The Street as a Three-Dimensional Urban Form

by Mateo Neira & Laura Narvaez Zertuche
Bartlett Centre for Advanced Spatial Analysis, UCL & The Alan Turing Institute, Urban Design Group, Foster + Partners LTD

Keywords: visual complexity, spatial information, design practice, interdisciplinary methods, street layout.

Abstract: In urban morphology research, as well as in practice amongst urban design professionals, there is often the challenge to understand the different elements of urban form as three-dimensional processes and not only as two-dimensional forms of spatial information. The purpose of this paper is to undertake an initial critical analysis of the street as the basic unit of space in our experience of the city as a three-dimensional urban form. The richness of subject matter presented by cities and their nature of street form and configuration has given rise to an equal richness in methods of investigation. As such, this research develops a measure for assessing the physical complexity of the built environment by generating cross-sectional data of streets comparing different cities. The first aim is to demonstrate an automatic, scalable and reproducible method to measure and visualize street cross-sections, revealing spatial patterns that are of visual importance. The second is to identify the morphological properties shared by clusters of cases, understanding aspects of urban design and development form. Findings of this study reveal a taxonomy of street typologies through classification, offering a composite view in which different morphological approaches are combined and providing a better understanding of how urban streets constitute the set of spatial relationships that determine the morphological identity of cities.

1. Introduction

The paper begins by reviewing literature that examines urban morphology from the point of view of its physical three-dimensionality, which has been prevalent in urban design practice, but often overlooked amongst studies in urban morphology research. Our focus on the three-dimensionality of urban form is the street. In a rapidly urbanising world, the challenge to better understand the relationship between urban processes and the built environment is through one of the most essential spatial elements of what composes the largest public realm of any city, the street. We believe that the street as spatial component of cities is the generator of different typologies of movement, a driver for facilitating economic transactions and the common denominator of creating place. To explore the spatial qualities of the street, a method to generate street cross-section, here after referred to as street profile, using data and analyzing cities in terms of data and analyse cities in terms of the visual complexity given by the variance of street profiles typologies within a local spatial unit.

DOI 10.36158/978889295357417
www.tabedizioni.it

Research aimed at looking at the element of the street can be distinguished in two main directions: Firstly, in urban morphology, typo-morphology and historical-geographical studies (Moudon, 1997; Samuels, 2008; Gil *et al.*, 2012) typically applying qualitative and descriptive approaches (Oliveria, 2016) and secondly, spatial analysis, displaying analytic and quantitative methodologies (Hillier *et al.*, 2012; Batty, 2013; Barthelemy, 2015). In this paper we continue the endeavour to bring these approaches together to a common framework of spatial information. Of particular importance to this endeavour is the idea of street profiles as representative of a city's urban DNA, which we believe is central to urban planning and design. However, on closer scrutiny of street typologies, in urban research and in practice they remain vague capturing most of the times a two-dimensional understanding of streets and its spatial layout rather than the three-dimensional performance and functionality of streets, which usually links aspects of density, vertical land uses, demand of types of mobility and even visual features that help ease of wayfinding (Conroy, 2003). Therefore, the aim of this paper is to propose a systematic and applicable methodology for generating street profiles from existing data sources, compare their spatial ordering and what this means to the character of place for each city, which is an essential driver of many urban processes (Hillier *et al.*, 1993) and relevant to urban design practice.

The paper is structured as follows: First, the role of complexity theory in urban morphology is given and the role of street types in the wider context of urban morphology research. Second, the methods for generating street profiles and measuring 'visual complexity' in terms of the variance of these profiles at a local scale are discussed. And third, the analysis and results are presented, where we analyse six different cities and compare them by both the typologies of street profiles present in them and their spatial distribution, which in turn draws our conclusions and formulate discussions for further research.

1.1. *Defining typology through spatial complexity*

Cities are an example of large complex systems (de Roo & Rauws, 2012) that display emergent phenomena and self-organized structure (Batty, 2009). On one hand, some of the principles to understand the complexity of cities have not only been focused in their planning and design, but also in the dynamics of emergent or spontaneous urban order, in the spatial structure of the city, its connectedness, accessibility, resilience, and robustness – factors which help linking qualitative theories of cities and quantitative studies of physical form, design and transportation (Portugali, 2006). On the other hand, the task in city planning has become less one of creating order through rational urban plans and spatial planning, but one of how to generate and maintain urban complexity that drive healthy urban processes.

Research on complexity theory of cities has found that to achieve a healthy urban environment, urban design and planning can encourage diversity, connectivity, resilience, and robustness (Batty, 2013; Barthelemy 2016). As Alexander (1977) states, one way of addressing this is to try to understand the underlying complexity and character of different places to better understand them. To help meet this task, we need to understand both the complexity of cities and the ways in which it could be generated through planning or design (Marshall, 2012).

1.2. *Street network measures and design*

Of importance to this endeavour is the role of streets, their spatial configuration and topology in articulating urban life, as they help organize the human dynamics within cities, influence travel behaviour, location decisions and the texture of the urban fabric (Giacomin & Levinson, 2015; Jacobs, 1993). Accordingly, researchers have devoted much attention to street network patterns, performance, complexity and configuration (Barthelemy, Bordin, Berestyecki, & Gribaudi, 2013; Batty, 2005). Urban scholars and planners have studied street networks in numerous ways, most of which have focused on urban form and transportation, and others on the topology (Porta, Crucitti, & Latora, 2006), complexity (Boeing, 2018), resilience, and evolution (Murcio, Masucci, Arcaute, & Batty, 2015) of street networks. Yet, most of this stream of research has focused only on the two-dimensional nature of streets.

The role of streets in creating healthy urban environments is not only given by their spatial configuration and topology at a city-wide level, but also by the quality and character of the street space as experienced at eye-level. As Smailes (1955) highlights, it is through the third dimension that much of the distinctiveness and variety of urban spaces arise. Research in this area has been mostly focused in the streetscape as a basic urban element which plays a major role in the 'livability' of a city (Cavalcante *et al.*, 2014). The physical and perceptual qualities of streetscapes directly influence how people interact and locally behave in the city (Ewing & Handy, 2009; Ewing, Handy, Brownson, Clemente, & Winston, 2006).

There have been recent attempts to quantify streetscape quality at a local level in systematics ways. For example, street-view images together with machine-learning methods to quantify urban greenery (Stubbings, Peskett, Rowe, & Arribas-Bel, 2019), as well as street quality measurement using multiple sources of urban data proposed in Zhang, et al (2019). In the latter, the role of enclosure, the three-dimensional space created by the buildings on either side of the street is highlighted as playing a key role in urban vitality. However, this is often difficult to measure directly by the amount of sky view in street view images. There has also been little research into quantifying the change in enclosure as we transverse urban environments.

1.3. *Measures of visual complexity in urban environments*

Although various complexity metrics have been proposed at multiple scales (Boeing, 2018), we only focus here on those that capture visual complexity at the scale of the street. Ewing and Clemente (2013) relate visual complexity to the number of perceptible differences a person is exposed whilst moving through the city. However, to our knowledge there has not been an attempt to systematically measure it. Some attempts have been made in the past using manual techniques, such in the case argued by Cooper (2003) where a manual technique to segment street skylines (i.e., edges formed between boundaries of buildings and the sky) and the fractal dimension of these skylines is used to assess the complexity. Here we propose a simple approach to capture the changing three-dimensional nature of the space between buildings by creating street cross-sections at regular intervals for the entire city and measuring the amount of change – visual information – as we move through the city by measuring the entropy of these cross-sections at a fixed spatial scale. We argue that this measure of entropy can be a proxy for visual complexity at a meso-scale.

Although the spatial structure and geometric properties of street networks play an important role in structuring human interaction and transportation processes, forming an important pillar of a city planner's search for spatial order (Rose-Redwood & Bigon, 2018), the visual cues and the three-dimensional space that is formed by the spatial structure, and not only of the street network, but by the buildings and their densities along the network, also have important functions for spatial cognition and visual complexity. Although complexity refers to the visual richness of a place, which depend on the variety of the physical environment, specifically the numbers and kinds of buildings, architectural diversity, ornamentation, landscape elements, street furniture, signage, and human activity, here we will only focus on the physical environment, and specifically the sense of enclosure produced by the specific configuration of buildings along the street network and their variance through space.

2. Methodology

This paper shows how street cross-sectional entropy can be calculated for a series of cities and how the resultant numerical measurement can be related to the presence of certain morphological features that, in combination, effect the character of a place. We selected six case studies to test our methodology: London, New York, Madrid, Washington DC, Barcelona and San Francisco. One of our main restrictions is the availability of data relating to building heights for different cities. Nevertheless, the results allow us to create a typology of street sections and quantify a proxy for visual complexity by measuring the entropy of our case studies at a local scale.

2.1. *Data*

Street network data is retrieved from Open Street Maps. To maintain consistency we query all roads within each city's administrative boundary. From the street network data, we construct a graph where intersections are nodes and streets are edges using the OSMnx python library (Boeing, 2017). The topology of the graphs is simplified such that only intersections and dead-ends are represented as nodes, whilst edges represent street segments where the complete spatial geometry is retained. Figure 1 shows the spatial structure of these street networks, along with key metrics in Table 1: Number of edges in the network, which give a sense of the size of the network, the average street length, which serves as a proxy for block size and indicates how fine-grained or coarse grained the network is, number of buildings, and number of generated street profiles.

We also compile building footprint data along with height attributes from the following: Department of Information Technology & Telecommunications (DoITT), Barcelona City Council Geoportal, the City and County of San Francisco Open Data Portal, and Madrid City Council Open Data Portal. Building height attributes from all the data sources where created from LiDAR or photogrammetrically that represent the height of the roof above ground level;

Figure 1. *Street networks of analysed cities.*

this gives a low level of detail (LOD-1) 3D model of the buildings. Both the street network data and building footprint data is projected to it's corresponding Universal Transverse Mercator (UTM) coordinate system and all measurements are given in meters.

2.2. *Analysis*

For each city we segment all edges from the street network every 40 meters. For each segment we calculate the geographic median and the azimuth , and create a new line that is perpendicular to at the point . The perpendicular line is used to create the street profile by intersecting it the closest building on either side of the street and querying the associated height attribute. This allow us to create a profile of the street at regular intervals along the network, as illustrated in figure 2.

In total we generated 1,275,254 street profiles. Once we have calculated the street profiles for each segment of all the streets in the six cities, we calculate the street enclosure as building height to street width ratio . We first compare the six cities by measuring the relative frequency of each of these variable (street width, building height, and enclosure). We do this by estimating the probability density function for each city through a kernel density estimation. These distributions are the simplest and first indicators that we use to compare the cities, as they capture both the physical scale at street level as well as the sense of visual enclosure.

Once we have compared the six cities we classify all the street segments and investigate how much these profiles change across space. In other words, we are interested in quantifying the experience of walking through these spaces by assessing the visual variance in terms of visual enclosure and scale within a local area. To achieve this, we classify the 1,275,254 street cross-sections into 64 categories that vary along three axis: Enclosure, height ratio of buildings at either side of the street, and scale.

We create uniform spatial units by dividing all the cities into 200 m hexagons, a 200 m hexagon was chosen as the unit of analysis as it captures the local area at which we experience the urban environment at street level. For each hexagon we calculate the Shannon entropy , of the different typologies of street profiles found. For each hexagon bin we calculate the entropy as:

$$H = -\sum_{i=1}^{n} P(w_i) log_e P(w_i)$$

where represents the total number of street profiles typologies, indexes the typologies, and represents the proportion of street segments that fall in the typology weighted by the edge

Table 1. *Data captured for each city.*

City	Nº of Streets	Nº of Buildings	Avg. Street Length	Nº of Generated Street Profiles
London	299,450	649,747	99 m	463,042
New York	142,328	1,084,108	142.32 m	308,611
Madrid	63,175	401,869	63.17 m	173,250
Washington DC	28,720	101,039	122.65 m	92,635
San Francisco	27,064	177,023	117 m	74,635
Barcelona	17,658	239,698	104 m	57,053

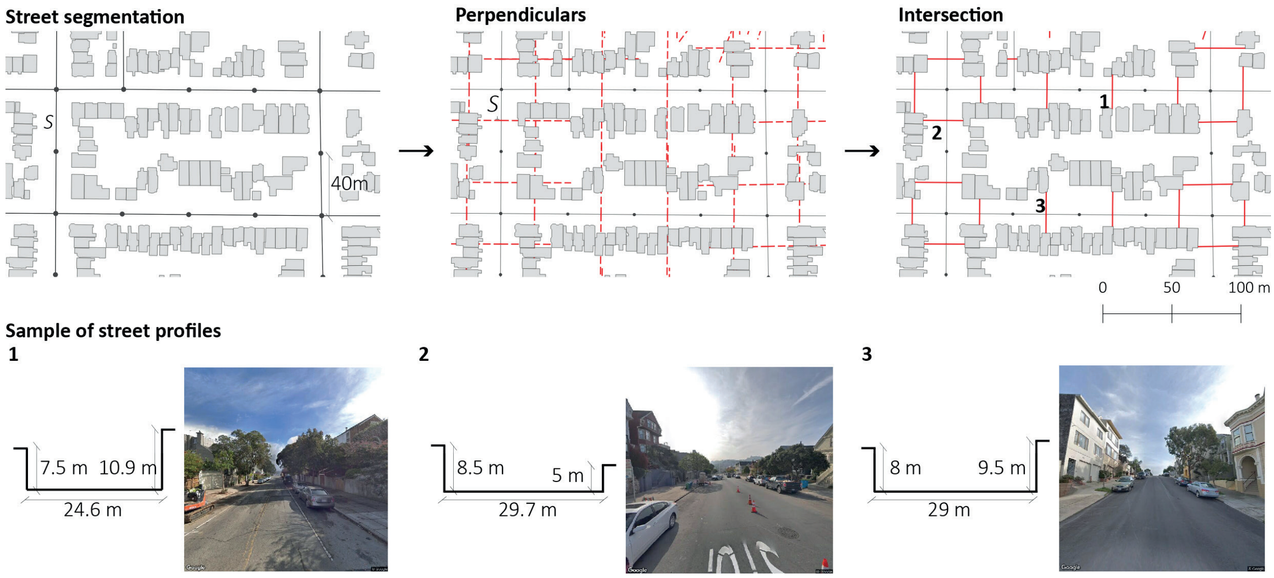

Figure 2. *Procedure to estimate street profiles. Top row shows the procedure to calculate street network width from building façade to building façade and join height attributes. Bottom row shows samples of estimated street profiles along with google street view imagery of each.*

length. The value of is dimensionless, and the maximum value it can take equals the logarithm of the number of unique typologies, while the minimum value is 0. Maximum entropy is achieved when there are equal number of segments that belong to each of the typology equal to 4.16, and minimum entropy achieved if all street segments fell into a single typology.

3. Results

3.1. *City profiles*

Figure 3a, 3b, 3c present the relative frequencies of street widths, building heights, and enclosure for each of the six cities studied given by the fitted probability density function. Three distinct trends can be seen. The first is similar for London, San Francisco, and Washington DC, defined by a street width distribution with two peaks, one around 20 meters and the second around 60 meters; building heights along these mostly range from 6 meters to 15 meters (equivalent to buildings of 2 to 4 stories) and enclosure values are centred around 0.4 (street profiles with a 1:2 building height to width ratio). The second is composed of Barcelona and Madrid. Both cities have relative high frequency of small streets of around 10 meters width, and building heights showing greater variance, with an average of around 18 meters or 4 story buildings. Lastly, New York shows a distinct profile, particularly for building heights that are higher than the rest of the cities with an average of 30 meters and an enclosure value centred around 1 (street profiles with a 1:1 height to width ratio).

Although the frequency of different types of street profiles for each city gives us a sense of the different urban characters of the cities, differentiating the prevalence of dense/sparse and high-rise/low-rise morphologies and different sense of enclosure at the street level, it fails to capture how these are structured in space. To account for this, in Figure 3d we plot the relationship of the street widths and average building height at either side of the street for each city to get a more detailed view of how these unfold through the street network. Both street widths and average building heights at either side of the street are grouped into four categories. In the case of streets these are divided into: 0m-20m, 20m-30m, 30m-50m, and streets greater than 50m. Average building heights at either side of the street are divided into: 0m-9m, 9m-16m, 16-50m, and greater than 50m.

In the case of London, Washington DC and San Francisco streets that have a low-high street width – building height relations are concentrated in the central business district with the relation inverting as we go towards the periphery, London being the most extreme of these cases. New York, Madrid, and Barcelona on the other hand have a more homogeneous distribution of mostly low-high values. In the case of New York, we can see this is particularly the case in the borough of Manhattan and parts of Brooklyn, while most other places have a low-low relation reflecting what is shown in figure 3c of a mean enclosure value centred around 1 (1:1 height to width ratio).

3.2. *Street typologies*

After classifying all the street profiles, we find 64 clusters that vary along the three metrics of enclosure, ratio of building-to-building height and scale. In Table 2, we show the properties of the most prevalent cluster in each city. Madrid and Barcelona share the most prevalent typology of street, with enclosure of 1.5:1 and small streets. In general, most streets for all cities tend to have similar sized building at either side, but different cities have varied distribution of different typologies, with Barcelona and Madrid having a more heterogeneous mix of typologies.

3.3. *Visual complexity*

Table 3 shows the statistical properties of the entropy values for each of the cities studied. It is interesting to note that for the six cities statistical properties of entropy values are consistent. Madrid has the lowest mean entropy value, with a mean of 0.54, and New York has the highest with a mean value of 1.17. Although the statistical properties are similar for all the cities studied, there spatial distribution is varied, which reflect the unique urban character of each place.

London shows a radial pattern of street profile entropy with high values concentrated in the centre and along main corridors with values decreasing as we go towards the periphery. This result reflects the varied character of London's centre versus more homogeneous residential areas. In contrast, both New York and Barcelona show a more even spatial distribution of entropy

Table 2. *Most common street typology for each city.*

City	Enclosure	Building/Building	Scale
London	0.23	0.91	24m
New York	1.03	0.89	25m
Madrid	1.40	0.91	14m
Washington DC	0.28	0.90	36m
San Francisco	0.23	0.88	24m
Barcelona	1.41	0.87	15m

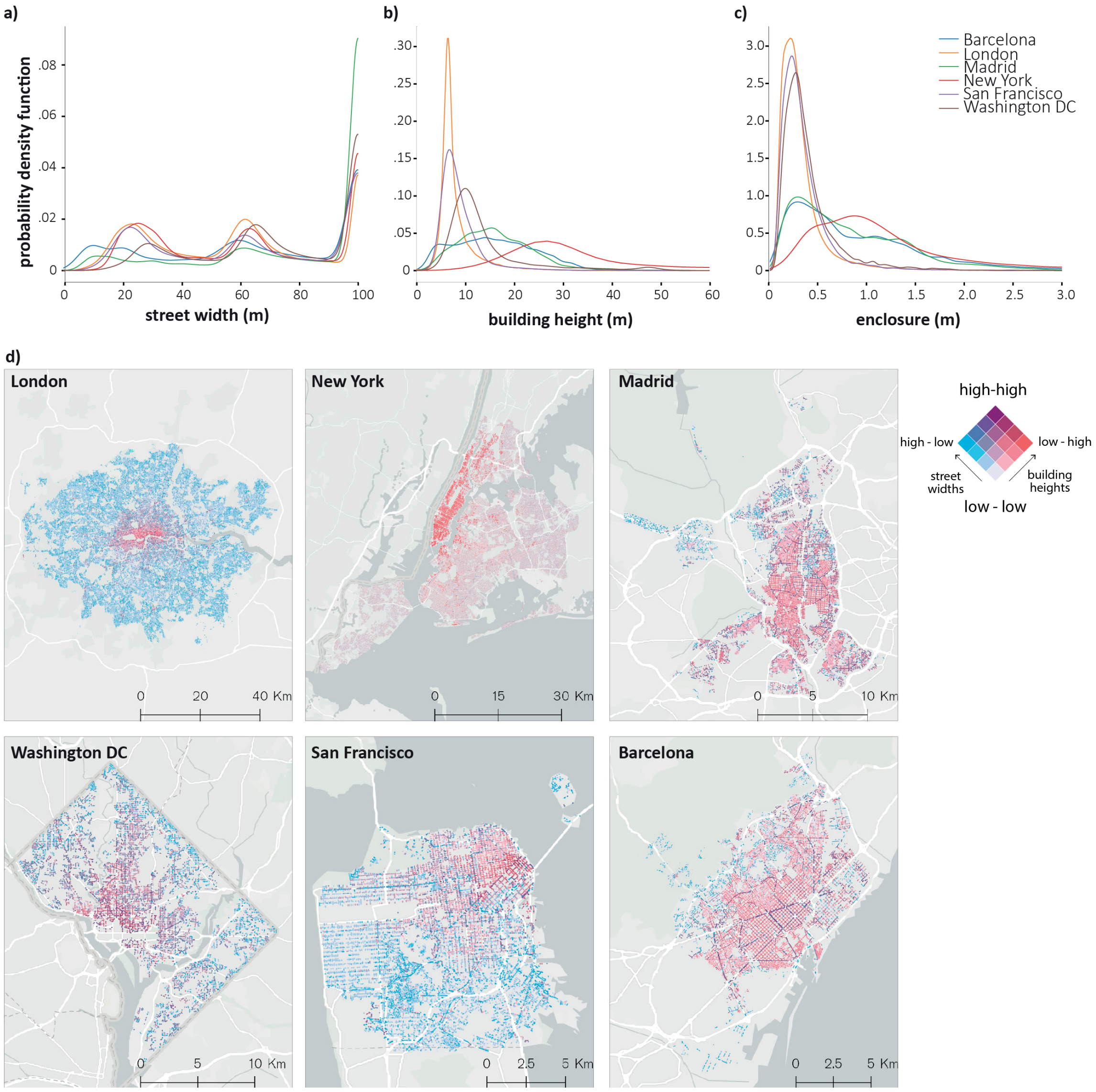

Figure 3. *Relative frequency of a) street widths, b) building height along street, and c) enclosure. d) spatial distribution of street width to building height relationship.*

Table 3. *Statistical properties of entropy values for each city.*

City			
London	2.73	0.53	0.91
New York	2.66	0.56	1.17
Madrid	2.53	0.66	0.54
Washington DC	2.28	0.75	0.78
San Francisco	2.28	0.57	0.87
Barcelona	2.73	0.73	1.03

throughout the city. In the Case of Madrid, we also see an even spatial distribution of entropy, however this is interrupted by the M-30 lateral motorway where there is a sharp change towards lower values east of the motorway. For San Francisco we can detect the residential area of mostly one and two-storey buildings in the west, versus the vibrant areas in both the Financial District and Mission District.

4. Discussion/Conclusion

4.1. *Concluding remarks*

This study proposed a method for generating street cross-section data by combining readily available street network data and building footprints with height attributes and assessing cities in terms of the typology of these street cross-sections as well as the visual complexity at a local scale as they change through the street network. The results show the similarities and differences in urban character of the space between buildings within and across six cities. The benefit of our approach is that it fuses existing data that are usually studied independent of each other to create a metric that can be used to assess visual complexity at a meso-scale. This resulting measure can be useful to urban designers interested in pursuing a more quantitative approach, as well as researchers interested in understanding how the physical qualities and spatial configurations of streets affect people's perceptions of the urban environment.

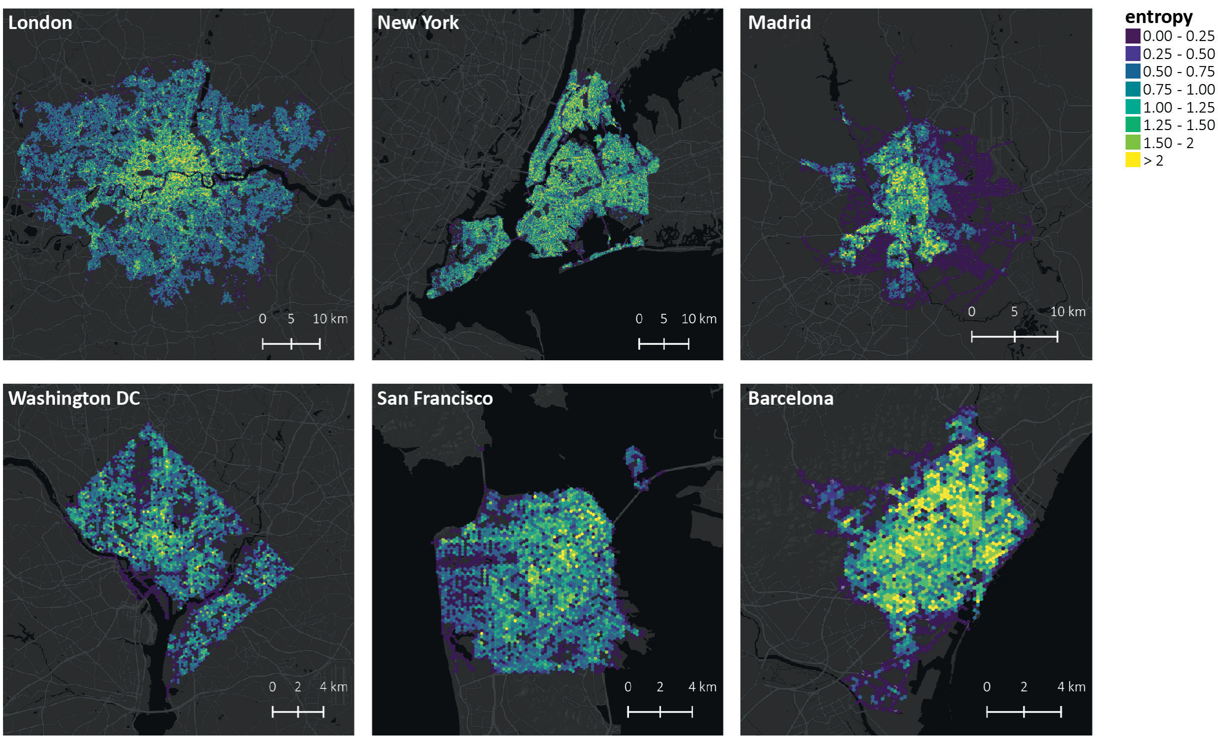

Figure 4. *Spatial distribution on street cross-section entropy for London, New York, Madrid, Washington DC, San Francisco, and Barcelona.*

4.2. *Limitations and future research*

Whilst the method proposed here is a first attempt to analyse streets as perceived at eye-level and systematically quantify visual complexity at a meso-scale there are many other aspects of the physical environment that influence the perception of space and contribute towards the visual complexity streets and its architecture, which include: Numbers and kinds of buildings, architectural diversity, ornamentation, landscape elements, street furniture, signage and human activity. Here we have only focused on the overall space created between buildings across the street network. Future research can combine this approach with more micro-scale and design features captured through street imagery. In addition, future directions of this research aim to enhance our studies in relation to how the entropy on street profiles can relate to other urban metrics such as land use diversity, network connectivity, population and built up density, among others. Overall, the complexity sciences hold promising potential to enlighten urban morphology theory and advance in the different morphological approaches, yet further efforts should be devoted to understand the heterogeneity of what street design entails that drive the spatial complexity of cities.

References

Alexander C. (1977), *A pattern language: towns, buildings, construction*, Oxford university press.

Barthelemy M. (2015), *From paths to blocks: New measures for street patterns*, in *Environment and Planning B: Planning and Design*, 44(2), pp. 256-271.

Batty M. (2009), *Cities as Complex Systems: Scaling, Interaction, Networks, Dynamics and Urban Morphologies*, in Meyers A.R. (Ed.), *Encyclopedia of Complexity and Systems Science*, pp. 1041-1071, Springer, New York, NY. https://doi.org/10.1007/978-0-387-30440-3_69.

Batty M. (2013), *The New Science of Cities*, MIT Press, Cambridge.

Boeing G. (2017), *OSMnx: New methods for acquiring, constructing, analyzing, and visualizing complex street networks*, in *Computers, Environment and Urban Systems*, 65, pp. 126-139.

Boeing G. (2018), *Measuring the complexity of urban form and design*, in *Urban Design International*, *23*(4), pp. 281-292.

Boeing G. (2019), *Urban spatial order: Street network orientation, configuration, and entropy*.

Cavalcante A., Mansouri A., Kacha L., Barros A.K., Takeuchi Y., Matsumoto N., Ohnishi N. (2014), *Measuring streetscape complexity based on the statistics of local contrast and spatial frequency*, in *PLoS One*, 9(2), e87097.

Conroy Dalton R. (2003), *The secret is to follow your nose*, in *Environment and Behavior*, 35, pp. 107-131.

Cooper J. (2003), *Fractal assessment of street-level skylines: a possible means of assessing*, in *Urban Morphology*, 7(2), pp. 73-82.

de Roo G., Rauws W.S. (2012), *Positioning planning in the world of order, chaos and complexity: On perspectives, behaviour and interventions in a non-linear environment*, in *Complexity theories of cities have come of age*, pp. 207-220, Springer.

Ewing R., Clemente O. (2013), *Measuring Urban Design, Island Press*, Washington, DC.

Ewing R., Handy S. (2009), *Measuring the unmeasurable: Urban design qualities related to walkability*, in *Journal of Urban Design*, 14(1), pp. 65–84.

Ewing R., Handy S., Brownson R.C., Clemente O., Winston E. (2006), *Identifying and measuring urban design qualities related to walkability*, in *Journal of Physical Activity and Health*, 3(s1), pp. S223-S240.

Giacomin D.J., Levinson D.M. (2015), *Road network circuity in metropolitan areas*, in *Environment and Planning B: Planning and Design*, 42(6), pp. 1040-1053. https://doi.org/10.1068/b130131p.

Gil J., Beirão J.N., Montenegro N., Duarte J.P. (2012), *On the discovery of urban typologies: data mining the many dimensions of urban form*, in *Urban Morphology*, 16, pp. 27-40.

Hedman R., Jaszewski A. (1984), *Fundamentals of urban design*.

Hillier B., Penn A., Hanson J. *et al.* (1993), *Natural movement: Or, configuration and attraction in urban pedestrian movement*, in *Environment and Planning B: Planning and Design*, 20, pp. 29-66.

Hillier B., Yang T, Turner A. (2012), *Normalising least angle choice in Depthmap and how it opens new perspectives on the global and local analysis of city space*, in *Journal of Space Syntax*, 3, pp. 155-193.

Jacobs A.B. (1993), *Great streets*, The MIT Press, Cambridge Massachusetts.

Marshall S. (2012), *Planning, design and the complexity of cities*, in *Complexity theories of cities have come of age*, pp. 191-205, Springer.

Moudon A.V. (1994), *Getting to know the built landscape: Typomorphology*, in Franck K., Schneekloth L. (eds), Ordering Space: Types in Architecture and Design, Van Nostrand Reinhold, New York, pp. 289-311.

Murcio R., Masucci A.P., Arcaute E., Batty M. (2015), *Multifractal to monofractal evolution of the London street network*, in *Physical Review E – Statistical, Nonlinear, and Soft Matter Physics*, 92(6), pp. 1-13. https://doi.org/10.1103/PhysRevE.92.062130.

Paolo Masucci A., Molinero C. (2016), *Robustness and closeness centrality for self-organized and planned cities*, in *European Physical Journal B*, 89(2), pp. 1-8. https://doi.org/10.1140/epjb/e2016-60431-2.

Portugali J. (2006), *Complexity theory as a link between space and place*, in *Environment and Planning A*, 38(4), pp. 647-664.

Porta S., Crucitti P., Latora V. (2006), The network analysis of urban streets: A dual approach, *Physica A: Statistical Mechanics and Its Applications*, 369(2), pp. 853–866. https://doi.org/10.1016/j.physa.2005.12.063.

Oliveira V. (2016), *Urban Morphology. An Introduction to the Study of the Physical Form of Cities*, Springer, Cham.

Samuels I. (2008), *Typomorphology and urban design practice*, in *Urban Morphology*, 12, pp. 58-62.

Stubbings P., Peskett J., Rowe F., Arribas-Bel D. (2019), *A Hierarchical Urban Forest Index Using Street-Level Imagery and Deep Learning*, in *Remote Sensing*, 11(12), p. 1395.

Turner A. (2007), *From Axial to Road-Centre Lines: A New Representation for Space Syntax and a New Model of Route Choice for Transport Network Analysis*, in *Environment and Planning B: Planning and Design*, vol. 34, issue 3, pp. 539-555

Zhang L., Ye Y., Zeng W., Chiaradia A. (2019), *A Systematic Measurement of Street Quality through Multi-Sourced Urban Data: A Human-Oriented Analysis*, in *International Journal of Environmental Research and Public Health*, 16(10), p. 1782.