Spatial Signatures
Dynamically building the built environment

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Abstract: Blah blah blah

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1. Introduction

- The spatial configuration of cities is related to productivity and job access, social inclusion and mobility, deprivation, service provision, energy consumption and carbon emissions, among others.

- need for detailed, consistent and scalable evidence (pick two of those)

- These needs relate to both developing world, where there is not data at all and most of the changes; but also to the developed world where life is being ”recast” and cities continue to evolve (housing crisis, remote work, climate change targets, technology, etc.)

- Fragmented literature –¿ fragmented measurement –¿ fragmented evidence - Fragmentation hinders our understanding

- SS are intellectually ”all-ecompassing”, get around fragmentation - SS are fine-grained, consistent

- SS data-driven but theoretically informed; granular but scalable;and flexible enough to be adapted to a wide variety of applied contexts

2. (Urban) form and function

2.1 Form

Urban form approaches environments from the perspective of their physical structure and appearance. Research studying urban form has a long tradition, dating back to the early XXth Century (Geddes, 1915, Trewartha, 1934). Urban morphology, subsequently, begun in the 1960s as an independent area of research. The field originated in parallel within geography (Conzen, 1960) and architecture (Muratori, 1959), reflecting its inherently multi-disciplinary nature, later reinforced by the inclusion of socio-economic elements, as in the work work of Panerai et al. (1997). The original methods are predominantly qualitative, a tendency that persists today (Dibble, 2016). The first notable quantitative approaches date to the late 1980s and 1990s, reflecting advancements in computation and newly available data capturing the built environment. In this context, two strains of research have emerged. One focuses on cartographic (vector) representation of the urban environment, assessing its boundaries (Batty and Longley, 1987), street networks (Hillier, 1996, Porta et al., 2006) and other elements (Pivo, 1993). The second one is based on earth observation, exploiting remotely sensed data to capture change in the footprint of urban areas (Howarth and Boasson, 1983), or producing classifications of land cover (European Environment Agency, 1990).

The current state of the art still retains this distinction between cartographic and remotely sensed approaches. A modern quantitative branch of urban morphology, or urban morphometrics, has emerged working predominantly discrete elements of urban form, and proposing an abundant selection of measurable characters that describe different aspects of form (Fleischmann et al., 2020b). As part of this trend, methods focusing on a single aspect (Porta et al., 2006) have been replaced by efforts to better reflect the complexity of urban form through the combination of multiple morphometric characters into a single model, often leading to data-driven typologies

(Song and Knaap, 2007). This focus on classification is becoming more prominent, fueled by the possibilities afforded by new datasets increasingly available. Indeed, the literature is now able to produce typologies that start from small-scale studies focused on blocks and streets (Gil et al., 2012), and zoom out into larger areas with higher granularity (Schirmer and Axhausen, 2015, Araldi and Fusco, 2019, Bobkova et al., 2019, Dibble et al., 2019, Jochem et al., 2020).

Advancements in remote sensing have also led to a range of classification frameworks based on various conceptualizations of the urban fabric. However, there is one significant difference between classification derived via morphometric characterization and the one based on remote sensing. Where the former is mostly unsupervised (Araldi and Fusco, 2019, Schirmer and Axhausen, 2015), exploiting the hidden structure in the data to develop organically the typology; the latter tends towards supervised techniques, relying on classes defined a priori (Pauleit and Duhme, 2000). Two emerging classification models used to inform these exercises are Local Climate Zones (Stewart and Oke, 2012), defining ten built-form types and seven land cover types, and used recently by Koc et al. (2017) or Taubenböck et al. (2020); and the Urban Structural Type, a generic typology based on the notion of internal homogeneity of types (Lehner and Blaschke, 2019).

2.2 *Function*

Urban function considers environments based on the activities that take place within them. The focus is thus not on what a space “looks like”, as it is the case on urban form, but on “what it is used for”. What activities occur within cities, how they are spatially configured, and how they relate to each other are key questions in this context. To the extent cities compress space and time to concentrate human activity of very diverse nature, the study of function is relevant to a variety of fields and is undertaken by a wider constituency of researchers. Disciplines as disparate as geography, economics or environmental sciences, to name only a few, have contributed in their own way to our understanding of urban function. Furthermore, because function has direct implications for a wide range of social and environmental processes at different geographic scales, their study also falls within the realm of policy. Given the breadth of perspectives and goals, research on urban form is difficult to classify and a complete overview of its contributions is beyond the scope of this paper. Instead, here we will highlight what we consider the most relevant domains involved in the study of urban form: environmental sciences, urban and public economics, urban and transport geography, planning, and sociology.

Environmental sciences have long considered urban function in the context of the broader interest on understanding the natural characteristics of the surface of the Earth. An area that has attracted much effort relates to the development of classifications of land cover and land use, the former describing the nature of surfaces while the latter focusing on how those surfaces are used. Several land cover classifications are available (e.g. CORINE, European Environment Agency, 1990, in Europe; the National Land Cover Database, Homer et al., 2012, in the US; or the Land Cover CCI, Defourny et al., 2012, globally), as well as some, although less, for land use (e.g. the Urban Atlas project, Copernicus Land Monitoring Service, 2021). It is important to note that the distinction between cover and use in this context is not clearcut and there is wide discussion around the relationship between the two (e.g. Fisher et al., 2005, Comber et al., 2008). This dichotomy resembles the more general one between form (cover) and function (use). While much of this research is not focused on urban environments, the urban remote sensing community (Weng and Quattrochi, 2018) is building a more explicit bridge between these approaches and the study of cities. Such connection is becoming possible thanks to methodological advances, including object-based image analysis (OBIA, e.g. Prasad, 2015), machine learning (e.g. Kuffer et al., 2016, Georganos et al., 2018, Jochem et al., 2018) or computer vision (e.g. Stark et al., 2020). Taken altogether, this body of research is allowing us to rethink the extent to which our understanding of function can in fact be inferred from form, particularly in urban environments.

While land use/cover classifications attempt to characterise landscape function in a broad way, many disciplines have developed more specific interests in urban function. Sustainability studies, for example, are interested in how function is configured within and across cities in so far as it relates to the level of emissions (Angel et al., 2018) or energy consumption (XXXrefsXXX). The social sciences have a long-standing interest on the spatial configuration of form because it affects several outcomes of prime interest. Depending on the nature of these outcomes, form is conceptualised in one or another way. Urban economics pays special attention to density of economic activity and, by extension, of population (Ahlfeldt and Pietrostefani, 2019, Duranton and Puga, 2020), since density is intimately related to theories of agglomeration, one of the intellectual pillars of the field. Although less central to its main goals, public economics is interested on the configuration of urban function to the extent that it determines the efficiency of certain public services provided by local governments (e.g. XXXrefsXXX). Sociologists and planners have also found that different spatial configurations of function over space is associated with different degrees of social mobility (Ewing et al., 2016) or socio-economic deprivation (Venerandi et al., 2018). More generally, transport researchers have built a robust body of knowledge linking urban function and its spatial distribution to different degrees of accessibility to jobs (XXXrefXXX) and amenities (XXXrefXXX), with clear implications for socio-economic disparities. These are some of the most relevant, but not all, connections that researchers from a wide variety of backgrounds have drawn between urban function, its location and different social, economic and environmental outcomes.

2.3 *Existing gaps*

Whilst literature often focuses either on form or on function, the two can be studies independently but and deeply interconnected. Form reflects and influences function and vice versa (REF). Therefore, any classification of built environment which aims to provide a comprehensive picture of the reality needs to work with both aspects at the same time. One example of a comprehensive combination of form and function into a singular classification is the work of Bourdic et al. (2012), proposing an inclusive system of spatial indicators ranging from form to biodiversity, culture and energy on a scale of individual cities. Common are links between form and land use (song 2007,2013, bourdic2012), where some authors even consider land use a part of form characterisation (dibble). Global availability and interpretability of available data (facebook, worldpop) fuels research linking form and population density (Zheng2014, Ewing 2002, OECD2018, ahlfeldt2019), alongside studies embedding accessibility and proximity to points of interests into their frameworks (venerandi2019, alexiou2016). However, the body of research directly working with both form and function in a single framework is not large and a balance between both aspects varies.

From the perspective of built environment classification, the existing methods have often limits, mostly related to detail, comprehensiveness and scalability, lacking at least one of them. The situation is similar in classification based on form, function, as well as their combination. Detail reflects spatial granularity of resulting classification, where more granular, i.e. more detailed, unit has the ability to capture smaller nuances of the urban environment and better reflect local characters or a place. Methods based on a unit which can be further subdivided (Dibble et al., 2019, Jochem et al., 2020, Araldi and Fusco, 2019, Gil et al., 2012), therefore does not ensure internal homogeneity, can result in classes driven by the heterogeneity instead of the unit instead of the actual pattern of built environment. Comprehensiveness refers to the number of characters (variables) used in the classification procedure. Small sets of characters as in Bobkova et al. (2019) or Serra et al. (2018) are prone to a selection bias and will less likely reflect the complexity of the urban environment. Finally, scalability reflects the ability of the proposed method to scale up to large extents of metropolitan areas or national-level studies. While some works illustrate such a potential (Jochem et al., 2020, Schirmer and Axhausen, 2015, Bobkova et al., 2019, Araldi and Fusco, 2019), others which may overcome other issues are less likely to scale from their original limits (Dibble et al., 2019). Furthermore, computational scalability can be limited by data availability. Methods dependent on a high amount of detailed vector data (Bobkova et al., 2019) or specific local demographic information (REF) can be hardly applied in other contexts where such input is not available.

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3. Spatial Signatures

3.1 *Definition*

We propose the notion of *Spatial Signatures* as:

A characterisation of space based on form and function designed to understand urban envionments

Spatial Signatures provide exhaustive coverage for an area of interest by drawing organic boundaries that delineate portions of consistent morphological and functional characteristics. We will refer to a single *spatial signature* in two related but distinct ways: first, as one of the multiple classes that make up a wider typology of Spatial Signatures; and second, as a geographical instance of that class, a contiguous portion of territory that shares those morphological and functional traits. As such, spatial signatures can be seen as organically grown delineations that organise space into urban and rural, orderly and irregular, formal and informal. Laid out together, they can be used to explore urban extents, to parse through the complexity of their spatial structure, or to understand the evolution of cities. In bringing together both form and function, with a focus on the urban, Spatial Signatures provide a nexus between purely morphological characterisations, such as those of the morphometric literature; and those entirely based on function, such as geodemographic classifications. To the extent form and function are intrinsically connected, its combination leads to more robust portraits of the space that makes up cities. And, since the focus is on the urban, Spatial Signatures provide a complementary perspective to most land cover and use classifications, which historically pay more attention to the portion of space not occupied by cities.

The development of the Spatial Signatures approach carries several benefits to studies of cities and their footprint. The concept is data-driven but theoretically informed; granular but scalable; and flexible enough to be adapted to a wide variety of applied contexts, from data-rich to those with limited availability. Spatial Signatures embed theoretical ideas about how cities are spatially arranged, how this configuration can be best conceptualised, and how it is perceived by humans into a data-driven framework that connects them to the vast amount of empirical information available representing the world. These theoretical underpinnings are sourced from a variety of disciplines, from architecture to environmental scienes, and thus are inherently interdisciplinary. The Spatial Signatures thus provide a shared vocabulary to bring together a variety of scholars and policy makers for whom form and function in cities is relevant, either as their object of study or as an input for their own domains of expertise.

Part of the flexibility of this approach stems from the fact it represents a way of thinking about form and function in cities as much as a set of techniques to parse through data. In the following two subsections, we cover the two core components of building Spatial Signatures: the delineation of atomic units that can be organically grown to delineate boundaries between signatures; and the approach to embed form and function into each of those units in a way that the aggregation is feasible. With these conceptual notions in mind, the following section provides an empirical illustration of how they can be implemented in a variety of contexts.

3.2 *Atomic units: the Enclosed Tesselation*

This section proposes a novel and theoretically-informed delineation of space to support the development of spatial signatures. Since spatial signatures are conceptualised as highly granular in space, considering the ideal unit of analysis at which to measure them is of utmost importance. This process involves identifying the fundamental building block that partitions space in a way that may later be meaningfully aggregated into organic delineations of spatial signatures. This step is worth spending enery and effort for two main reasons. First, if ignored, there is an important risk of incurring the modifiable areal unit problem (MAUP, Openshaw, 1981). The urban fabric is not a spatially smooth phenomenon; rather, it is lumpy, irregular and operates at very small scales. Choosing a spatial unit that does not closely match its distribution will subsume interesting variation and will hide features that are at the very heart of what we are trying to capture with spatial signatures. Second, and conversely, we see adopting a meaningful unit a step of analysis itself. Rather than selecting an imperfect but existing unit to try to characterise spatial signatures, delineating our own is an opportunity in itself to learn about the nature of urban tissue and better understand issues about distribution and composition within urban areas.

Let us first focus on what is required from an ideal unit of analysis for spatial signatures. We need a partition of space into sections of built *and* lived environment that can later be pieced together based on their characteristics. The result will feed into an organic delineation that captures variation in the appearance and character of urban fabric as it unfolds over space. To be more specific, a successful candidate for this task will need to fulfill at least three features: indivisibility, internal consistency, and exhaustivity. An ideal unit will need to be *indivisable* in the sense that if it were to be broken into smaller components, none of them would be enough to capture the notion of spatial signature. Similarly, every unit needs to be *internally consistent*: one and only one type of signature should be represented in each observation. Finally, the resulting delineation needs to be geographically *exhaustive*. In other words, it should assign every location within the area of interest (e.g. a region or a country) to one and only one class. A unit that is indivisable, consistent, and exhaustive can thus form the basis of meaningful aggregation of space into spatial signatures.

The existing literature does not appear to have a satisfying candidate to act as the building block of spatial signatures. Martin: [Add a note on the work of Mansueto institute.] Without attempting an exhaustive review, an endeavour beyond the scope of this article, the vast majority of existing approaches to delineate meaningful units of urban form and function fall within one of the following three categories. The first group relies on *administrative* units such as postcodes, census geographies or municipal boundaries (e.g. Taubenböck et al., 2020). These are practical as they usually are exhaustive of the geography and readily available. However, their partition of space is usually driven by different needs that rarely align with the measurement of spatial signatures, or indeed those of any morphological or functional urban process. For example, Puente-Ajovín et al. (2020) compare the size distribution of urban areas in Spain across several definitions and conclude they are fundamentally different; similarly, Taubenböck et al. (2019) rank world's largest cities based on their administrative size and on an alternative methods they proposed following built-up area, reaching similar conclusions and even going on to argue that "administrative units obscure morphologic reality". An emerging body of work relies on granular, *uniform grids* as the main unit of analysis. The building blocks may be squares (e.g. Jochem et al., 2020) or hexagons, as in the case of the H3 spatial indexing system (Brodsky, 2018). This choice is usually explicitly or implicitly motivated by the lack of a better, bespoke partitioning; the use of input data distributed in grids (e.g. satellite imagery); and the assumption that, with enough resolution, grids can be organically aggregated into units that match the processes of interest. A third approach followed mostly by the literature on urban morphology relies on the definition of morphometric units. These include street segments (Araldi and Fusco, 2019), plots (Bobkova et al., 2019), building footprints (Schirmer and Axhausen, 2015), or constructs such as the sactuary area (Mehaffy et al., 2010, Dibble et al., 2019). In all these cases, the choice of an administrative, uniform or morphometric choice is justified by the particular application in which it take place. However none of these approaches meet the three characteristics we require for spatial signatures. Administrative boundaries are exhaustive but rarely indivisable or consistent when it comes to urban form, usually grouping very different types of fabric within a single area. Uniform grids are also exhaustive but, similarly to administrative definition, the arbitrariety of their delineation with respect to urban form usually leaves them divisable and internatlly inconsistent. Morphometric units are the most theoretically appealing since they are built to match the distribution of urban features and are usually granular enough to warrant internal consistency and indivisibility. Most of them are however not exhaustive as they are anchored to particular elements of the build environment, such as streets or building footprints, which do not provide full coverage. Plots would theoretically meet all characteristics but can be problematic due to their variable definition leading to different geometric representations (Kropf, 2018).

We propose the development of a new spatial unit that we term the *enclosed tessellation cell* (EC). An EC is defined as:

The portion of space that results from growing a morphological tesselation within an enclosure delineated by a series of natural or built barriers identified from the literature on urban form, function and perception.

Let us unpack this concept a bit further. ECs result from the combination of three sequential steps. First, they rely on a set of enclosing components: features of the landscape that divide it in smaller, fully delimited portions. The list of what should be counted as enclosing is informed by theory and, as we will see below, may vary by context. But, as an illustration, it includes elements such as the street network, rivers and coastlines, or railways. Second, these enclosing features are integrated into a single set of boundaries that partition the geography into smaller areas. In some cases, they will be small, as with urban blocks in dense city centres; in others, they will be larger in size, as in rural sections with lower density of enclosing features. We call each of this fully delimited areas an enclosure. Third, enclosures are further subdivided using a morphological tesselation. Originally proposed by (Fleischmann et al., 2020a), morphological tesselations exhaustively partition space based on a set of building footprints, which are used in this context as anchors to draw catchment polygons. This process generates geographical boundaries for a given area that result in a new spatial unit. This unit provides full geographical coverage without any overlap. Since the essence of the approach resides in growing a tessellation inside a set of enclosing features, we call the resulting areas "enclosed tesselation cells".

The enclosed tessellation (ET) intersects two perspectives of how space can be understood and organised. The first relies on the use of features that *delimit* the landscape and partition it into smaller, fully enclosed portions. These include the road and street networks, but also others such as railways or rivers. Each feature is conceptualised as a line that acts as a boundary, dividing space into what falls within each of its sides. A long tradition in the literature on urban morphology and perception relies on variations of these delimiters to parse through the urban fabric. Prominent early examples include the edges and paths highlighted by Lynch (1960) as two of the five core elements that define legibility and imageability of a city; as well as the large amount of work inspired by this framework that continues to contribute new understandings of how the internal structure of cities is spatially arranged and perceived by humans (e.g. Filomena et al., 2019).

The second perspective that ET integrate is a vision organised around *anchors*. In this view, space is best understood as the area in between a discrete set of relevant features. Unlike delimiters, these elements do not partition space per se, but instead act as origins to which the rest can be "attached". The choice of anchors might vary by context but, in this case, the literature on morphometrics has extensive evidence to support the use of buildings as the primary feature

(Hamaina et al., 2012, Usui and Asami, 2013, Schirmer and Axhausen, 2015). Tesselations grow areas around a point of focus. In our case, we use the morphological tesselation (Fleischmann et al., 2020a), which has been shown to be an efficient proxy for cadastral plots, the traditional smallest spatial unit in morophological analysis.

The combination of delimiters and anchors as the parsers of space make ECs an ideal spatial unit to study spatial signatures. Building on recent morphometric advances and integrating them with well-established understandings of how cities are read and perceived, the ECs meet the three requirements we outlined above. They are indivisable in that a single EC will contain no delimiters, at most a single anchor, and potentially none. They are also internally consistent because they are delineated as the area within the delimiters that contain at most one anchor. And finally ECs are exhaustive in that every location within the area of interest is assigned to one and only one EC, providing full geographical coverage without any overlap.

3.3 *Embedding form and function into Spatial Signatures*

Enclosed tessellation cells take the role of a structural unit, which itself has a descriptive value reflecting configuration of the built environment, and a container, into which other morphometric and functional characters can be embedded. We aim to describe the intrinsic character of each cell depending on its own geometry and nature, and, importantly, its immediate spatial context. The set of descriptors has to reflect both form and function to reflect the essence and definition of spatial signatures, leading to a heterogeneous selection of morphometric characters, capturing patterns of physical, built-up environment, and functional characters, reflecting demographics, proximity to points of interest, land use classification or historical importance. The specific composition of descriptors is not set and should always react to local conditions in terms of both data availability (e.g. to capture morphometric characters requiring high granularity or known building height may not be possible) and the specificity of each place (e.g. you would not capture proximity to theatres in a rural case study where are none but you would in metropolitan areas). However, it should always aim to reflect the nature of the form and function of each place in an exhaustive way. The inherent spatial autocorrelation of data derived from mutually overlapping *contexts* of each EC then allows a feasible aggregation of ECs into spatial signatures using cluster analysis, as K-Means, or Kohonen Self-organized Map, without explicit spatial contiguity constraint.

4. Illustration

4.1 *Method*

The classification of built form into spatial signatures is a conceptual framework and as such, can materialise in different ways depending on the particular implementation of a description of both form and function and the method of aggregation of enclosed cells into singatures. Here we present the concept applied to five case studies, reflecting different environments and heterogeneous input data requiring the adaptation of the classification to individual situations.

The sample offers a geographical variation covering Europe (Barcelona, Spain), North America (Houston, TX, United States), South America (Medellin, Colombia), Africa (Dar es Salaam, Tanzania) and South-east Asia (Singapore), coupled with cultural diversity, different planning paradigms involved in shaping the respective environments as well as varied historical and social contexts in which the selected cities were built. At the same time, the selection brings a variety of input data covering both extremes in terms of quality (e.g., official mapping in Barcelona vs remote sensing in Houston), the richness of information on functional aspects of places (e.g., detailed data on the municipal level in Medellin vs global gridded datasets in Dar es Salaam) and scale (82,375 units in Barcelona vs 2,043,581 units in Houston). We present this variety to illustrate the flexibility of spatial signatures to accommodate varied inputs and adapt to a local specificity, while retaining the merit of the concept.

The delineation of spatial signatures starts with the input data reflecting form and function of each place. We use enclosed tessellation, outlined in the section 3.2, as a basic spatial unit. Therefore, the input data should consist of building footprints and physical barriers denoting streets, railways, and water bodies. Using barriers, we first identify the geometry of enclosures to determine the external boundaries of consequently generated enclosed tessellation. Resulting set of geometric data is rich enough for a comprehensive morphometric analysis composed of primary measurable characters, capturing individual aspects of form, and contextualisation, following the model proposed by Fleischmann et al. (2021) (ADD REF). In the contextualisation step, we measure the tendencies of the distribution of each character within the neighbouring context of each tessellation cell. Function is captured as a heterogeneous set of datasets reflecting aspects from population to location of points of interest. All aspects are linked to enclosed cells using the most appropriate method for each data input (e.g., areal interpolation or network accessibility).[1] The complete list of used characters relfecting both form and function is available as an appendix XXX.

Spatial signatures are then identified using cluster analysis of tessellation cells based on their form-function characteristics, combined with the notion of contiguity, where each contiguous portion of land belonging to a single cluster is seen as a single signature. The combined data reflecting both form and function are therefore standardised and clustered using K-Means clustering. Since the number of classes is not known a priori, we use clustergram (schonlau) to understand clustering behaviour within different options and select the optimal number according to its structure. The final clustering is run with 1000 initialisations to ensure the stability of the results. The geometry of each spatial signature is then derived as dissolution of a contiguous patch of enclosed tessellation within the same cluster.

4.2 Results

Figures XXX-YYY illustrate the resulting spatial signatures in the respective case studies.[2] The geometries reflect the spatial extent of individual signatures derived from the enclosed tessellation with colour coding reflecting the type of a signature, i.e. the initial cluster. Two areas within the

[1] See the technical appendix for details on the implementation.

[2] For intermediate steps (e.g. clustergram) please refer to the technical appendix.

same type are expected to share the characteristics of built environment, being more similar (not necessarily the same) to each other than to the rest of the classes. Note that the similarity of different colours does not encode similarity of signatures. Also note, that due to varied extent of case studies, maps are not printed at the same scale.

The granularity of classification ranges from 9 (Houston) to 19 (Medellin) signature types per case study. However, the actual number is not dependent on the size of each city but rather on each place's actual heterogeneity, best illustrated on the comparison of Houston and Barcelona, the largest (2 million cells) and the smallest (80 thousand cells) case. Houston, representing north American sprawling urban fabric shows a considerably smaller diversity of spatial patterns (9 types of spatial signatures) than Barcelona (16 types), reflecting the richness of their respective historical developments. The distribution of cluster sizes follows the same pattern of unequal abundance across all cases. The most extensive types contain between 15 and 28observations, and the abundance is gradually decreasing towards a small number of outlier clusters containing less than a per cent of all observations within each sample. All the cases clearly defined both extremes on the urbanisation axis, with delineated central districts on the one hand and non-urban countryside signatures on the other. The transition between the two tends to follow the gradual pattern of signatures each less urban than the previous. The only exception where this tendency is not so profound (but still present) is Singapore, which geographical extent limited to the defined area of the main island does not allow the full transition.

Barcelona is known for its industrial grid, which is captured as a unique signature. However, the Cerda's grid is historically an infill between the city's medieval core and smaller existing settlements around. Both core and former independent villages are reflected in the typology of signatures, which reflect the historical origin of distinct places. The transition between the two, the historical organic fabrics and rigid Eixample is reflected as another signature, stitching together different patterns into a coherent city. Spatial distribution of signatures in Medellin tells the story of its intricate topography, even though the input data do not contain any information on altitude. The city lies in the valley surrounded by steep slopes. While the central parts lie on the relatively flat floor allowing paradigmatic planning and rigidness of the built environment, hillsides are becoming more vernacular leading to a sharp urban edge where the topography does not allow further development.

Signatures in Dar es Salaam reflect the changes in the formality of development, with formal areas distributed in the central parts of the city in the vicinity of a coastline. The transition between different degrees of formality is not always gradual as the most informal parts of the city are infills of the space not occupied by more planned neighbourhoods.

The character of spatial signatures in Houston follows two primary principles. One type forms the spine of activity spreading from the city centre radially to the suburbs. The other, filling the areas in between the former, is a story of the deterioration of compact, walkable urban block into convoluted dendritic street network patterns of modern suburbs. The change in these predominantly residential signatures is gradual and reflect the waves of development of the city as it was growing over the years.

A similar situation is in Singapore, where different types of signatures can be linked to the period of the origin of the development of each specific neighbourhood. Contrary to previous cases, the development and, consequently, spatial signatures followed radial manner, not entirely contiguous, with major infills built in the last 50 years.

5. Conclusions

References

Ahlfeldt, G. M. and Pietrostefani, E. (2019). The economic effects of density: A synthesis. *Journal of Urban Economics*, 111:93–107.

Angel, S., Franco, S. A., Liu, Y., and Blei, A. M. (2018). The shape compactness of urban footprints. *Progress in Planning*.

Araldi, A. and Fusco, G. (2019). From the street to the metropolitan region: Pedestrian perspective in urban fabric analysis:. *Environment and Planning B: Urban Analytics and City Science*, 46(7):1243–1263.

Batty, M. and Longley, P. A. (1987). Fractal-based description of urban form. *Environment and Planning B: Planning and Design*, 14(1961):123–134.

Bobkova, E., Berghauser Pont, M., and Marcus, L. (2019). Towards analytical typologies of plot systems: Quantitative profile of five European cities. *Environment and Planning B: Urban Analytics and City Science*, page 239980831988090.

Bourdic, L., Salat, S., and Nowacki, C. (2012). Assessing cities: A new system of cross-scale spatial indicators. *Building Research & Information*, 40(5):592–605.

Brodsky, I. (2018). H3: Uber's hexagonal hierarchical spatial index. *Available from Uber Engineering website: https://eng. uber. com/h3/[22 June 2019]*.

Comber, A. J., Wadsworth, R. A., and Fisher, P. F. (2008). Using semantics to clarify the conceptual confusion between land cover and land use: the example of 'forest'. *Journal of Land Use Science*, 3(2-3):185–198.

Conzen, M. R. G. (1960). Alnwick, northumberland: a study in town-plan analysis. *Transactions and Papers (Institute of British Geographers)*, (27):iii–122.

Copernicus Land Monitoring Service (2021). Urban atlas.

Defourny, P., Kirches, G., Brockmann, C., Boettcher, M., Peters, M., Bontemps, S., Lamarche, C., Schlerf, M., and Santoro, M. (2012). Land cover cci. *Product User Guide Version*, 2.

Dibble, J., Prelorendjos, A., Romice, O., Zanella, M., Strano, E., Pagel, M., and Porta, S. (2019). On the origin of spaces: Morphometric foundations of urban form evolution. *Environment and Planning B: Urban Analytics and City Science*, 46(4):707–730.

Dibble, J. L. (2016). *Urban morphometrics: towards a quantitative science of urban form*. PhD thesis, University of Strathclyde.

Duranton, G. and Puga, D. (2020). The economics of urban density. *Journal of Economic Perspectives*, 34(3):3–26.

European Environment Agency (1990). CORINE Land Cover. pages 1–163.

Ewing, R., Hamidi, S., Grace, J. B., and Wei, Y. D. (2016). Does urban sprawl hold down upward mobility? *Landscape and Urban Planning*, 148:80–88.

Filomena, G., Verstegen, J. A., and Manley, E. (2019). A computational approach to 'The Image of the City'. *Cities*, 89:14–25.

Fisher, P., Comber, A. J., and Wadsworth, R. (2005). Land use and land cover: contradiction or complement. In Fisher, P. and Unwin, D. J., editors, *Re-presenting GIS*, chapter 6, pages 85–98. John Wiley & Sons, Ltd, The Atrium, Southern Gate, Chichester,West Sussex PO19 8SQ, England.

Fleischmann, M., Feliciotti, A., Romice, O., and Porta, S. (2020a). Morphological tessellation as a way of partitioning space: Improving consistency in urban morphology at the plot scale. *Computers, Environment and Urban Systems*, 80:101441.

Fleischmann, M., Romice, O., and Porta, S. (2020b). Measuring urban form: Overcoming terminological inconsistencies for a quantitative and comprehensive morphologic analysis of cities. *Environment and Planning B: Urban Analytics and City Science*, page 2399808320910444.

Geddes, P. (1915). *Cities in evolution: an introduction to the town planning movement and to the study of civics*. London, Williams.

Georganos, S., Grippa, T., Vanhuysse, S., Lennert, M., Shimoni, M., and Wolff, E. (2018). Very high resolution object-based land use–land cover urban classification using extreme gradient boosting. *IEEE geoscience and remote sensing letters*, 15(4):607–611.

Gil, J., Montenegro, N., Beirão, J. N., and Duarte, J. P. (2012). On the Discovery of Urban Typologies: Data Mining the Multi-dimensional Character of Neighbourhoods. *Urban Morphology*, 16(1):27–40.

Hamaina, R., Leduc, T., and Moreau, G. (2012). Towards Urban Fabrics Characterization Based on Buildings Footprints. In *Bridging the Geographic Information Sciences*, volume 2, pages 327–346. Springer, Berlin, Heidelberg, Berlin, Heidelberg.

Hillier, B. (1996). *Space is the machine : a configurational theory of architecture*. Cambridge University Press, Cambridge.

Homer, C. H., Fry, J. A., and Barnes, C. A. (2012). The national land cover database. *US Geological Survey Fact Sheet*, 3020(4):1–4.

Howarth, P. J. and Boasson, E. (1983). Landsat digital enhancements for change detection in urban environments. *Remote sensing of environment*, 13(2):149–160.

Jochem, W. C., Bird, T. J., and Tatem, A. J. (2018). Identifying residential neighbourhood types from settlement points in a machine learning approach. *Computers, Environment and Urban Systems*, 69:104 – 113.

Jochem, W. C., Leasure, D. R., Pannell, O., Chamberlain, H. R., Jones, P., and Tatem, A. J. (2020). Classifying settlement types from multi-scale spatial patterns of building footprints. *Environment and Planning B: Urban Analytics and City Science*, page 239980832092120.

Koc, C. B., Osmond, P., Peters, A., and Irger, M. (2017). Mapping local climate zones for urban morphology classification based on airborne remote sensing data. In *2017 Joint Urban Remote Sensing Event (JURSE)*, pages 1–4. IEEE.

Kropf, K. (2018). Plots, property and behaviour. *Urban Morphology*, 22(1):1–10.

Kuffer, M., Pfeffer, K., and Sliuzas, R. (2016). Slums from space-15 years of slum mapping using remote sensing. *Remote Sensing*, 8(6):455.

Lehner, A. and Blaschke, T. (2019). A Generic Classification Scheme for Urban Structure Types. *Remote Sensing*, 11(2):173.

Lynch, K. (1960). *The Image of the City*, volume 11. MIT press.

Mehaffy, M., Porta, S., Rofe, Y., and Salingaros, N. (2010). Urban nuclei and the geometry of streets: The 'emergent neighborhoods' model. *Urban Design International*, 15(1):22–46.

Muratori, S. (1959). Studi per una operante storia urbana di venezia. *Palladio*, 1959:1–113.

Openshaw, S. (1981). The modifiable areal unit problem. *Quantitative geography: A British view*, pages 60–69.

Panerai, P., Castex, J., and Depaule, J.-C. (1997). *Formes urbaines: de l'îlot à la barre*. Editions Parentheses.

Pauleit, S. and Duhme, F. (2000). Assessing the environmental performance of land cover types for urban planning. *Landscape and urban planning*, 52(1):1–20.

Pivo, G. (1993). A taxonomy of suburban office clusters: the case of toronto. *Urban Studies*, 30(1):31–49.

Porta, S., Crucitti, P., and Latora, V. (2006). The network analysis of urban streets: A primal approach. *Environment and Planning B: Planning and Design*, 33(5):705–725.

Prasad, S. (2015). *Remotely sensed data characterization, classification, and accuracies*, volume 1.

Puente-Ajovín, M., Ramos, A., Sanz-Gracia, F., and Arribas-Bel, D. (2020). How sensitive is city size distribution to the definition of city? the case of spain. *Economics Letters*, page 109643.

Schirmer, P. M. and Axhausen, K. W. (2015). A multiscale classification of urban morphology. *Journal of Transport and Land Use*, 9(1):101–130.

Serra, M., Psarra, S., and O'Brien, J. (2018). Social and Physical Characterization of Urban Contexts: Techniques and Methods for Quantification, Classification and Purposive Sampling. *Urban Planning*, 3(1):58–74.

Song, Y. and Knaap, G.-J. (2007). Quantitative Classification of Neighbourhoods: The Neighbourhoods of New Single-family Homes in the Portland Metropolitan Area. *Journal of Urban Design*, 12(1):1–24.

Stark, T., Wurm, M., Zhu, X. X., and Taubenböck, H. (2020). Satellite-based mapping of urban poverty with transfer-learned slum morphologies. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 13:5251–5263.

Stewart, I. D. and Oke, T. R. (2012). Local Climate Zones for Urban Temperature Studies. *Bulletin of the American Meteorological Society*, 93(12):1879–1900.

Taubenböck, H., Debray, H., Qiu, C., Schmitt, M., Wang, Y., and Zhu, X. (2020). Seven city types representing morphologic configurations of cities across the globe. *Cities*, 105:102814.

Taubenböck, H., Weigand, M., Esch, T., Staab, J., Wurm, M., Mast, J., and Dech, S. (2019). A new ranking of the world's largest cities—do administrative units obscure morphological realities? *Remote Sensing of Environment*, 232:111353.

Trewartha, G. T. (1934). Japanese cities distribution and morphology. *Geographical Review*, 24(3):404–417.

Usui, H. and Asami, Y. (2013). Estimation of mean lot depth and its accuracy. *Journal of City Planning Institute of Japan*, 48(3):357–362.

Venerandi, A., Quattrone, G., and Capra, L. (2018). A scalable method to quantify the relationship between urban form and socio-economic indexes. *EPJ Data Science*, 7:1–21.

Weng, Q. and Quattrochi, D. A. (2018). *Urban remote sensing*. CRC press.