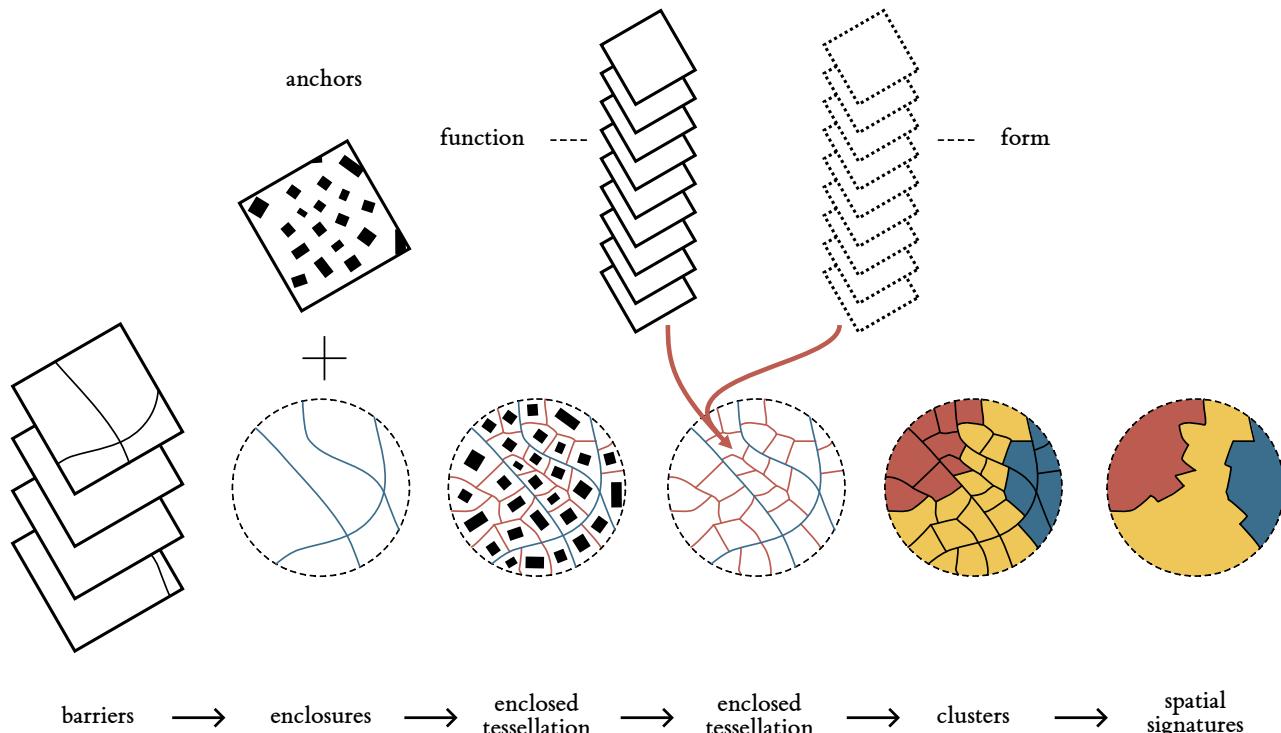


Figure 1. Diagram illustrating the sequential steps leading to the delineation of spatial signatures. From a series of enclosing components, to enclosures, enclosed tessellation (ET), the addition of form and function characters to ET cells, and the development of spatial signatures.

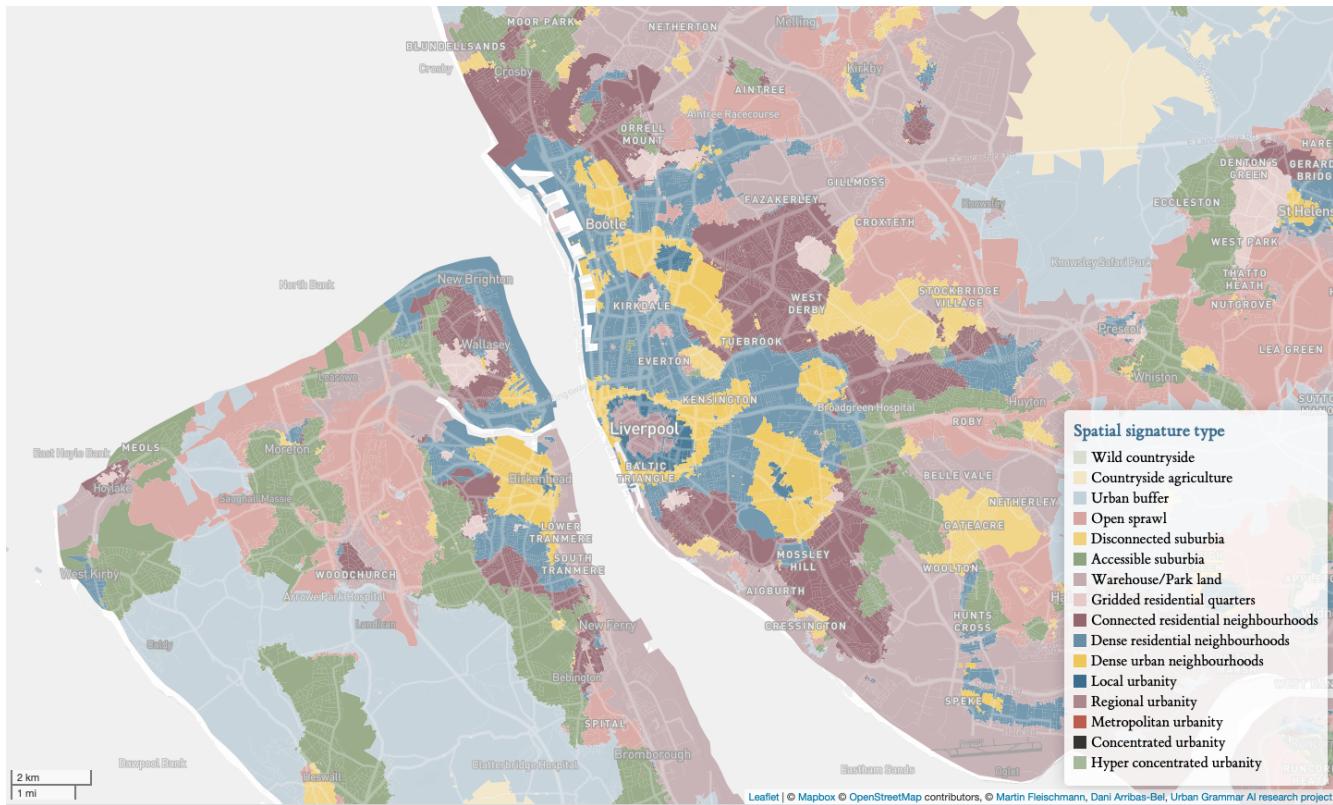


Figure 2. Illustration of a classification of spatial signatures in Liverpool and Birkenhead area, in the north west of England.

Table 1. Morphometric characters used to describe the form component of spatial signatures. For details of the implementation, refer to the reproducible Jupyter notebooks available at urbangrammarai.xyz.

character	category	reference
area of building	dimension	39
perimeter of building	dimension	40
courtyard area of building	dimension	41
circular compactness of building	shape	21
corners of building	shape	42
squareness of building	shape	42
equivalent rectangular index of building	shape	43
elongation of building	shape	42
centroid - corner distance deviation of building	shape	23
centroid - corner mean distance of building	dimension	41
orientation of building	distribution	41
street alignment of building	distribution	41
cell alignment of building	distribution	23
longest axis length of ETC	dimension	23
area of ETC	dimension	13
circular compactness of ETC	shape	23
equivalent rectangular index of ETC	shape	23
orientation of ETC	distribution	23
covered area ratio of ETC	intensity	44
length of street segment	dimension	12

Continued on next page

character	category	reference
width of street profile	dimension	11
openness of street profile	distribution	11
width deviation of street profile	diversity	11
linearity of street segment	shape	11
area covered by edge-attached ETCs	dimension	23
buildings per meter of street segment	intensity	23
area covered by node-attached ETCs	dimension	23
alignment of neighbouring buildings	distribution	45
mean distance between neighbouring buildings	distribution	45
perimeter-weighted neighbours of ETC	distribution	23
area covered by neighbouring cells	dimension	23
reached ETCs by neighbouring segments	intensity	23
reached area by neighbouring segments	dimension	23
node degree of junction	distribution	46
mean distance to neighbouring nodes of street network	dimension	23
mean inter-building distance	distribution	47
weighted reached enclosures of ETC	intensity	23
reached ETCs by tessellation contiguity	intensity	23
reached area by tessellation contiguity	dimension	23
area of enclosure	dimension	21
perimeter of enclosure	dimension	12
circular compactness of enclosure	shape	41
equivalent rectangular index of enclosure	shape	43
compactness-weighted axis of enclosure	shape	48
orientation of enclosure	distribution	12
perimeter-weighted neighbours of enclosure	distribution	23
area-weighted ETCs of enclosure	intensity	23
local meshedness of street network	connectivity	48
mean segment length within 3 steps	dimension	23
local cul-de-sac length of street network	dimension	23
reached area by local street network	dimension	23
reached ETCs by local street network	intensity	23
local node density of street network	intensity	23
local proportion of cul-de-sacs of street network	connectivity	49
local proportion of 3-way intersections of street network	connectivity	46
local proportion of 4-way intersections of street network	connectivity	46
local degree weighted node density of street network	intensity	21
local closeness of street network	connectivity	50
square clustering of street network	connectivity	23

Table 2. Functional characters used to describe the function component of spatial signatures. For details of the implementation, refer to the reproducible Jupyter notebooks available at urbangrammarai.xyz.

character	data	source	input geometry	transfer method
Population	Population estimates	ONS Census Output Area population estimates, Statistics.gov.scot	Vector (output area polygon)	Building-based dasymetric areal interpolation
Night lights	Night Lights	VIIRS DNB Nighttime Lights	Raster (500m)	Zonal statistics

Continued on next page

character	data	source	input geometry	transfer method	
Workplace population [Agriculture, energy and water]	Workplace population	ONS Census Workplace population, Scotland's census	Workplace population	Vector (output area polygon)	Building-based dasymetric areal interpolation
Workplace population [Manufacturing]	Workplace population	ONS Census Workplace population, Scotland's census	Workplace population	Vector (output area polygon)	Building-based dasymetric areal interpolation
Workplace population [Construction]	Workplace population	ONS Census Workplace population, Scotland's census	Workplace population	Vector (output area polygon)	Building-based dasymetric areal interpolation
Workplace population [Distribution, hotels and restaurants]	Workplace population	ONS Census Workplace population, Scotland's census	Workplace population	Vector (output area polygon)	Building-based dasymetric areal interpolation
Workplace population [Transport and communication]	Workplace population	ONS Census Workplace population, Scotland's census	Workplace population	Vector (output area polygon)	Building-based dasymetric areal interpolation
Workplace population [Financial, real estate, professional and administrative activities]	Workplace population	ONS Census Workplace population, Scotland's census	Workplace population	Vector (output area polygon)	Building-based dasymetric areal interpolation
Workplace population [Public administration, education and health]	Workplace population	ONS Census Workplace population, Scotland's census	Workplace population	Vector (output area polygon)	Building-based dasymetric areal interpolation
Workplace population [Other]	Corine land cover	Copernicus Land Monitoring Service	Vector (land cover zone polygon)	Areal interpolation	
Land cover [Airports]	Corine land cover	Copernicus Land Monitoring Service	Vector (land cover zone polygon)	Areal interpolation	
Land cover [Non-irrigated arable land]	Corine land cover	Copernicus Land Monitoring Service	Vector (land cover zone polygon)	Areal interpolation	
Land cover [Industrial or commercial units]	Corine land cover	Copernicus Land Monitoring Service	Vector (land cover zone polygon)	Areal interpolation	
Land cover [Salt marshes]	Corine land cover	Copernicus Land Monitoring Service	Vector (land cover zone polygon)	Areal interpolation	
Land cover [Estuaries]	Corine land cover	Copernicus Land Monitoring Service	Vector (land cover zone polygon)	Areal interpolation	
Land cover [Sport and leisure facilities]	Corine land cover	Copernicus Land Monitoring Service	Vector (land cover zone polygon)	Areal interpolation	
Land cover [Green urban areas]	Corine land cover	Copernicus Land Monitoring Service	Vector (land cover zone polygon)	Areal interpolation	
Land cover [Discontinuous urban fabric]	Corine land cover	Copernicus Land Monitoring Service	Vector (land cover zone polygon)	Areal interpolation	
Land cover [Pastures]	Corine land cover	Copernicus Land Monitoring Service	Vector (land cover zone polygon)	Areal interpolation	
Land cover [Broad-leaved forest]	Corine land cover	Copernicus Land Monitoring Service	Vector (land cover zone polygon)	Areal interpolation	
Land cover [Mineral extraction sites]	Corine land cover	Copernicus Land Monitoring Service	Vector (land cover zone polygon)	Areal interpolation	

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character	data	source	input geometry	transfer method
Land cover [Port areas]	Corine land cover	Copernicus Land Monitoring Service	Vector (land cover zone polygon)	Areal interpolation
Land cover [Road and rail networks and associated land]	Corine land cover	Copernicus Land Monitoring Service	Vector (land cover zone polygon)	Areal interpolation
Land cover [Water bodies]	Corine land cover	Copernicus Land Monitoring Service	Vector (land cover zone polygon)	Areal interpolation
Land cover [Land principally occupied by agriculture, with significant areas of natural vegetation]	Corine land cover	Copernicus Land Monitoring Service	Vector (land cover zone polygon)	Areal interpolation
Land cover [Mixed forest]	Corine land cover	Copernicus Land Monitoring Service	Vector (land cover zone polygon)	Areal interpolation
Land cover [Peat bogs]	Corine land cover	Copernicus Land Monitoring Service	Vector (land cover zone polygon)	Areal interpolation
Land cover [Natural grasslands]	Corine land cover	Copernicus Land Monitoring Service	Vector (land cover zone polygon)	Areal interpolation
Land cover [Moors and heathland]	Corine land cover	Copernicus Land Monitoring Service	Vector (land cover zone polygon)	Areal interpolation
Land cover [Transitional woodland-shrub]	Corine land cover	Copernicus Land Monitoring Service	Vector (land cover zone polygon)	Areal interpolation
Land cover [Continuous urban fabric]	Corine land cover	Copernicus Land Monitoring Service	Vector (land cover zone polygon)	Areal interpolation
Land cover [Intertidal flats]	Corine land cover	Copernicus Land Monitoring Service	Vector (land cover zone polygon)	Areal interpolation
Land cover [Sea and ocean]	Corine land cover	Copernicus Land Monitoring Service	Vector (land cover zone polygon)	Areal interpolation
Land cover [Coniferous forest]	Corine land cover	Copernicus Land Monitoring Service	Vector (land cover zone polygon)	Areal interpolation
Land cover [Construction sites]	Corine land cover	Copernicus Land Monitoring Service	Vector (land cover zone polygon)	Areal interpolation
Land cover [Sparsely vegetated areas]	Corine land cover	Copernicus Land Monitoring Service	Vector (land cover zone polygon)	Areal interpolation
Land cover [Bare rocks]	Corine land cover	Copernicus Land Monitoring Service	Vector (land cover zone polygon)	Areal interpolation
Land cover [Inland marshes]	Corine land cover	Copernicus Land Monitoring Service	Vector (land cover zone polygon)	Areal interpolation
Land cover [Dump sites]	Corine land cover	Copernicus Land Monitoring Service	Vector (land cover zone polygon)	Areal interpolation
Land cover [Fruit trees and berry plantations]	Corine land cover	Copernicus Land Monitoring Service	Vector (land cover zone polygon)	Areal interpolation
Land cover [Complex cultivation patterns]	Corine land cover	Copernicus Land Monitoring Service	Vector (land cover zone polygon)	Areal interpolation
Land cover [Beaches, dunes, sands]	Corine land cover	Copernicus Land Monitoring Service	Vector (land cover zone polygon)	Areal interpolation
Land cover [Water courses]	Corine land cover	Copernicus Land Monitoring Service	Vector (land cover zone polygon)	Areal interpolation
Land cover [Burnt areas]	Corine land cover	Copernicus Land Monitoring Service	Vector (land cover zone polygon)	Areal interpolation
Land cover [Agro-forestry areas]	Corine land cover	Copernicus Land Monitoring Service	Vector (land cover zone polygon)	Areal interpolation
Land cover [Coastal lagoons]	Corine land cover	Copernicus Land Monitoring Service	Vector (land cover zone polygon)	Areal interpolation

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character	data	source	input geometry	transfer method
NDVI	NDVI	GHS-composite-S2 R2020A	Raster (10m)	Zonal statistics
Supermarkets [distance to nearest]	Retail POIs (supermarkets)	Geolytix	Vector (point)	Network-constrained accessibility
Supermarkets [counts within 1200m]	Retail POIs (supermarkets)	Geolytix	Vector (point)	Network-constrained accessibility
Listed buildings [distance to nearest]	Listed Buildings	Historic England, Historic Environment Scotland, Lle Geo-Portal for Wales	Vector (point)	Network-constrained accessibility
Listed buildings [counts within 1200m]	Listed Buildings	Historic England, Historic Environment Scotland, Lle Geo-Portal for Wales	Vector (point)	Network-constrained accessibility
FHRS points [distance to nearest]	Food Hygiene Rating Scheme Ratings	CDRC.ac.uk	Vector (point)	Network-constrained accessibility
FHRS points [counts within 1200m]	Food Hygiene Rating Scheme Ratings	CDRC.ac.uk	Vector (point)	Network-constrained accessibility
Cultural venues [distance to nearest]	Culture (theatres, cinemas)	OpenStreetMap	Vector (point)	Network-constrained accessibility
Cultural venues [counts within 1200m]	Culture (theatres, cinemas)	OpenStreetMap	Vector (point)	Network-constrained accessibility
Water bodies [distance to nearest]	Water bodies	OS OpenMap Local	Vector (water body polygon)	Euclidean accessibility
Retail centres [distance to nearest]	Retail centres	CDRC.ac.uk	Vector (retail centre polygon)	Euclidean accessibility

Table 3. Numerical portraits characterising each signature type. Each value is computed as a mean of values of all ETCs within the type.

type	Accessible suburbia	Connected residential neighbourhoods	Countryside/agriculture	Dense residential neighbourhoods	Dense urban neighbourhoods	Disconnected suburbia	Concentrated urbanity	Gridded residential quarters	Hyper concentrated urbanity	Local urbanity	Metropolitan urbanity	Open sprawl	Regional urbanity	Urban buffer	Warehouse / Park land	Wild countryside
area of building	176.95	272.52	204.10	375.60	588.36	212.71	3713.38	283.89	3358.10	823.35	2413.94	226.72	1480.26	209.42	393.22	209.86
perimeter of building	53.90	69.12	56.05	80.56	107.36	61.63	376.30	69.67	330.82	135.54	283.94	59.64	195.98	55.94	75.68	57.12
court yard area of building	0.48	1.07	0.51	2.13	5.03	0.52	159.09	0.75	90.82	12.67	118.95	0.90	43.19	0.74	3.26	0.22
circular compactness of building	0.53	0.48	0.51	0.47	0.44	0.49	0.43	0.49	0.45	0.41	0.40	0.52	0.39	0.52	0.47	0.50
corner of building	4.25	4.45	4.37	4.69	5.21	4.35	12.48	4.51	9.27	6.01	9.72	4.37	7.78	4.34	4.56	4.38
squareness of building	0.78	1.47	0.81	1.86	3.28	1.02	18.59	1.66	22.51	5.07	12.41	0.99	8.84	0.86	1.35	0.71
equivalent rectangular index of building	0.99	0.98	0.98	0.97	0.95	0.98	0.78	0.98	0.80	0.92	0.82	0.98	0.87	0.98	0.98	0.98
elongation of building	0.64	0.56	0.60	0.56	0.52	0.57	0.59	0.58	0.62	0.51	0.53	0.62	0.51	0.63	0.54	0.59
centroid - corner mean distance of building	9.60	12.41	9.79	13.96	18.00	11.11	35.93	12.41	37.22	20.71	29.68	10.49	25.25	9.81	13.20	9.95
centroid - corner distance deviation of building	0.36	0.71	0.56	1.07	1.88	0.54	9.03	0.80	7.70	2.98	6.78	0.55	4.98	0.49	0.88	0.60
orientation of building	19.56	25.50	20.57	16.41	20.64	26.39	20.32	23.13	26.26	20.78	22.30	20.21	21.82	21.10	23.30	21.86
longest axis length of ETC	50.84	57.72	220.30	64.46	73.56	53.55	112.12	52.89	126.58	80.14	100.52	60.97	91.91	105.16	78.67	449.71
area of ETC	1147.25	1517.81	31193.48	1917.31	2410.32	1259.03	5708.23	1251.54	8654.32	2696.40	4442.21	2000.37	3535.28	8658.83	3520.84	155623.92

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type	Accessible suburbia	Connected residential neighbourhoods	Countryside agriculture	Dense residential neighbourhoods	Dense urban neighbourhoods	Disconnected suburbia	Concentrated urbanity	Gridded residential quarters	Hyper concentrated urbanity	Local urbanity	Metropolitan urbanity	Open sprawl	Regional urbanity	Urban buffer	Warehouse / Park land	Wild country-side
circular compactness of ETC	0.47	0.48	0.38	0.48	0.47	0.49	0.46	0.48	0.47	0.46	0.42	0.47	0.44	0.44	0.46	0.35
equivalent rectangular index of ETC	0.97	0.97	0.93	0.96	0.96	0.97	0.94	0.97	0.95	0.95	0.93	0.97	0.94	0.95	0.96	0.91
orientation of ETC covered area ratio of ETC	20.40	24.94	21.92	17.77	21.07	25.28	20.37	23.06	25.96	21.22	22.38	21.07	21.88	21.86	23.27	22.51
cell alignment of building	0.19	0.20	0.07	0.52	0.27	0.22	0.91	0.23	0.61	0.60	4.85	0.18	1122.51	0.14	0.18	0.04
alignment of neighbouring buildings	7.38	6.12	11.49	6.52	5.61	8.08	4.43	5.48	2.72	5.64	4.86	8.64	5.25	9.76	8.03	12.55
mean distance between neighbouring buildings	5.31	5.36	8.45	5.39	5.17	5.67	5.95	4.93	6.55	5.67	6.37	6.48	6.27	7.06	6.06	10.05
perimeter-weighted neighbours of ETC	0.04	0.04	0.02	0.04	0.07	0.05	0.03	0.04	0.04	0.11	0.04	0.06	7.46	0.13	0.04	0.01
area covered by neighbouring cells	8620.11	11990.46	277883.95	15619.36	20375.37	9503.57	52023.10	9962.17	61122.40	22892.04	39665.51	16780.98	31594.99	76942.43	31956.96	1485709.28
weighted reached enclosures of ETC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
mean inter-building distance	21.97	24.07	167.60	26.48	27.37	22.03	22.73	21.34	23.74	26.28	26.99	28.94	26.32	67.27	40.97	367.72
width of street profile	28.38	26.84	32.84	26.29	24.84	27.65	19.47	24.27	17.47	24.56	22.61	28.59	23.44	31.00	30.85	34.31
width deviation of street profile	3.30	3.27	3.91	3.50	3.45	3.71	3.29	3.87	2.85	3.60	3.50	3.74	3.62	3.76	3.26	3.41
openness of street profile	0.42	0.41	0.83	0.43	0.41	0.44	0.28	0.38	0.22	0.41	0.37	0.48	0.39	0.62	0.53	0.92
length of street segment	187.61	162.45	574.25	153.66	151.58	150.53	108.90	126.02	93.90	143.14	123.30	183.43	132.18	333.77	220.94	842.79
linearity of street segment	0.93	0.94	0.93	0.92	0.93	0.92	0.94	0.94	0.97	0.92	0.93	0.90	0.92	0.91	0.91	0.91
mean segment length within 3 steps	2327.31	2374.39	5884.25	1992.44	2113.58	1707.52	1944.94	1950.07	2057.70	2011.42	2112.12	1862.02	2034.72	3170.78	2339.74	8062.03
node degree of junction	2.87	3.00	2.78	2.89	2.94	2.68	3.12	3.04	3.33	2.94	3.14	2.68	3.01	2.70	2.77	2.69
local meshedness of street network	0.08	0.11	0.06	0.10	0.11	0.05	0.14	0.13	0.17	0.11	0.14	0.06	0.12	0.05	0.08	0.05
local proportion of 3-way intersections of street network	0.74	0.74	0.72	0.74	0.74	0.71	0.76	0.72	0.70	0.75	0.75	0.71	0.76	0.71	0.75	0.68
local proportion of 4-way intersections of street network	0.07	0.12	0.04	0.09	0.11	0.04	0.15	0.16	0.23	0.11	0.17	0.04	0.13	0.04	0.05	0.04
local proportion of cul-de-sacs of street network	0.19	0.14	0.24	0.17	0.14	0.25	0.09	0.12	0.06	0.14	0.08	0.25	0.11	0.25	0.20	0.28
local closeness of street network	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
local cul-de-sac length of street network	228.58	163.78	636.07	196.63	170.89	275.96	84.41	133.13	75.11	167.72	79.56	288.26	128.76	408.67	253.49	1186.52
square clustering of street network	0.03	0.04	0.01	0.03	0.04	0.01	0.03	0.04	0.04	0.03	0.04	0.02	0.03	0.02	0.03	0.01
mean distance to neighbouring nodes of street network	132.49	118.06	373.74	112.48	111.55	111.69	86.38	92.19	81.24	106.90	93.66	129.03	99.79	212.34	150.43	601.60
local node density of street network	0.02	0.02	0.01	0.02	0.02	0.03	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02	0.02	0.01
local degree weighted node density of street network	0.03	0.03	0.02	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.01
street alignment of building	8.73	7.53	11.81	8.25	7.57	9.98	7.84	6.95	6.23	8.05	8.32	10.97	8.06	11.33	10.02	12.77
area covered by node-attached ETCs	22426.36	14599.22	286081.33	14037.94	13513.86	15656.96	13069.71	9488.11	20051.57	11878.66	13201.87	25443.99	12080.93	100470.30	33097.00	1215083.95
area covered by edge-attached ETCs	36496.96	24423.69	502883.47	25413.44	26111.44	26810.65	33257.27	17094.77	38566.99	25905.75	31497.77	47178.87	29440.27	188719.66	66614.68	2174736.93
buildings per meter of street segment	0.11	0.08	0.05	0.08	0.07	0.10	0.05	0.09	0.05	0.06	0.05	0.10	0.05	0.09	0.07	0.02
reached ETCs by neighbouring segments	49.09	33.99	38.08	26.79	21.56	32.35	8.88	26.76	8.57	16.97	11.04	35.17	13.53	43.96	30.27	26.08
reached area by neighbouring segments	113290.06	88462.74	1591397.39	89313.79	97515.74	84060.33	145420.68	64059.40	151507.35	100616.06	132683.99	140813.94	119718.73	556190.10	211678.46	5556960.68
reached ETCs by local street network	166.98	126.07	110.89	90.93	74.36	102.39	28.79	99.87	27.00	56.17	36.29	103.45	43.97	123.39	93.33	71.94
reached area by local street network	451276.21	390719.33	5858316.88	369240.03	416784.68	316062.25	703631.50	296524.52	621126.10	439804.09	643746.00	506987.49	540975.07	1982158.35	794621.33	17403052.98
reached ETCs by tessellation contiguity	36.80	40.24	46.23	43.10	45.61	39.57	53.52	42.04	48.46	47.29	51.81	41.55	51.95	43.57	42.93	47.56
reached area by tessellation contiguity	60511.46	87537.63	2410926.40	115962.63	152810.21	63671.98	372984.21	73335.07	306427.88	173857.48	302746.84	136577.35	238390.55	692699.47	297667.66	14081627.81
area of enclosure	242778.35	95677.02	3591565.15	133719.21	105561.74	282930.77	28859.85	110195.65	31788.41	83656.67	29460.25	640071.17	63476.79	1854684.23	430998.35	44036373.80
perimeter of enclosure	2046.29	1360.81	7599.46	1693.62	1463.16	2380.50	683.27	1150.58	538.87	1299.32	671.29	3793.33	1009.07	5664.05	2992.30	21952.84
circular compactness of enclosure	0.40	0.39	0.40	0.38	0.38	0.42	0.44	0.41	0.45	0.39	0.40	0.38	0.39	0.38	0.38	0.38
equivalent rectangular index of enclosure	0.85	0.87	0.84	0.84	0.86	0.83	0.91	0.89	0.94	0.85	0.89	0.77	0.87	0.80	0.80	0.79
compactness-weighted axis of enclosure	515.77	344.74	1777.66	441.16	397.37	567.78	144.75	289.81	120.13	345.64	153.64	986.37	249.05	1434.02	780.52	5069.06
orientation of enclosure	19.24	25.62	21.39	16.18	20.88	27.07	20.23	23.04	24.93	21.09	21.77	20.39	22.00	21.52	24.08	22.66
perimeter-weighted neighbours of enclosure	0.01	0.01	0.01	0.02	0.08	0.02	0.04	0.02	0.08	0.12	0.06	0.05	9.94	0.11	0.01	0.01
area-weighted ETCs of enclosure	36.32	2.82	746.28	3.03	4.63	2137242.86	0.00	0.43	0.00	0.14	0.01	330422.61	0.01	1178106554.76	27879.43	2270509.66
Population	4.51	8.57	1.91	10.02	17.52	6.55	36.91	7.74	37.93	28.87	43.70	5.06	42.99	3.43	6.93	1.31
Night lights	11.02	19.99	1.39	22.63	34.74	12.35	115.70	15.17	183.23	51.19	87.38	10.96	67.53	5.08	18.29	0.48
Workplace population [Agriculture, energy and water]	0.01	0.03	0.08	0.07	0.11	0.02	2.44	0.03	1.41	0.18	1.01	0.04	0.39	0.05	0.10	0.11
Workplace population [Manufacturing]	0.12	0.29	0.22	0.64	1.10	0.21	12.80	0.36	20.14	1.32	4.18	0.42	2.03	0.38	1.25	0.09
Workplace population [Construction]	0.12	0.22	0.10	0.33	0.56	0.18	9.16	0.20	10.68	0.80	3.80	0.17	1.40	0.14	0.34	0.07
Workplace population [Distribution, hotels and restaurants]	0.21	0.61	0.19	1.17	2.30	0.38	54.16	0.73	152.31	4.16	22.76	0.45	11.90	0.32	1.00	0.12

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type	Accessible suburbia	Connected residential neighbourhoods	Countryside agriculture	Dense residential neighbourhoods	Dense urban neighbourhoods	Disconnected suburbia	Concentrated urbanity	Gridded residential quarters	Hyper concentrated urbanity	Local urbanity	Metropolitan urbanity	Open sprawl	Regional urbanity	Urban buffer	Warehouse / Park land	Wild country-side
Workplace population [Transport and communication]	0.07	0.21	0.07	0.41	0.88	0.13	39.51	0.18	97.90	1.96	18.93	0.16	5.70	0.14	0.51	0.04
Workplace population [Financial, real estate, professional and administrative activities]	0.15	0.40	0.13	0.78	1.81	0.26	258.67	0.38	172.75	4.89	65.30	0.27	16.45	0.21	0.61	0.06
Workplace population [Public administration, education and health]	0.43	0.94	0.22	1.67	3.21	0.59	41.70	0.98	30.82	5.71	42.90	0.59	14.50	0.39	1.06	0.12
Workplace population [Other]	0.06	0.15	0.05	0.26	0.56	0.10	23.06	0.17	38.16	1.14	8.74	0.09	3.40	0.07	0.16	0.03
Land cover [Airports]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Land cover [Non-irrigated arable land]	0.00	0.00	0.35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.02	0.00	0.15
Land cover [Industrial or commercial units]	0.00	0.02	0.01	0.05	0.09	0.01	0.00	0.00	0.00	0.09	0.01	0.03	0.06	0.03	0.14	0.00
Land cover [Salt marshes]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Land cover [Estuaries]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Land cover [Sports and leisure facilities]	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.02	0.01	0.01
Land cover [Green urban areas]	0.01	0.01	0.00	0.01	0.01	0.00	0.03	0.00	0.00	0.01	0.03	0.01	0.01	0.00	0.02	0.00
Land cover [Discontinuous urban fabric]	0.98	0.95	0.20	0.88	0.75	0.98	0.06	0.92	0.00	0.63	0.08	0.91	0.34	0.68	0.77	0.03
Land cover [Pastures]	0.00	0.00	0.36	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.02	0.00	0.12	0.02	0.59
Land cover [Broad-leaved forest]	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.03
Land cover [Mineral extraction sites]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Land cover [Port areas]	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.01	0.00
Land cover [Road and rail networks and associated land]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Land cover [Water bodies]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Land cover [Land principally occupied by agriculture, with significant areas of natural vegetation]	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Land cover [Mixed forest]	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02
Land cover [Peat bogs]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02
Land cover [Natural grasslands]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04
Land cover [Moors and heathland]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04
Land cover [Transitional woodland-shrub]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Land cover [Continuous urban fabric]	0.00	0.02	0.00	0.04	0.13	0.00	0.90	0.07	0.97	0.25	0.88	0.00	0.57	0.00	0.00	0.00
Land cover [Intertidal flats]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Land cover [Sea and ocean]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Land cover [Construction sites]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
Land cover [Burnt areas]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Land cover [Dump sites]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Land cover [Complex cultivation patterns]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Land cover [Inland marshes]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Land cover [Water courses]	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.00
Land cover [Coniferous forest]	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04
Land cover [Bare rocks]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Land cover [Coastal lagoons]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Land cover [Beaches, dunes, sands]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Land cover [Agroforestry areas]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Land cover [Sparse vegetated areas]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Land cover [Fruit trees and berry plantations]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NDVI	0.29	0.25	0.48	0.23	0.19	0.29	0.03	0.21	0.00	0.16	0.06	0.29	0.11	0.37	0.29	0.56
Supermarkets [distance to nearest]	828.82	679.96	4751.23	661.77	587.28	761.86	229.90	577.68	324.42	483.02	299.93	948.03	331.07	1752.87	1043.84	9854.12
Supermarkets [counts within 1200m]	1.89	2.86	0.09	3.13	4.44	2.07	22.51	3.41	18.79	6.85	17.27	1.47	12.53	0.65	1.43	0.03
Listed buildings [distance to nearest]	744.22	596.61	557.94	506.61	350.89	729.61	31.73	516.20	69.75	216.86	51.87	760.26	115.00	673.93	934.00	1324.03
Listed buildings [counts within 1200m]	11.27	24.28	11.22	37.47	62.78	24.18	685.16	31.77	1142.57	140.03	456.53	18.17	324.50	16.14	10.57	4.21
FHRS points [distance to nearest]	218.46	152.48	725.69	144.02	106.08	217.95	16.22	129.24	14.10	82.47	40.06	267.24	56.87	379.17	256.22	1699.17
FHRS points [counts within 1200m]	334.43	692.66	44.47	860.93	1568.44	342.08	6297.61	1081.38	9213.15	2167.91	4490.95	253.88	3163.83	132.66	271.09	33.07
Cultural venues [distance to nearest]	5384.64	3946.05	13156.20	3497.51	2287.43	5831.52	702.75	4094.92	351.33	1273.23	644.53	6309.75	850.25	8939.65	5121.47	20695.29
Cultural venues [counts within 1200m]	0.06	0.13	0.00	0.26	0.48	0.08	10.39	0.24	34.20	1.13	4.45	0.06	2.23	0.02	0.06	0.00
Water bodies [distance to nearest]	542.61	555.96	304.49	483.12	528.85	523.05	565.25	522.09	759.60	507.71	467.71	378.36	461.42	345.79	417.43	236.73

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type	Accessible suburbia	Connected residential neighbourhoods	Countryside agriculture	Dense residential neighbourhoods	Dense urban neighbourhoods	Disconnected suburbia	Concentrated urbanity	Gridded residential quarters	Hyper concentrated urbanity	Local urbanity	Metropolitan urbanity	Open sprawl	Regional urbanity	Urban buffer	Warehouse / Park land	Wild country-side
Retail centres [distance to nearest]	849.45	536.47	4943.97	421.09	224.33	725.57	29.80	445.52	32.54	161.85	66.32	1002.66	90.87	2102.46	898.17	11041.32

Table 4. Interpretative pen portraits characterising each signature type based on its numerical profile.

Signature type	Pen Portait
Wild countryside	In “Wild countryside”, human influence is the least intensive. This signature covers large open spaces in the countryside where no urbanisation happens apart from occasional roads, cottages, and pastures. You can find it across the Scottish Highlands, numerous national parks such as Lake District, or in the majority of Wales.
Countryside agriculture	“Countryside agriculture” features much of the English countryside and displays a high degree of agriculture including both fields and pastures. There are a few buildings scattered across the area but, for the most part, it is green space.
Urban buffer	“Urban buffer” can be characterised as a green belt around cities. This signature includes mostly agricultural land in the immediate adjacency of towns and cities, often including edge development. It still feels more like countryside than urban, but these signatures are much smaller compared to other countryside types.
Open sprawl	“Open sprawl” represents the transition between countryside and urbanised land. It is located in the outskirts of cities or around smaller towns and is typically made up of large open space areas intertwined with different kinds of human development, from highways to smaller neighbourhoods.
Disconnected suburbia	“Disconnected suburbia” includes residential developments in the outskirts of cities or even towns and villages with convoluted, disconnected street networks, low built-up and population densities, and lack of jobs and services. This signature type is entirely car-dependent.
Accessible suburbia	“Accessible suburbia” covers residential development on the urban periphery with a relatively legible and connected street network, albeit less so than other more urban signature types. Areas in this signature feature low density, both in terms of population and built-up area, lack of jobs and services. For these reasons, “accessible suburbia” largely acts as dormitories.
Warehouse/Park land	“Warehouse/Park land” covers predominantly industrial areas and other work-related developments made of box-like buildings with large footprints. It contains many jobs of manual nature such as manufacturing or construction, and very little population live here compared to the rest of urban areas. Occasionally this type also covers areas of parks with large scale green open areas.
Gridded residential quarters	“Gridded residential quarters” are areas with street networks forming a well-connected grid-like (high density of 4-way intersections) pattern, resulting in places with smaller blocks and higher granularity. This signature is mostly residential but includes some services and jobs, and it tends to be located away from city centres.
Connected residential neighbourhoods	“Connected residential neighbourhoods” are relatively dense urban areas, both in terms of population and built-up area, that tend to be formed around well-connected street networks. They have access to services and some jobs but may be further away from city centres leading to higher dependency on cars and public transport for their residents.
Dense residential neighbourhoods	A “dense residential neighbourhood” is an abundant signature often covering large parts of cities outside of their centres. It has primarily residential purpose and high population density, varied street network patterns, and some services and jobs but not in high intensity.

Continued on next page

Signature type	Pen Portait
Dense urban neighbourhoods	“Dense urban neighbourhoods” are areas of inner-city with high population and built-up density of a predominantly residential nature but with direct access to jobs and services. This signature type tends to be relatively walkable and, in the case of some towns, may even form their centres.
Local urbanity	“Local urbanity” reflects town centres, outer parts of city centres or even district centres. In all cases, this signature is very much urban in essence, combining high population and built-up density, access to amenities and jobs. Yet, it is on the lower end of the hierarchy of signature types denoting urban centres with only a local significance.
Regional urbanity	“Regional urbanity” captures centres of mid-size cities with regional importance such as Liverpool, Plymouth or Newcastle upon Tyne. It is often encircled by “Local urbanity” signatures and can form outer rings of city centres in large cities. It features high population density, as well as a high number of jobs and amenities within walkable distance.
Metropolitan urbanity	Signature type “Metropolitan urbanity” captures the centre of the largest cities in Great Britain such as Glasgow, Birmingham or Manchester. It is characterised by a very high number of jobs in the area, high built-up density and often high population density. This type serves as the core centre of the entire metropolitan areas.
Concentrated urbanity	Concentrated urbanity” is a signature type found in the city centre of London and nowhere else in Great Britain. It reflects the uniqueness of London in the British context with an extremely high number of jobs and amenities located nearby, as well as high built-up and population densities. Buildings in this signature are large and tightly packed, forming complex shapes with courtyards and little green space.
Hyper concentrated urbanity	The epitome of urbanity in the British context. “Hyper concentrated urbanity” is a signature type present only in the centre of London, around the Soho district, and covering Oxford and Regent streets. This signature is the result of centuries of urban primacy, with a multitude of historical layers interwoven, very high built-up and population density, and extreme abundance of amenities, services and jobs.

Table 5. Relative importance of top 10 most important characters in predicting spatial signature types using the Random Forest model.

	relative importance
covered area ratio of ETC (Q1)	0.036944
covered area ratio of ETC (Q2)	0.031717
perimeter-weighted neighbours of ETC (Q2)	0.023476
mean inter-building distance (Q2)	0.016662
area of ETC (Q3)	0.016005
area covered by node-attached ETCs (Q3)	0.014813
longest axis length of ETC (Q2)	0.014501
weighted reached enclosures of ETC (Q1)	0.014115
reached area by neighbouring segments (Q3)	0.014000
reached area by neighbouring segments (Q1)	0.013904

Table 6. Relative importance of top 10 most important characters for each signature type in predicting using the Random Forest model.

Wild country-side	name	1 longest axis length of ETC (Q1)	2 covered ratio of ETC (Q2)	3 covered ratio of ETC (Q1)	4 area of ETC (Q2)	5 perimeter-weighted neighbours of ETC (Q3)	6 reached area by neighbouring segments (Q1)	7 reached area by tessellation contiguity (Q1)	8 area of ETC (Q3)	9 mean distance between neighbouring buildings (Q2)	10 mean inter-building distance (Q2)
importance		0.197	0.151	0.146	0.096	0.075	0.049	0.018	0.016	0.015	0.011

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		1	2	3	4	5	6	7	8	9	10
Countryside agriculture	name	covered area ratio of ETC (Q1)	covered area ratio of ETC (Q2)	mean inter-building distance (Q2)	area of ETC (Q2)	area covered by node-attached ETCs (Q2)	mean distance to neighbouring nodes of street ...	reached area by neighbouring segments (Q1)	Land cover [Discontinuous urban fabric] (Q2)	perimeter-weighted neighbours of ETC (Q2)	longest axis length of ETC (Q2)
Gridded residential quarters	importance name	0.154 local closeness of street network (Q3)	0.144 local closeness of street network (Q2)	0.079 perimeter of enclosure (Q1)	0.073 area of enclosure (Q2)	0.067 local closeness of street network (Q1)	0.066 weighted reached enclosures of ETC (Q3)	0.063 local proportion of 4-way intersections of str...	0.055 area covered by node-attached ETCs (Q2)	0.022 area covered by node-attached ETCs (Q2)	0.021 weighted reached enclosures of ETC
Accessible suburbia	importance name	0.095 weighted reached enclosures of ETC (Q3)	0.046 reached ETCs by tessellation contiguity (Q3)	0.044 reached area by tessellation contiguity (Q2)	0.037 area of ETC (Q2)	0.037 reached ETCs by neighbouring segments (Q1)	0.032 reached ETCs by neighbouring segments (Q2)	0.019 perimeter-weighted neighbours of ETC (Q1)	0.018 reached area by tessellation contiguity (Q1)	0.017 reached ETCs by local street network (Q1)	0.017 reached ETCs by local street network (Q1)
Connected residential neighbourhoods	importance name	0.064 cell alignment of building (Q1)	0.062 local proportion of 4-way intersections of str...	0.048 cell alignment of building (Q2)	0.045 area of enclosure (Q2)	0.037 orientation of ETC (Q2)	0.03 local proportion of 4-way intersections of str...	0.026 perimeter of enclosure (Q1)	0.023 local proportion of cul-de-sacs of street netw...	0.02 orientation of enclosure (Q1)	0.02 orientation of enclosure (Q1)
Urban buffer	importance name	0.028 area covered by neighbouring cells (Q2)	0.023 mean distance covered area ratio of ETC (Q2)	0.017 mean distance to neighbouring nodes of street ...	0.017 covered area ratio of ETC (Q1)	0.016 circular compactness of ETC (Q2)	0.014 buildings per meter of street segment (Q2)	0.014 reached area by tessellation contiguity (Q1)	0.014 area covered by neighbouring cells (Q1)	0.013 area covered by node-attached ETCs (Q3)	0.013 area covered by node-attached ETCs
Open sprawl	importance name	0.072 reached area by local street network (Q1)	0.05 reached area by neighbouring segments (Q1)	0.049 area covered by node-attached ETCs (Q2)	0.046 covered area ratio of ETC (Q2)	0.038 local node density of street network (Q3)	0.035 reached area by neighbouring segments (Q2)	0.032 area of enclosure (Q2)	0.032 compactness-weighted axis of enclosure (Q3)	0.028 area of ETC (Q2)	0.028 area of ETC
Warehouse/Park land	importance name	0.058 elongation of building (Q1)	0.034 centroid - corner mean distance of building (Q3)	0.024 elongation of building (Q2)	0.022 circular compactness of building (Q1)	0.019 centroid - corner distance deviation of buildi...	0.018 perimeter of building (Q3)	0.018 width of street profile (Q2)	0.017 circular compactness of building (Q2)	0.017 reached area by tessellation contiguity (Q1)	0.016 perimeter of building (Q2)
Local urbanity	importance name	0.034 perimeter of building (Q2)	0.028 equivalent rectangular index of building (Q1)	0.025 centroid - corner mean distance of building (Q2)	0.02 squareness of building (Q3)	0.017 area of building (Q2)	0.017 centroid - corner distance deviation of buildi...	0.016 Workplace population [Financial, real estate, ...]	0.016 Workplace population [Distribution, hotels and...]	0.016 perimeter of building (Q3)	0.015 area of building (Q1)
Dense residential neighbourhoods	importance name	0.101 centroid - corner mean distance of building (Q2)	0.094 centroid - corner mean distance of building (Q3)	0.082 area of building (Q3)	0.054 Population (Q3)	0.051 perimeter of building (Q2)	0.045 area of building (Q2)	0.035 orientation of enclosure (Q1)	0.034 perimeter of building (Q3)	0.023 area of enclosure (Q1)	0.023 area of enclosure
Disconnected suburbia	importance name	0.037 local proportion of cul-de-sacs of street netw...	0.03 local meshedness of street network (Q3)	0.029 local meshedness of street network (Q2)	0.028 equivalent rectangular index of building (Q1)	0.026 circular compactness of building (Q1)	0.023 Population (Q1)	0.021 elongation of building (Q2)	0.018 reached area by neighbouring segments (Q2)	0.017 area covered by edge-attached ETCs (Q3)	0.015 circular compactness of building (Q2)
Dense urban neighbourhoods	importance name	0.024 perimeter of building (Q2)	0.021 centroid - corner mean distance of building (Q2)	0.021 perimeter of building (Q3)	0.02 area of building (Q2)	0.019 Population (Q3)	0.018 squareness of building (Q3)	0.016 centroid - corner distance deviation of buildi...	0.016 Workplace population [Financial, real estate, ...]	0.016 equivalent rectangular index of building (Q1)	0.015 Workplace population [Other] (Q2)
Regional urbanity	importance name	0.107 centroid - corner distance deviation of buildi...	0.084 centroid - corner mean distance of building (Q2)	0.082 squareness of building (Q3)	0.066 Workplace population [Financial, real estate, ...]	0.04 perimeter of building (Q2)	0.039 perimeter of building (Q3)	0.034 area of building (Q2)	0.029 Workplace population [Distribution, hotels and...]	0.018 corners of building (Q3)	0.016 centroid - corner distance deviation of buildi...
Metropolitan urbanity	importance name	0.115 equivalent rectangular index of building (Q2)	0.088 centroid - corner mean distance of building (Q2)	0.071 corners of building (Q2)	0.065 Workplace population [Financial, real estate, ...]	0.058 Workplace population [Distribution, hotels and...]	0.05 perimeter of building (Q2)	0.049 squareness of building (Q3)	0.029 Workplace population [Financial, real estate, ...]	0.029 centroid - corner mean distance of building (Q1)	0.021 centroid - corner mean distance of building
Concentrated urbanity	importance name	0.111 area of building (Q1)	0.087 Workplace population [Distribution, hotels and...]	0.081 Workplace population [Other] (Q2)	0.072 Workplace population [Financial, real estate, ...]	0.06 Workplace population [Distribution, hotels and...]	0.051 Workplace population [Financial, real estate, ...]	0.047 perimeter of building (Q2)	0.039 perimeter of building (Q2)	0.03 centrod - corner mean distance of building (Q2)	0.019 Land cover [Non-irrigated arable land]
Hyper concentrated urbanity	importance name	0.128 covered area ratio of ETC (Q2)	0.1 Workplace population [Manufacturing] (Q2)	0.077 Workplace population [Other] (Q2)	0.076 Workplace population [Distribution, hotels and...]	0.071 covered area ratio of ETC (Q1)	0.06 Workplace population [Manufacturing] (Q3)	0.055 centrod - corner mean distance of building (Q2)	0.047 perimeter of building (Q2)	0.045 openness of street profile (Q2)	0.026 NDVI (Q3)
	importance	0.154	0.144	0.102	0.082	0.079	0.075	0.07	0.055	0.031	0.027

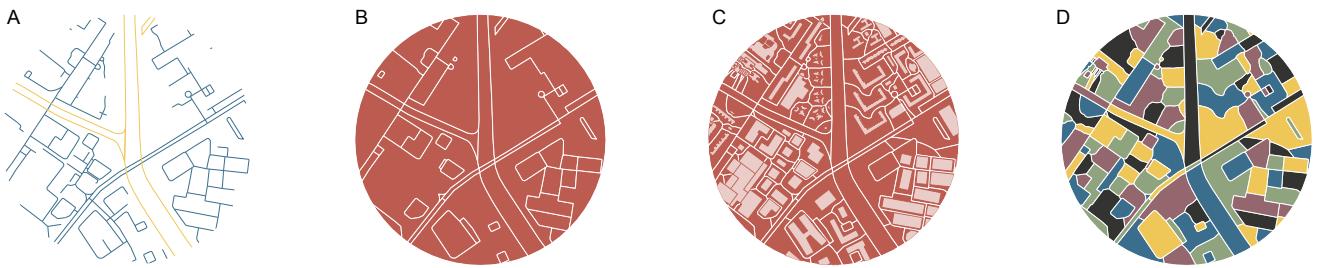


Figure 3. Diagram illustrating the sequential steps leading to the delineation of enclosed tessellation. From a series of enclosing components, where blue are streets and yellow river banks (A), to enclosures (B), incorporation of buildings as anchors (C) to final tessellation cells (D).

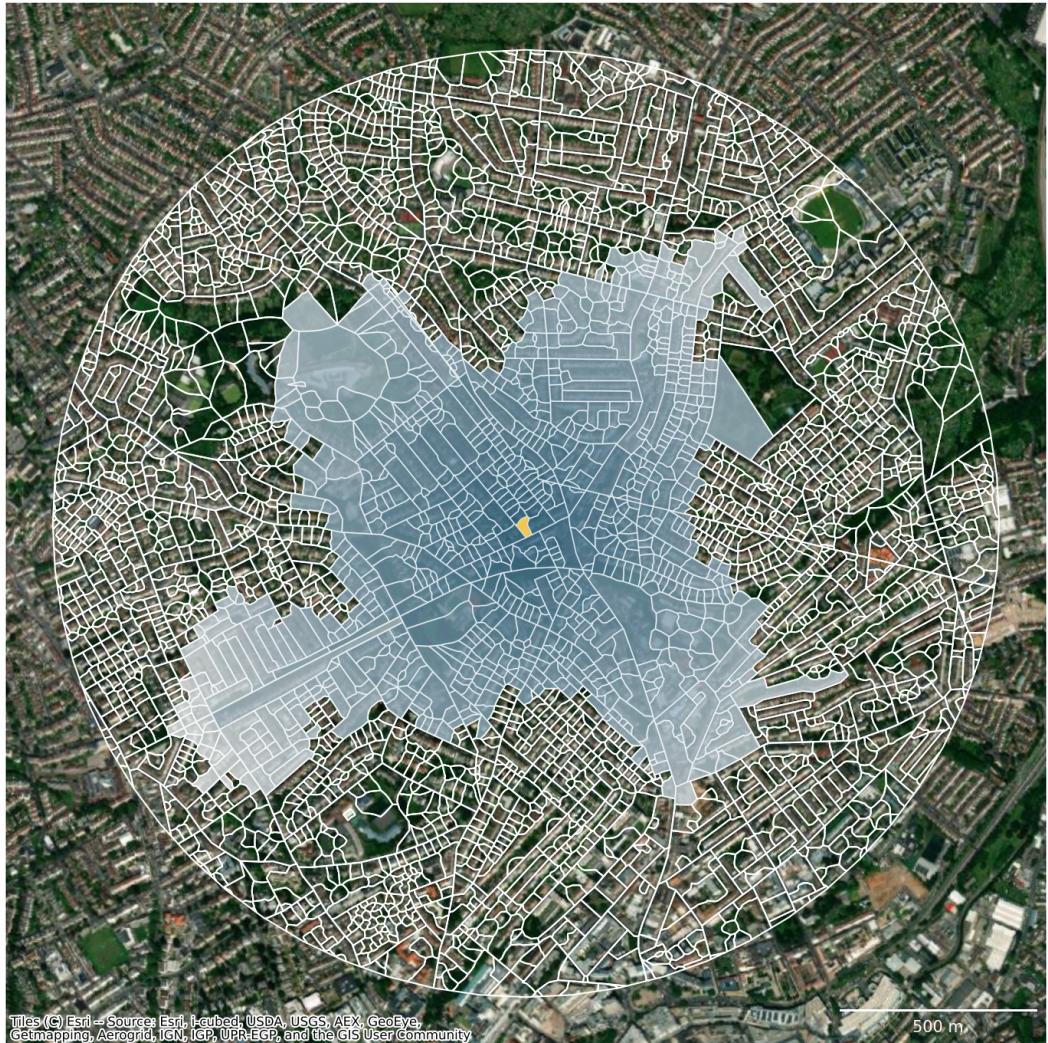


Figure 4. Illustration of a definition of spatial context used to capture the distribution of values around each ET cell. For the yellow ET cell in the middle, we propose to define a neighbourhood of 10 topological steps on the tessellation and weight the importance of each cell within such an area by inverse distance between poles of inaccessibility of each cell.

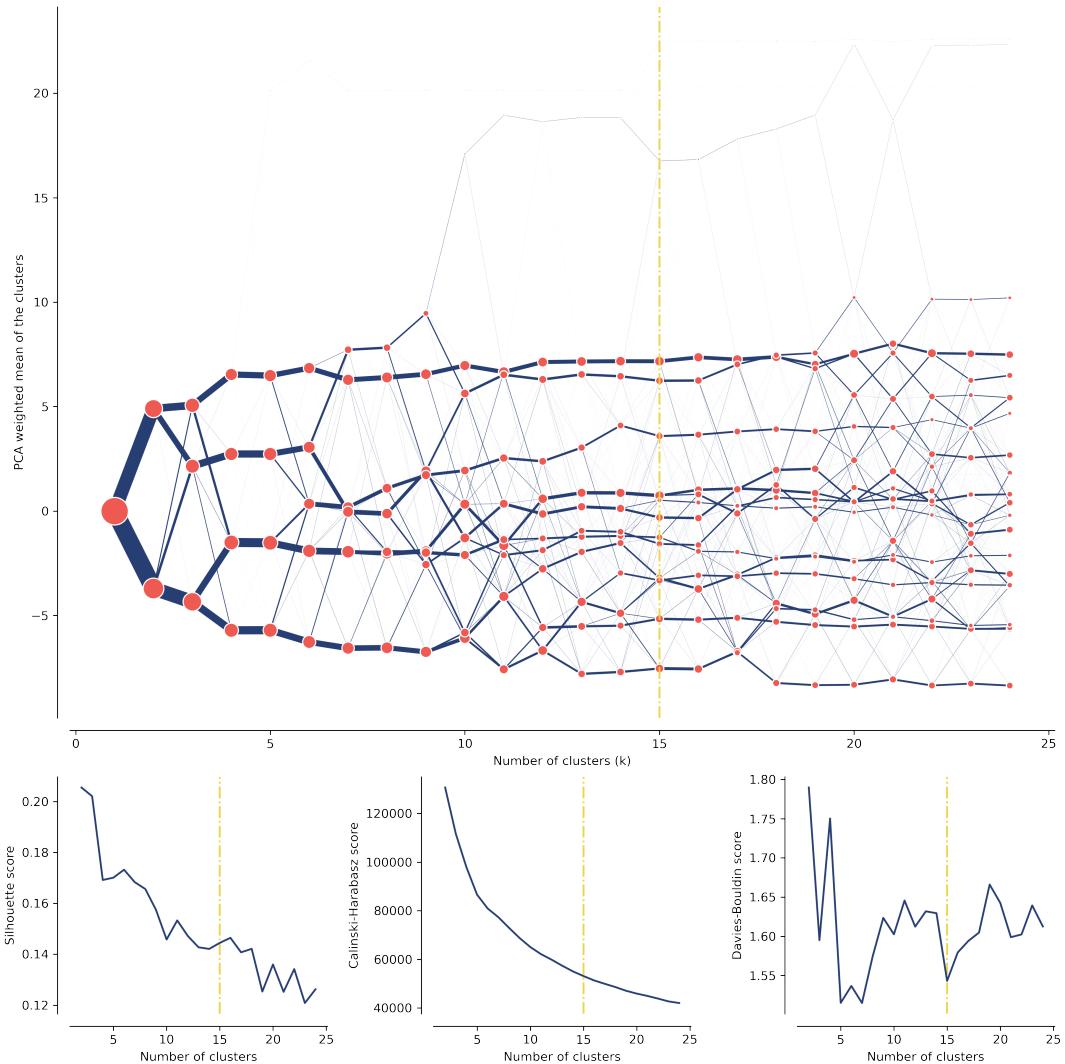


Figure 5. Clustergram and relevant metrics of a goodness of fit (Silhouette score, Calinski-Harabasz score, Davies-Bouldin score) for tested numbers of clusters. The clustergram suggest two potential solutions, the very conservative option of 4 clusters and 10 clusters selected as an optimal result (indicated by a vertical yellow line).

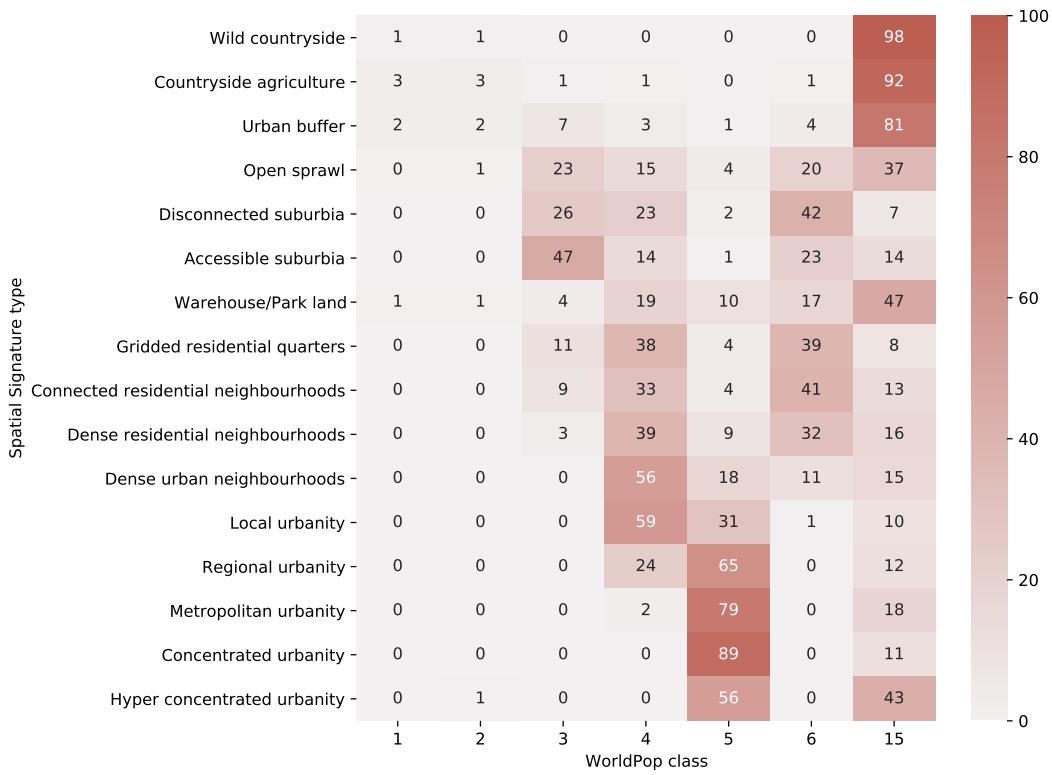


Figure 6. Contingency table showing frequencies (in %) of WorldPop classes within signature types.

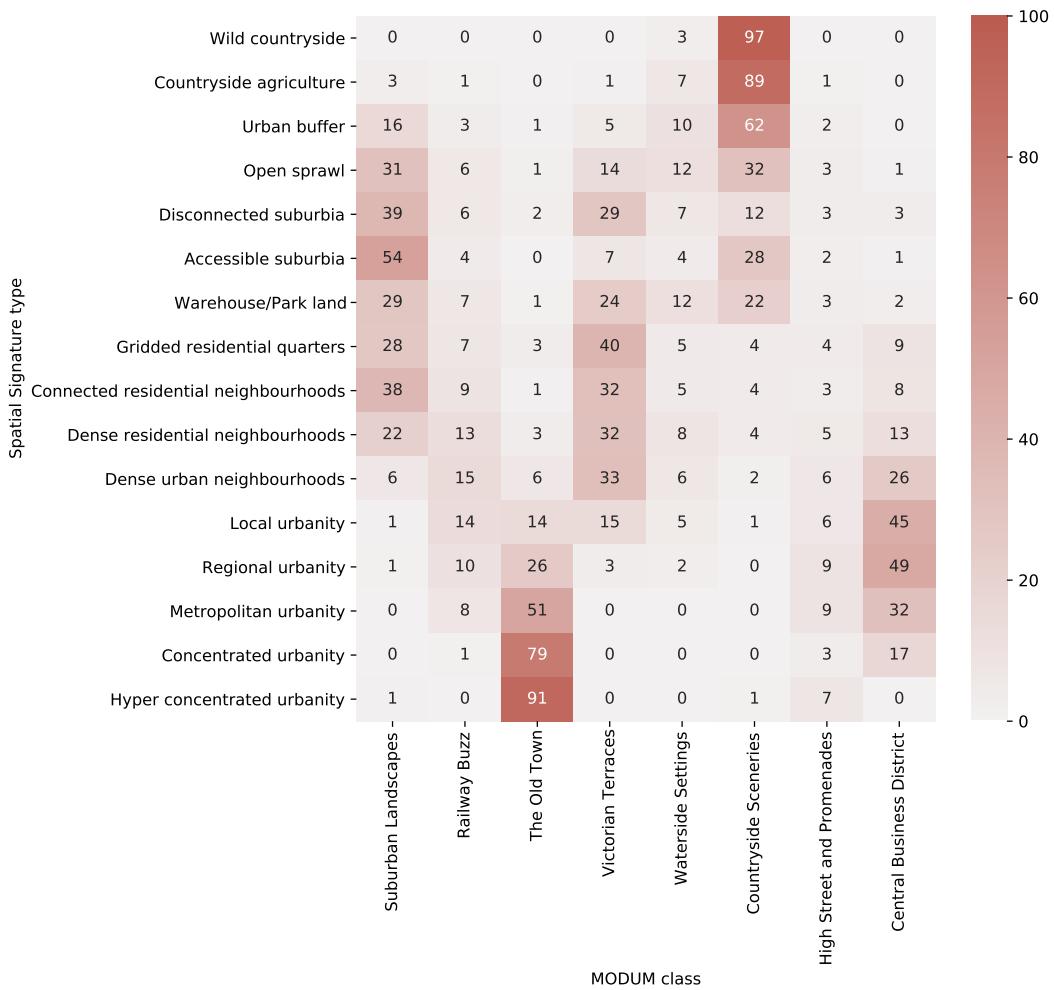


Figure 7. Contingency table showing frequencies (in %) of MODUM classes within signature types.

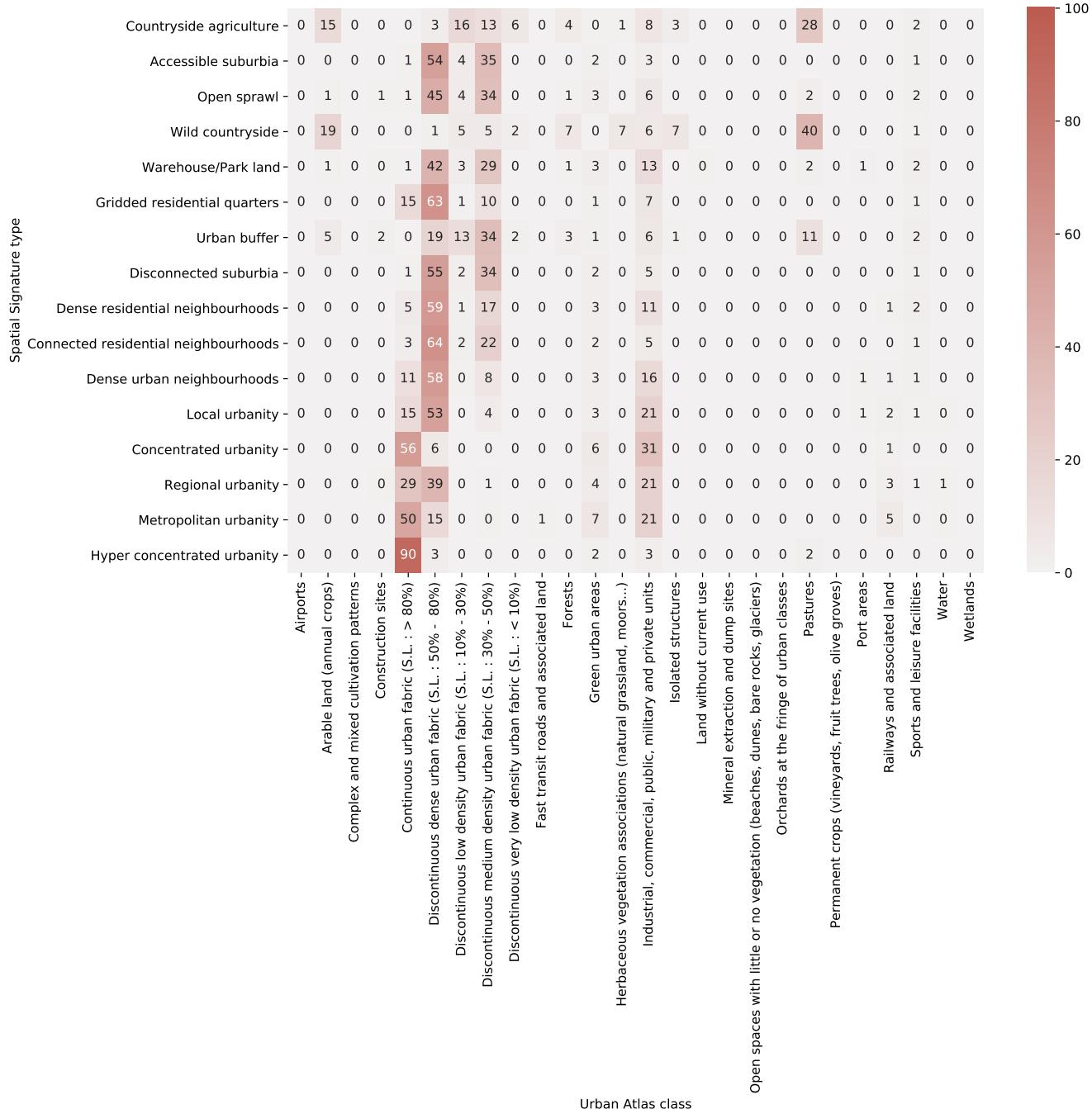


Figure 8. Contingency table showing frequencies (in %) of Urban Atlas classes within signature types.

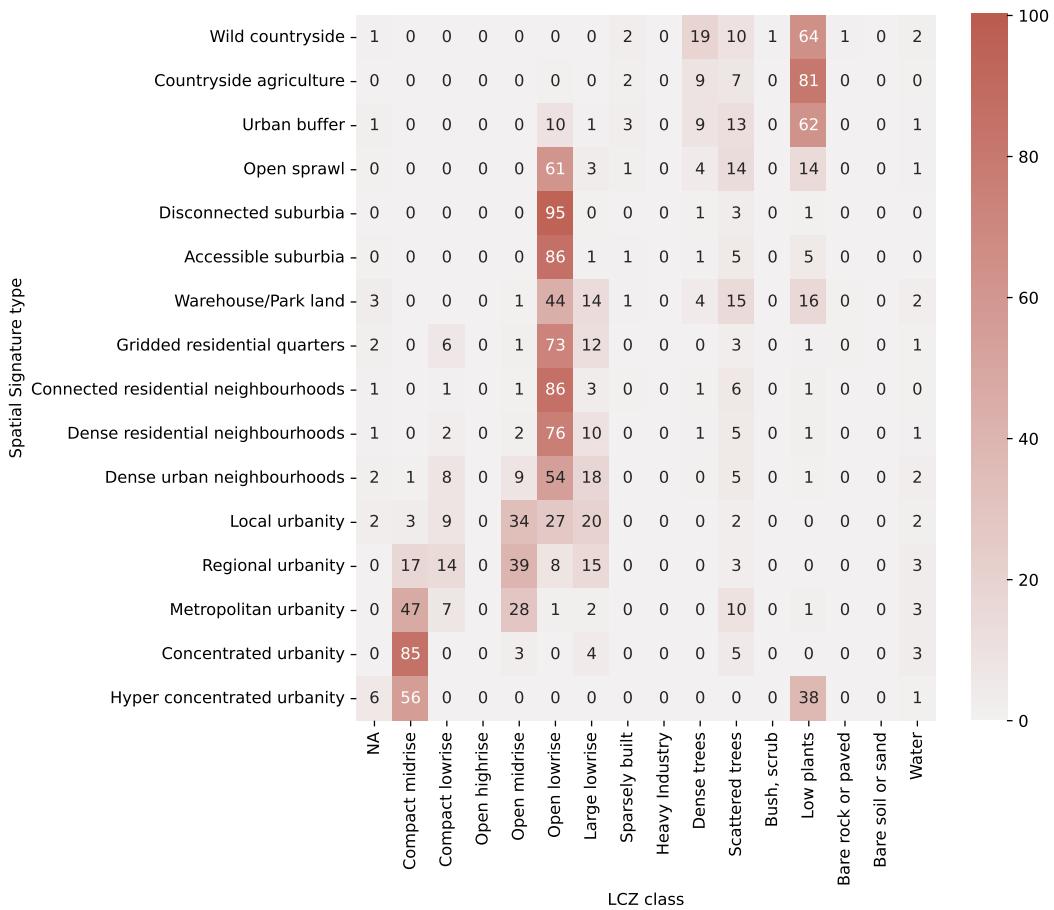


Figure 9. Contingency table showing frequencies (in %) of Local Climate Zones within signature types.