Spatial Signatures
Dynamically building the built environment

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Abstract: Blah blah blah

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1. Introduction

Fleischmann et al. (2020a) is king.

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 As part of this trend, methods focusing on a single aspect (Porta et al., 2006) have been replaced by efforts to better reflect the complexity of urban form through the combination of multiple morphometric characters into a single model, often leading to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, 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 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.

3. Spatial Signatures

3.1 Definition

SS sit in between purely morphological and purely functional.

characterisation of space based on form and function designed to understand urban environment - geared towards understadning urban spaces - SS - a distinct type of space based ... - both granularity and scalability built-in

tissue def A distinct area of a settlement in all three dimensions, characterised by a unique combination of streets, blocks/plot series, plots, buildings, structures and materials and usually the result of a distinct process of formation at a particular time or period.

3.2 Building blocks: 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 funtion into Spatial Signatures

4. Illustration

5. Conclusions

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