FROM FORM TO INFORMATION: 
ANALYSING BUILT ENVIRONMENTS IN DIFFERENT SPATIAL CULTURES

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ABSTRACT

Cities are different around the world, but does this fact have any relation to culture? The idea that urban form embodies idiosyncrasies related to cultural identities captures the imagination of many in urban studies, but it is an assumption yet to be carefully examined. Approaching spatial configurations in the built environment as a proxy of urban culture, this paper searches for differences potentially consistent with specific regional cultures or cultures of planning in urban development. It does so focusing on the elementary components shaping cities: buildings and how they are aggregated in cellular complexes of built form. Exploring Shannon’s work, we introduce an entropy measure to analyse the probability distribution of cellular arrangements in built form systems. We apply it to downtown areas of 45 cities from different regions of the world as a similarity measure to compare and cluster cities potentially consistent with specific spatial cultures. Findings suggest a classification scheme that sheds further light on what we call the ‘cultural hypothesis’: the possibility that different cultures and regions find different ways of ordering space.

Keywords  Spatial information, built form, entropy, order, spatial cultures.

1 Introduction

Cities of different cultural types and different scales embody different spatial identities... human societies order their spatial milieu in order to construct a spatial culture, that is, a distinctive way of ordering space. Hillier [38, p.5-6]

The idea that urban form embodies idiosyncrasies that express cultural identities seems to be a frequent assumption in urban studies. It has to do with the contextual role of custom and institutional settings, from regional idiosyncrasies assimilated to traditional ways of building to the dichotomies of planned and unplanned cities, shaped through top-down agencies or as chance-grown arrangements [46]. However, can local cultures actually leave traces in urban space? Despite its persistence in the urban imagination, the problem of how built environments might embody specific cultural identities seems yet to be fully addressed in urban morphology. To begin with, there is an “evident lack of a quantitatively rigorous, comprehensive and systematic framework for the analysis of urban form” [68]. In this sense,
historically- and culturally-informed quantitative methods are essential for uncovering forms and patterns resulting from city organization processes [17].

In this paper, we look closely into that assumption, and address the question of whether cities find distinct regional characteristics as material forms and cultural milieu, or take on physically specific forms under certain cultural conditions [38]. This implies examining the existence of contextualised ways of shaping cities – and features that might transcend context. We shall do so approaching the spatial configurations of the built environment as a proxy of urban culture, looking into the very constituents of urban form. Differently from emphases on street networks [42, 58], our approach focuses on the elementary components shaping the tangible spaces of cities: buildings and how they are aggregated in complexes of built form. It also means taking into account a feature that seems to differentiate cities from non-urban settlements: the systems of built forms arranged in urban blocks. Closely related to systems of streets and open spaces, the urban block has become emblematic, uniquely defining the form of cities in urban societies emerged in regions and cultures seemingly with no contact with one other [55].

We will look into 45 cities around the world and measure their spatial configurations to assess differences and similarities between them. In order to do so, we shall lay down an approach based on Shannon’s [65] measure of information and entropy. We will argue that Shannon’s measure is particularly suited for the task of capturing amounts of information related to randomness and order in configurations of built form. Our approach takes the following steps:

- Inquire into built form as ‘spatial culture’.
- Propose a measure of configuration of built form based on Shannon’s entropy.
- Apply this measure to examine cities of different regions of the world.
- Finally, use the results as a similarity measure to compare and cluster the studied cities, as ‘information signatures’ potentially associated with specific regions or spatial cultures.

2 Does culture leave traces in urban space?

‘Culture’ was famously described by Raymond Williams [27] as one of the most complex words in the English language, an elusive phenomenon notoriously difficult to conceptualise and frequently challenged as an explanatory category [51, 32]. We use the term not to refer to an ‘independent entity’ with explanatory force [25] but as an ongoing process involving the practices, works and products of human activity situated in time and place. Therefore, ‘culture’ is embedded in material contexts and social frameworks, and relates to institutions and institutionalised behaviours, values, meanings and orientations, and capacities for self-regulation [15]. Such processual notion of culture also as a field of action [37] takes into account forms of self-organisation and coordination between agencies in material production. In this sense, we wish to explore urban form as an expression of cultural systems as inherently material processes, aware of potential contingencies that must be considered in empirical analysis.

One of the under-examined assumptions about the connections between society and urban form is that the latter may somehow express cultural identities that constitute the former. Conzen [21] was a pioneer in studying patterns of change in urban form in relation to changes in the economic, social, and technological milieu, proposing a cyclical nature of the development of urban form [59]. Going a step further, Aldo Rossi [61] argued that the material form of the city is intrinsic to its sociological and cultural reality. Later on, Hillier [38] addressed the possibility of cities of different cultural types embodying different spatial identities. His analytical approach allowed him to claim that human societies order their built environment to construct a ‘spatial culture’, a ‘distinctive way of ordering space’. Cities take on different forms in different cultural conditions in non-contingent ways, as spatial arrangements shape the field of encounters that animate different social cultures. Physical space is systematically ordered to reproduce culturally-specific patterns of social behaviour based on co-presence as a principle for ordering social relations.

Recent discussions have enriched this construct by approaching a spatial culture as “a fundamentally performative and temporal process” [55, p.xxxiv] Focusing on “questions of cultural specificity in the formation of space”, these works assess how culture affects spatial formation, and the possibility of “encoding and transmitting social and cultural information” in urban space [45]. Contingencies are added by the possibility that “different cultures invest differently in space, be it in regards to what is manifested, or to what extent society is manifested through built form” [45] (p.i). Difficulties are also of an epistemological nature, since the space-culture relation may be indivisible analytically [57], and therefore hard to be scrutinised.

In a careful opposition to some of these views, the late urban historian Spiro Kostof [46] was suspicious of the belief that buildings and city-forms fully embody recognisable idiosyncrasies enough to be medium of cultural expression. Even though his works relate processes like ‘reading’, ‘encoding’ and ‘information’ to culture, he claimed that a same urban form does not express an invariable human content. Despite this position, the quest for underlying explanations
for systematic differences in urban form has led to the idea that physical patterns encapsulate an extra-physical reality, as different social and cultural agencies are seen to shape physical space. These agencies can range from tradition and custom, material requirements of interaction, associations with socially shared symbols or principles of societal organisation. For instance, cities with irregular physical patterns are thought to be the result of development left entirely to individuals, as bottom-up processes leading to the random ways of the unplanned city. In turn, top-down processes triggered by governing bodies would be able to guide the organisation of urban land and built form, leading to uniformly ordered cities [Castagnoli in [46], p.43].

Some studies looked into spatial features, logics or organising principles in comparative studies of cities consistent with distinct regions. To be sure, most of these works deal with street networks rather than built form systems. Medeiro’s [50] topological analysis of betweenness centrality and depth in the street networks of 164 cities in different parts of the world identified regional differences. For instance, American and Canadian cities appear prominently with the highest levels of accessibility, as opposed to Brazilian cities in South America, the most spatially segregated. Louf and Barthelemy [48] searched for the ‘fingerprints’ of cities analysing the distribution of blocks extracted from street networks of 131 city centres. Their classification scheme is based on information about the area and a simplified proxy for the shape of blocks. The method identifies that nearly two thirds of American cities in their sample are structurally different from European cities. Rashid [59] carried on a comparative study of urban morphology in 104 cities in six continents. Using uni-variate statistics of data for 44 spatial measures of street configurations and basic geometric measures of built form, like block perimeters and areas, he found limited differences between downtown areas in developed and developing countries. Furthermore, disaggregated measures of geometry of urban layouts have little power to describe actual form (say, of blocks) and do not grasp information encoded in relations between components of built form.

In turn, our configurational approach focuses on buildings as the elementary components shaping cities, and how they are aggregated in combinations and complexes. By looking into frequencies of cellular arrangements representing buildings in selected cities, we wish to understand if and to what extent their configurations can be seen as particular cultural features, regardless of whether these features are intentionally embodied in urban space. Recognising that urban structures are different around the world, and approaching spatial configuration as a proxy of urban culture, we attempt to measure such configurations to assess their differences and similarities. For that, we shall explore Shannon’s view of ‘information’ and “entropy” to investigate whether spatial cultures entail ‘distinctive ways of ordering space’, as Hillier suggests.

3 Information and entropy in physical spatial systems

A number of works have explored information and entropy measures in relation to urban systems, beginning with Wilson’s [72] pioneering study of utility-maximising systems in 1970. The entropy-maximising paradigm was frequently used to derive model formulations for spatial interactions and urban distributions, microeconomic behaviour and input-output analysis [7]. Batty developed a number of studies on entropy in spatial aggregations and interaction since the early 1970s [8,9,10]. More recently, Batty et al. [13] proposed a measure of complexity based on Shannon information able to grasp the complexity of cities as they vary in scale, size and spatial distribution of population, dealing with spatial entropy related to the distribution of information, and with information density related to city size. Other approaches used modifications of Shannon entropy and information-theoretical metrics as methods to capture, quantify and group similar two-dimensional spatial patterns in landscape ecology, including efforts towards a universal classification of configuration types in a linear sequence according to increasing values [20,4,56].

Entropy measures have also been applied to purely urban morphological problems, namely in street network analysis. Gudmundsson and Mohajeri [34] developed a method based on Shannon’s entropy to measure angular variation between streets, applied to 41 British cities. Boeing [17] applied Gudmundsson and Mohajeri’s method to analyse 100 cities around the world focusing on street networks downloaded from Open Street Maps (OSM). However interesting as morphological approaches, these applications do not seek to uncover spatial information patterns, focusing instead on entropy as a measure of variation in street angles and lengths. The entropy measure of the distribution of crossing angles does not necessary capture the global degree of order/disorder of street networks. Even if they do, street orientation does not describe spatial configurations in a relational sense. These considerations are reflected by the fact that the resulting values of the measure applied are concentrated in the extremes, suggesting that it is not so sensitive. Furthermore, entropy measures applied to street orientation are not a comprehensive morphological approach since they not take into account entropy in built form. In other words, they ignore discrepancies between levels of order in street networks and built form systems. Cities can be physically disordered even if their street networks are perfectly ordered. As Kostof [46] put it: “[s]treets that read as straight and uniform on the city plan may be compromised by the capricious behavior of the bordering masses” (p.44). In short, we can have low entropy in street orientation, yet highly disordered morphological structures (figure 1).
Figure 1: A same street network can support very different built form systems.

More comprehensively, Haken and Portugali [35, 36] focused on how the built environment actually embodies information. They explore Shannon information quantitatively in connection with Haken’s synergetic qualitative approach to semantic information, in order to empirically assess how basic cellular arrangements and categorisations of building facades convey different amounts of information. Finally, other approaches to spatial information have adopted different measures of entropy, distribution of spatial co-occurrences, or information density to assess the amount of redundancy and grouping related to cognitive efforts to extract task relevant information from the built environment [73, 60]. In turn, our approach will explore Shannon entropy to measure levels of randomness and disorder in physical space, namely in cellular arrangements of built form. We shall look into the possibility that consistent differences between cities can be perceived at this scale, and that cultures and regions find different ways of ordering such configurations, which may be captured by this measure.

4 Analysing built form systems

Our first procedure involves a reduction of urban form to two-dimensional arrangements based on building footprints. Since Giambattista Nolli’s 1748 Map of Rome, the figure/ground diagrams have become a classic methodological resource in urban studies, showing built/unbuilt distinctions. For instance, Nineteenth century scholar Camillo Sitte [66] represented public buildings and the ordinary fabric of the city exploring such diagrams. More recently, Rowe and Koetter [62] have described the theoretical significance of the figure-ground map or ‘Nolli map’ [59, 44, 69]. The figure-ground diagram provides a spatial data-driven method to analyse and study the urban form and circulation networks that structure human activities and social relations [17].

Our second procedure looks into different cellular arrangements of built form and attempts to characterize their configurations. We do so analysing the probability distribution of built form configurations, by estimating the Shannon entropy [65] of Nolli maps of different cities of the world. Of course, this has to do with the level of randomness in the cellular arrangements of built form in cities. By analysing cellular arrangements, we capture the structures of urban blocks in relation to the open spaces of streets and public squares. Indeed, the layout of the environment encodes more information than two-dimensional configurations can express. However, we opted for an analytic approach able to sufficiently describe differences in built form – hence the reduction of 3-dimensions (3D) urban form to 2-dimensions (2D) cellular aggregations (figure 2).

We characterise the spatial information encoded in two-dimensional configurations of buildings in the following terms. As mentioned, information will be quantified measuring Shannon entropy, operationally estimated by looking at the sequence of bits 1 and 0 representing built form cells and open space cells within sections of cities. Theoretically, this corresponds to measuring the Shannon entropy of a 2D symbolic sequence of 1 and 0. In this context, information finds a precise meaning: the entropy of the sequence, a measure of the surprise a source that produces the sequence causes in the observer [65]. Physical arrangements characterised by higher levels of randomness, uncertainty or unpredictability are associated with high entropy. In contrast, the presence of regularities and patterns in urban structures corresponds to lower entropy, which means a higher predictability.

The next step involves the preparation of our set of empirical cases, and the conversion of city maps into Nolli maps. We selected cities for their importance in their region or country. Selection also had to take into account the availability of information on built form. Many cities, particularly in Latin America, Africa and Asia, have incomplete information regarding building footprints, i.e. their precise location, position and form.
For methodological reasons, we selected areas within these cities for the application of our measure. This selection procedure follows two critical considerations. The first and most important one observes that it is interesting to decouple the analysis of urban structures between small-scale, detailed and denser urban areas, and large-scale regional and peripheral urban areas. In fact, the two areas are different, and for this reason, they can be naturally described using different methodologies. The first small-scale urban area is defined by specific features such as buildings and urban blocks, which introduce typical characteristic scales. This means that there are some well-defined scales related to the distance above which configurations loose their correlations. These characteristic scales define sub-systems characterised by typical local patterns (urban blocks, individual buildings and possible neighborhoods). Here, human action is the principal vector defining shapes and patterns which generally appear in a stratified form, like the ones we see in older and traditional central areas. In turn, large-scale regional and peripheral urban areas are likely to include sparse occupation, frequently with a scale-free character. This means that the characteristics of their patterns are independent of the scale we fix for analysing them. Looking at different scales, the underlying structure remains the same. In these regions, physical features linked to topography, geographical formations and barriers (e.g. water bodies, mountains, and valleys), along with the presence of very large infrastructures (e.g. highways) might play relevant roles in the definition of the spatial patterns. In this work, we will focus only on small-scale areas with dense urban form.

The second consideration takes into account that our method is well fitted for estimating entropy for dense and continuous urban areas. Fixing the density of built form cells allows us to obtain results independent from this parameter. The high continuity and homogeneity of built form allows us to use a specific extrapolation technique that will prove useful for estimating the entropy of our 2D symbolic sequences. For these reasons, the selection of sections was based on the identification of dense areas, with a high spatial continuity in the fabric of built form. We will consider occupation rates close to 50%, which means avoiding large empty areas or rarefied patterns of urbanisation.

We prepared our sample extracting building footprints in sections of cities from the public map repository Google Maps API. We tested trade-offs between resolution and availability of data for distinct scales. We chose geographic areas of 9,000,000 m², which were considered sufficient for representing the general spatial characteristics of dense urban areas regarding the configuration of buildings, urban blocks and open spaces of 45 cities around the world (figure 3). Built form maps of the selected cities were then prepared and exported in high resolution, filtering layers and converting entities representing buildings into solid raster cells. Images underwent a re-sizing process for 1000² cells and were converted to a monochrome system and then into a matrix of size 1000 × 1000 cells with binary numerical values (figure 4).

Estimation of the Shannon entropy of the considered 2D cellular arrangements uses a method commonly applied for estimating the entropy of sequences of symbols encoded in one-dimensional strings [64]. For 1D data sets, the method consists of defining the block entropy of order \( n \) through

\[
H_n = - \sum_k p_n(k) \log_2[p_n(k)],
\]

where blocks are string segments of size \( n \), and the sum runs over all the \( k \) possible \( n \)-blocks. Equation (1) corresponds to the Shannon entropy of the probability distribution \( p_n(k) \). The Shannon entropy of the considered system (the whole 1D string) [64, 47], which we indicate with \( h \), is obtained from the following limit:
which measures the average amount of randomness per symbol that persists after all correlations and constraints are taken into account. The above limit exists for all spatial-translation invariant systems, as demonstrated in [23]. More details about this method can be found in [64, 47].

This approach can be generalized to sequences of symbols in two dimensions, which correspond to our situation. We have to define the $n$-blocks for a two-dimensional matrix [30]. The most intuitive idea is to consider a block of size $n$ as a square which contains $n^2$ cells. To obtain the sequence of $H_n$ also for $n$ values that do not correspond to squares, we considered blocks that interpolate perfect squares, as described in figure 5. Note that there is no unique natural way to scan a 2D matrix. We tested our approach for different reasonable forms of constructing the blocks, and the use of different paths does not seem to significantly influence the estimation of $H_n$ for the considered data set.

Equation 2 gives precisely the entropy for a theoretical infinite set of data. In real situations, where the data set is finite, our method estimates the probabilities of distinct arrangements of cells within blocks up to a certain size $n$, counting their frequencies. For example, for $H_1$, it is sufficient to have knowledge of the symbol distribution $p_1(2)$, which is approximated by the frequency of 0 and 1 present in the data set. It is important to note that it is common to find in the literature of image processing, urban studies and ecological landscapes approaches that perform some entropy based analysis measuring our $H_1$ or, at best, our $H_2$. Unfortunately, sometimes these quantities are wrongly referred to as the Shannon entropy of the system, which, in contrast, is our $h$.

If our data were a purely random set, $h$ would coincide with $H_1$, and $p_1(2)$ would give a full account of the spatial configuration. This is obviously not true for urban situations, where evident structures and strong long-range correlations are present. In this case, estimating entropy is a difficult task, as taking correlations into account means computing $H_n$ for a large $n$. In fact, the estimation of $h$ is good when the spatial range of correlations is smaller than the maximum size of the block entropy we are able to compute. This estimation can be rendered difficult because of the exponential increase in the number of distinct cells arrangements in blocks with $n$. When working with two symbols, as in our case, the estimation of $H_n$ becomes not reasonable when $2^n \approx N$, where $N$ is the number of elements in our data set. Thus, in our case, this condition is verified for $n \approx 20$. Even if this is a rough evaluation, it reasonably fixes the maximum size of the blocks that can be investigated with sufficient statistical quality [47]. The limit taken in equation 2 can be empirically obtained fitting the set of $H_n/n$ points with an appropriate function and then taking its limit for $n \to \infty$.

We found heuristically that, for all examined cases, the following ansatz provides an excellent fit:

$$H_n/n \approx a + b/n^c, \quad b, c > 0.$$  (3)
Figure 4: Nolli maps with building footprint distributions in downtown areas of 45 analysed cities (9,000,000 m² windows, 1,000,000 cells), extracted from Google Maps. These sections are used to compute Shannon entropy. Rotation in grids and built form systems does not affect results.
Figure 5: Areas in Rio de Janeiro and Manhattan, NYC (left). Examples of blocks with nine cells shown in red are amplified on the right. Configurations of the type (a) show great variation, like those found in Rio, while the type (b) shows regular arrangements frequently found in Manhattan. Blocks are constructed following the fixed path represented on the bottom right. Numbers indicate the order in which cells are added to blocks. The first block of size 1 corresponds to cell 1. Neighbouring cells are added in the corresponding order. Nolli maps are scanned with this set of different cell blocks.

The fitted value of $a$ gives a reasonable extrapolation of the Shannon Entropy $h$.

Considering our database of 45 cities from North America, Europe, Asia, Oceania, Africa, and South America, our goal is to develop a classification scheme based on the similarities and differences between the entropy levels of the sampled cities. In this sense, the next step consists in performing a proximity network analysis based on the measured entropy values, with the aim of identifying the presence of communities or clusters of cities sharing similar entropy levels. In short, entropy estimation will allow us to order our pool of cities and define a classification scheme. This scheme may help us find similarities possibly consistent with same spatial cultures or world regions.

Once we obtained the entropy $h$ for all considered cities, we can quantify the levels of similarity defining a distance between cities $i$ and $j$ based on the values of $h$: $d_{ij} = |h_i - h_j|$. We created a matrix of distances for the analysed cities and then defined a network where cities are nodes, and edges (links between nodes $i$ and $j$) are present only if the value of $d_{ij}$ is smaller than a fixed threshold value. The detection of clusters displayed by this network is a straightforward task considering the relatively small size of our data set.

We further developed the cluster analysis applying a method for constructing a dendrogram representation of the distance matrix. We used the unweighted pair group method with arithmetic mean (UPGMA). This method constructs a dendrogram that reflects the structure present in the similarity matrix, building a hierarchy of clusters. The algorithm used in the analysis is part of the module Bio.Phylo in the Biopython package. When this approach incorporates a reliable dating of entities, it can be used to identify cultural phylogenies, like in the work of Barbrook et al. in the phylogenetic analysis of written texts. This is an interesting exception. In general, like in our case, cultural objects are related in an involved form between themselves, and dating is a major challenge for long standing living entities, whether they are cities or languages.

5 Results: proximity networks and hierarchical clustering

The use of the empirical functions of equation provides an excellent fit for all the considered cities. The values of the parameters $c$ are contained in the interval $[0.37, 0.68]$. These values are consistent with the entropy convergence found in written texts, where $c$ ranges from 0.4 to 0.6, and with a result for a Beethoven sonata where an exponent 0.75 was found. These results seem typical of language-like systems, where the presence of long-range order is characterised by a slowly decaying contribution to the asymptotics of the entropy for large $n$. Despite the relative slow
convergence, the fine quality of the fits allows a good extrapolation of the Shannon Entropy $h$. As an example, the results for the estimation of $H_n/n$ and the corresponding fitting procedure for the city of Los Angeles are displayed in figure 6. Results for the estimation of entropy $h$ for the sampled cities can also be seen on a horizontal axis in figure 6 showing how this measure introduces a clear sorting among our data.

The similarity networks were constructed fixing the threshold value to 0.018, which corresponds to the 90% confidence interval of the extrapolated values of $h$. We chose to implement the clustering analysis in increasing subsets of our pool of cities, starting within a same region. This way, it was easier to extract and visualise potential patterns or clusters of cities sharing similar entropy levels.

We started by looking into European cities (figure 7). Selected cities in Europe cluster in two main groups in the proximity network and corresponding dendrogram. The first one includes predominantly cities in Northern Europe, along with Barcelona and Madrid, which present lower levels of entropy. The second one includes mostly cities in Southern Europe, with higher entropy levels. The clustering displayed by the proximity network shows how Madrid and Amsterdam lie at the connection between both communities.

Next, we analysed the cities of Europe and the Americas along with Lagos in Africa (figure 8). We can distinguish different clusters in the proximity network. While Brazilian cities São Paulo, Rio de Janeiro and Fortaleza remain as isolated clusters, other Latin American cities Mexico City, Ecatepec and Lagos in Africa form a small cluster joint to a
large cluster dominated by cities of Southern Europe. Another major cluster aggregates cities of Northern Europe and Canada, along with US city San Francisco, Spanish cities Barcelona and Madrid, and South American cities Buenos Aires and Santiago de Chile. A smaller connected cluster is formed by major cities in the United States, whereas Chicago stands as an outlier. The doodrogram further clarifies these relations: Mexico City and Ecatepec along with Lagos share a common branch with the cluster comprised of Brazilian cities. Major US cities Chicago, Los Angeles, New York and Washington are placed in related branches, close to other North American cities (except San Francisco). Birmingham, Santiago and Buenos Aires relate to a same branch, as cities with the lowest entropy levels in their respective regions. There is also a branch relating Northern European cities, Madrid and Barcelona, and a major cluster dominated by Southern European cities.

![Image of proximity network and dendrogram]

**Figure 8:** Proximity network and dendrogram of the analysed European, North and South American cities, and Lagos in Africa.

The concluding analysis joins together all the considered cities, adding the Asian and Oceanian data. The number of clusters in the proximity network is similar to the previous analysis, with the addition of a new one with the most ordered cities, Beijing and Chicago. Apart from this fact, the community structure seems unchanged. Other Asian cities distribute themselves among pre-existing clusters: most Asian cities join either the cluster dominated by Southern European cities or the cluster with most Latin American cities. Furthermore, the network shows an interesting connectivity, from the most ordered cities Beijing and Chicago to major North American cities, then to a mixed cluster formed by cities from different regions sharing relatively low entropy levels, connected through Shanghai to a large cluster dominated by Southern European cities. This cluster in turn connects to the highest entropy groups, from Mexico City to Tokyo and Brazilian cities. The complete dendrogram can be seen in figure 9.

### 6 Discussion

What can the proximity networks and hierarchical clusters based on entropy values tell us about the cultural hypothesis? That means examining the possibility that similarities in the ways of ordering built form can be explained either by (i) regional proximity, as cities from a geographically defined culture and identity (e.g. ‘American cities’, ‘Italian cities’, ‘Islamic cities’); or by (ii) similarities in the form of producing patterns historically shaped by tradition in self-organised, bottom-up processes or by top-down agencies of self-regulation, allowing us to find elements in common even between different regions. Of course, our analysis brings no value judgement in the sense of pointing out a certain level of entropy as desirable. We may start by interpreting these differences in the light of the 'planned versus unplanned' dichotomy so persistent in the urban imagination.
Beginning with the analysis of European cities, we found a subtle difference in levels of entropy between Northern and Southern cities. Northern European (i.e. Anglo-Saxon, Germanic and Russian) cities in our sample displayed in general lower levels of entropy – from Birmingham (0.209) and Munich (0.225) to Amsterdam (0.254) and Vienna (0.263) – than Southern (i.e. Latin European) cities, from Rome (0.260) to Paris (0.286) and Marseille (0.292), with the exception of Spanish cities Barcelona (0.227) and Madrid (0.240). While the analysed area of Madrid is composed as a patchwork, its parts are mostly regular in themselves. In turn, a large part of contemporary Barcelona was notoriously built according to Ildefonso Cerdà’s 1859 *Eixample* orthogonal plan. These features echo the Spanish tradition of regular grids deployed in colonized regions in Latin America, coupled with a strict alignment of buildings frontal facades, and contribute to set them apart from other Southern European cities. Potential common traces in Northern cities include grids usually composed like a patchwork of partially regular areas (e.g. London, Munich, Amsterdam). This development pattern is frequently related to prior rural ownership and property boundaries. Regular grid sections relate to resources like land survey and delimitation based on measurement, prior to subdivision into building plots [46]. These cities also display considerable consistency in the building type adopted, leading to regularity in urban block surfaces. Even though Munich’s historical core shows curved urban blocks, frontal and back facades are predominantly aligned. Geometric variation in the position of rear facades may be intense, combined with frequently sinuous urban blocks (e.g. Moscow, Vienna, Brussels).

In turn, frequent curves in streets and block systems may follow medieval footpaths of previous open fields and rural field divisions related to landscape features (e.g. historic cores of Milan, Lisbon and Athens). Practical modes of plot division and building seem to closely relate to topography (e.g. Lisbon) and watercourses (e.g. Nice, Toulouse and Zaragoza). In these areas, buildings can be frequently strung along topographic lines and watercourses. Despite such irregular features, there is considerable consistency in the position of frontal facades aligned along streets and open spaces.

To be sure, bottom-up processes of cellular aggregation take morphogenetic paths involving randomness [41] [11], trial and error [2] [3], and path dependence [53]. These are processes where location decisions may influence the direction of subsequent decisions. If an urban system shows positive feedback from a particular configuration, an increasing proportion of that choice increases the probability of another building being added in a similar way to the system, favouring the dominant pattern. This means that the built form system can phase-lock in a specific, path-dependent configuration. Geometric consistencies resulting from trial and error processes and urban advantages triggered by increasing densities and decreasing internal distances [53] can be reproduced as traditional modes of building. This process may eventually lead to institutionalised rules, like those prescribing particular building types, facade alignments or uniform setbacks even along originally unplanned street networks.

When we take the 45 cities into account, we notice three main branches in the hierarchical clusters (figure 9, at a branch length around 0.075). A first cluster clearly emerges with cities with the lowest levels of entropy in the sample.
lower entropy cases. It is further divided into three initial branches. Beijing ($h = 0.111$) and Chicago (0.116) have
the lowest levels of entropy, and are in a branch of their own. Beijing is an exception in the Asian context, which
generally has higher entropy values, from Shanghai (0.243) and Kyoto (0.206) to Tokyo (0.380). Beijing is probably
the most strictly planned city in China. Planning was implemented rigorously along cardinal directions (East, West,
South, North) following a tradition traced back to early Ming dynasty (1368-1644 AD), in turn based on ‘regulations
of construction’ from the Fifth century BC, as expressions of both regal power and social order [70]. Buildings and urban
blocks frequently display regular forms and aligned facades. In turn, Chicago epitomises the US tradition of planning
cities based on orthogonal grids – and it does so with great regularity in urban blocks and building surfaces.

Other branches bifurcate into a group with major American cities New York (0.174), Washington (0.167) and Los
Angeles (0.162), and configurations with the lowest entropy levels from other world regions, like Kyoto, Melbourne
and Birmingham, along with other US/Canadian cities Montreal (0.190), Toronto (0.202) and Philadelphia (0.208).
Interestingly, Buenos Aires (0.198) and Santiago (0.209) cluster here, quite apart from other cities in Latin America,
with high entropy levels. This somewhat surprising result runs counter the first aspect of the cultural hypothesis:
the similarity in entropy levels for cities within a same culture or region. This might have to do with the evolution
of these cities in comparison to others in the Latin American region. Cities founded in the Sixteenth century by
Spanish colonizers in the Americas were often created in a rigid orthogonal pattern, following the 1573 Ordenanzas de
Poblaciones, the first code of urbanism of the early modern period in the West. This was the case for Santiago and
particularly Buenos Aires, with its plain topography [63]. These areas became the historical and economic core of these
cities, with high density and compact patterns of built form. As these cities expanded, patchworks were added around
the core’s regular structure, adding entropy to the mix. Nevertheless, the levels of order in those central configurations
are felt in the analysis, bringing them to closer to cities with higher levels of order in built form, like Toronto and
Philadelphia.

The second cluster highlights the highest entropy group in the sample, comprised of Brazilian cities Rio de Janeiro
and São Paulo, in Latin America ($h = 0.391$ and 0.382, respectively), followed closely by Tokyo (0.380) and another
Brazilian city, Fortaleza (0.347).

The third major cluster divides into communities from high to middle entropy. This cluster further bifurcates into
a group with slightly lower entropy levels, Mexico City (0.303) and Ecatepec (0.320) in Mexico, Istanbul (0.322)
in Turkey, and Lagos in Africa (0.315). Another bifurcating branch between the opposing clusters is comprised of
Southern European cities Marseilles, Porto, Toulouse, Athens and Paris, along with Brussels. A final large branch of
middle to lower entropy cities bifurcates into cities from diverse regions, like Manila (0.274) in the Philippines, Milan
(0.277), Rome (0.260), Lisbon (0.268), Zaragoza (0.260) and Nice (0.262) in Southern Europe, and Amsterdam and
Vienna in Northern Europe; and into more diverse groups with lower entropy cities, like Shanghai and Madrid, Moscow
(0.231) and São Francisco (0.233), Sydney (0.224) and Munich, London (0.223) and Barcelona.

These distinct clusters show that we cannot associate particular levels of entropy exclusively with particular regions,
a first possibility of verifying the cultural hypothesis. We have to ask ourselves what in different regions could have
triggered similar entropy levels. The idea of a planned-unplanned dichotomy suggests that we should look into the actual
evolution and planning conditions existing (or not) in these different cities, many of them having faced considerable
growth in the twentieth century. We checked the existence of modern planning rules that act specifically upon built
form, namely: (1) Land parcelling: how land is divided into urban plots, and whether there are rules guiding the shape
and regularity of plots. (2) The layout of urban blocks and streets: what are the rules for layouts – say, whether they
impose orthogonal systems or ‘planned picturesque’ systems like intentionally curved and varied block shapes and
street networks. (3) Regulations on building design and location: whether there are rules that specify the position
of buildings in plots (e.g. frontal and lateral setbacks), and in relation to neighbouring buildings. We examined the
legislation in emblematic cases in Turkey, Nigeria, China, Brazil, Mexico, United States, England and The Netherlands.
We found something that goes counter the planned-unplanned account of ordered and disordered cities: cities which
have top-down planning may also exhibit high built form entropy. They do have rules and government agencies that
regulate building and urbanisation.

But how can high entropy in built form be somehow influenced by top-down rules? We found that cities from different
regions – namely, Brazil, Nigeria, Mexico and Turkey – may have certain aspects of planning in common, which allow
great variation in built form to come into being. For instance, these cities share emphases on parcel-based, piecemeal
developments. New urbanised areas are mostly exempt from requirements to keep connections to neighbouring areas,
including street continuity and grid alignment. Another crucial instance here is how individual buildings can be
positioned in their plots. Some regulations may enforce frontal and lateral setbacks, and define rules like increasing
setbacks as buildings grow taller. Simple local rules focused exclusively on individual buildings rather than coordinated
construction among nearest neighbours lead to a high level of fragmentation in built form.
Going a step further, whole areas in these cities are urbanised and built by people’s own hands in informal settlements, hence apart from planning regulations. This is especially the case throughout the Twentieth century, when cities in developing countries experienced fast growth. We are likely to find high entropy mostly associated with variation in the shape of urban blocks (related to angular variation in surrounding streets) in those settlements. In short, parcel-based, piecemeal developments, patchworks of diverse blocks and street networks, and fragmented built form are key features of highly entropic urban landscapes.

Figure 10: Urban sections (500x500m) with similar entropy levels, different spatial configurations: Toronto ($h = 0.202$), Buenos Aires (0.198) and Melbourne (0.207); and Istanbul ($h = 0.322$), Ecatepec (0.320) and Lagos (0.315).
All this shows that cities from distinct regions may share similar entropy levels as far as built form is concerned. Their typical combinations of cells might be different, and they might share neither geographical proximity nor common historical roots, but they still can contain similar levels of disorder, as captured by our measure (figure 10). This suggests certain common traits between different regional cultures shaping how built form is ordered.

That said, even though regions do not have entropy values necessarily different from others, individual regions do seem to converge around certain values. This interesting pattern emerges once we visually distribute a classification of the 45 cities according to increasing entropy values on a global map (figure 3). Some regions show higher levels of regularity and predictability in built form systems than others. We suggest that our measure seems to capture spatial information potentially related to different emphases on order and coordination latent in different planning cultures, the second aspect of the cultural hypothesis seen above.

How do these findings on regional differences compare with previous studies, based on different spatial entities and methods? We have seen that Medeiros’s [50] analysis of street networks based on betweenness centrality and topological depth identified clusters of US/Canadian cities with the highest levels of accessibility, in contrast with Brazilian cities in South America, followed by European cities. Largely echoing Medeiros’s findings, Boeing [17] explored angular orientation entropy and grid order indicators to identify US/Canadian cities with the lowest orientation entropy. European cities also exhibit higher orientation entropy than Latin American cities. Louf and Barthelemy’s [48] classification based on block areas also identifies differences between most American cities and European cities.

US/Canadian cities display low entropy in our analysis as well, but our results on European cities differ from those studies. Consistency in built form in European cities brings entropy to lower levels. Our approach was also able to identify differences between Northern and Southern European cities. In their turn, São Paulo and Rome exhibit the highest entropy levels in Boeing’s study. In our approach, despite the varied shapes in its block system, Rome’s consistency around aligned buildings lowers its entropy to a level far from São Paulo. Interestingly, these different approaches converge about Brazilian cities: they exhibit the lowest average betweenness centrality, and highest orientation entropy and built form entropy in these different samples – probably due to an extraordinary variation in the position of buildings in plots, coupled with fragmented grid patchworks. Nevertheless, the differences between findings are clearly related to differences between the morphologies of street networks and built form systems: the fact that a same street network can support endlessly different configurations of buildings. Levels of order in street networks do not necessary cause low entropy in built form.

7 Conclusion

In this paper, we developed an approach to spatial information based on Shannon entropy. The approach was designed to (1) measure the entropy characterising levels of order and disorder in cellular configurations present in 45 cities around the world. (2) we applied the method to investigate the hypothesis of ‘spatial cultures’ as ways of ordering urban form. Put another way, we verified whether the entropy measure could accurately grasp features and differences in built form systems; then we looked for traces of ‘information signatures’ potentially consistent with specific regions or cultures. This method is intended as a step towards a more precise understanding of spatial cultures as emergent patterns – i.e. how typical configurations of built form emerge from local rules of aggregation active at the scale of cellular configurations.

Of course, any search for ‘information signatures’ of spatial cultures embodied in the tangible spatiality of cities faces certain risks: (a) Different cultures or regions may not have distinct ways of ordering space. In other words, there could be no ‘spatial cultures’ related to regions or even enough differences between cities to be associated with a particular culture. (b) Spatial cultures may well have specific information signatures, but these may not be encoded at the scale of local cellular configurations of built form systems. (c) In case the possibilities above were wrong, a measure of spatial information based on Shannon’s entropy in cellular configurations may not be precise enough to capture information signatures or even qualitative differences in configurations.

In the research process, our method allowed us to find the distribution and clustering of cities around certain values of built form entropy. We would like to conclude our work discussing such entropy values and clusters in connection with characteristics of these cities, including aspects particularly related to what we called ‘cultural hypothesis’: the idea that similarities in the ways of ordering built form can be explained by (i) regional proximity, as geographically defined cultures and identities, or by (ii) common features in urban morphogenesis shared by distinct regions, say rules in similar ‘planning cultures’. That meant looking for reasons of non-contingent similarities and differences between cities.

The usual association of bottom-up processes of spatial production in disordered, unplanned cities, as opposed to top-down processes of spatial production in ordered, planned cities, suggested that we should look specifically into
planning rules guiding built form. We found that the ‘planned/unplanned’ dichotomy in urban studies may have been valid in pre-modern periods of certain urban cultures, but it seems of limited explanatory power once we consider modern and contemporary planning. Cities with top-down planning may also have high built form entropy.

A key difference lies in the kind of rules applied and how they deal with buildings. Cities with high entropy in different regions in our sample seem to have in common rules that focus mostly on individual buildings, allowing great variation in how they are placed in plots and blocks, including increasing lateral and frontal setbacks as buildings grow taller. This focus may happen for specific periods of their histories – long enough to shape the evolution and morphology of large portions of these cities. This is the case of planning in countries like Brazil, Mexico, Nigeria and Turkey, especially when the analysed cities faced fast growth in the Twentieth century. In short, we found that simple local rules centred on individual buildings rather than coordinated construction lead to high fragmentation in ensembles of built form. These rules are frequently coupled with piecemeal developments and grid patchworks, including informal settlements, shaping a visible fragmentation of urban landscapes.

Our analysis brings other findings. First, proximity networks and hierarchical clusters show similarities in cities from different regions (e.g. high entropy cities including São Paulo, Tokyo, Istanbul and Lagos), with close entropy values even if they have geometrically distinct arrangements (figure 10). This suggests that the measure does not necessarily generate specific values as exclusive ‘information signatures’ for each region, a first possibility of verifying the cultural hypothesis.

Second, despite that fact, the measure seems to capture something of the ‘planning culture’ of these regions. We found higher frequencies of certain regular arrangements in cities with top-down planning coupled with a strong focus on rules for coordinated modular construction, each building adjusting and aligning to those around, taking into account systemic consequences of ensembles of built form. The high frequency of certain arrangements can also be found in cases of bottom-up processes of cellular aggregation potentially involving path dependence, i.e. built form systems locked into specific configurations, reproduced in traditional modes of building – patterns that can be eventually institutionalised into formal planning rules. This seems to be the case especially in the passage from pre-modern to modern urbanisation of European cities. On the other hand, we found plenty of variation in cellular aggregations in urban cultures that allow the construction of buildings in uncoordinated actions between individual developers. This clearly leads to less regularity and higher unpredictability in what surrounding built forms will be like as cities grow. Summing up, in both top-down and bottom-up form-making processes, local rules guiding how to position buildings in relation to others seem to trigger bifurcated developments as the built form system evolves in size and complexity, leading either into greater consistency or into greater fragmentation. But that is not the whole story, of course. We may find many possibilities in between those archetypal paths, or combinations of them in different parts of cities, like patchworks, or intermingled in layers of ordered and disordered aggregations – say, the iconic case of Manhattan, based on the regularity of a gridiron street layout, and planning rules that made room for enormous variation in built form.

Third, although regions do not necessarily have exclusive values of built form entropy, individual regions do seem to converge around certain values. Our results show certain consistencies, grouping cities from a same region (e.g. Brazilian cities, American cities). To use Hillier’s words [38], this echoes the idea that societies create their own spatial cultures – their distinctive ways of ordering space and shaping cities. Such finding needs to be further examined through a larger sample of cities and comparisons with other approaches, along the lines we explored above. Of course, deep historical conditions and local contingencies are likely be at play, and must be carefully taken into account.

Finally, differences between results obtained from street network-based measures and our measure of entropy shed light on the potential dissociation between the morphology of streets and the morphology of built form systems in every city: the endless combinatory possibilities of configurations of buildings, missing from street network approaches, add complexity to urban phenomena and suggest the need for a renewed interest in built form systems.

Our sample is not a random set, which would be impossible due to the lack of information on building footprints in many cities and countries. Methodologically, at the present stage, our approach takes account of the spatial information latent in the arrangements of cells capturing relations of proximity, but eventually missing some correlations at large distances. On the one hand, cellular growth shapes larger structures as fundamental features of cities – a subject explored in other works [35] [40] [12] [11]. On the other hand, humans have a clear hierarchical reading [11], and structures at larger scales seem to have more weight than structures at smaller scales to differentiate objects. Further development of this research will look into broader spatial structures in cities by introducing measures of statistical complexity. In addition, we wish to expand this approach to other forms of physical information, such as three-dimensional differences between buildings, physical cues and landmarks [22] [67].
Even though there is no value judgement in our work or claims of particular levels of entropy as desirable, different levels of built form entropy may well trigger different cognitive and practical responses from people. Higher degrees of entropy may be associated with spatial and visual surprises in navigation. Surprises can be considered desirable by some, as famously suggested by Camillo Sitte [66] and explored by Gordon Cullen’s [24] concept of ‘serial vision’. Notwithstanding, empirical studies in spatial cognition and neuroscience have shown that certain regularities and alignment effects (say, between paths or objects like buildings, or triggered by cardinal directions) improve our judgement of relative direction in navigation and our capacity to determine the position of objects in a surrounding area, affecting intelligibility and our memory of the built environment [49, 31, 29]. Effects of urban form on cognition are a hot research topic and could benefit from explorations into entropy and regularity in physical space as informational features in navigation [35, 36, 39]. Furthermore, human knowledge of spatial properties and patterns goes beyond physical information and can integrate configurational, visual and semantic aspects of an urban environment [52, 36, 54]. More work is needed to understand how physical information is associated with non-physical information, and is enacted by social agents making decisions and cooperating in cities.

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