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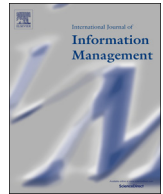
# Spatial information and the legibility of urban form: Big data in urban morphology

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## ARTICLE INFO

## ABSTRACT

Urban planning and morphology have relied on analytical cartography and visual communication tools for centuries to illustrate spatial patterns, conceptualize proposed designs, compare alternatives, and engage the public. Classic urban form visualizations – from Giambattista Nolli's ichnographic maps of Rome to Allan Jacobs's figure-ground diagrams of city streets – have compressed physical urban complexity into easily comprehensible information artifacts. Today we can enhance these traditional workflows through the Smart Cities paradigm of understanding cities via user-generated content and harvested data in an information management context. New spatial technology platforms and big data offer new lenses to understand, evaluate, monitor, and manage urban form and evolution. This paper builds on the theoretical framework of visual cultures in urban planning and morphology to introduce and situate computational data science processes for exploring urban fabric patterns and spatial order. It demonstrates these workflows with OSMnx and data from OpenStreetMap, a collaborative spatial information system and mapping platform, to examine street network patterns, orientations, and configurations in different study sites around the world, considering what these reveal about the urban fabric. The age of ubiquitous urban data and computational toolkits opens up a new era of worldwide urban form analysis from integrated quantitative and qualitative perspectives.

## 1. Introduction

Information management is an important component of urban research and praxis. Data-driven modeling and exploration of cities entail cycles of information management activities – from data acquisition and transformation, to structuring and interpreting data to produce useful information, to knowledge dissemination for planning and advocacy. This paper considers urban morphology through these information management processes in the Smart Cities paradigm.

The Smart Cities paradigm aims to understand cities through user-generated content, ubiquitous sensing, and automatically harvested data (Batty et al., 2012). While this often takes the form of a modernized cybernetics through top-down monitoring, optimization, and control, there is greater potential in this paradigm's critical turn to richer problem sets (Goodspeed, 2015; Kitchin, 2016). Rather than considering livability as an optimization problem, planners might use urban data to enrich socio-political processes of community advocacy, understanding, consensus-forming, and public decision-making. Critical approaches might identify sampling biases in user-generated content to adjust for over-representation of certain groups in these datasets and to foreground marginalized voices. User-generated spatial data can be used to introspectively unpack planning and design histories and the spatial logics they have manifested in different places as a function of era, politics, culture, and local economic conditions. Interpretative and narrative approaches can enrich and contextualize data-driven urban morphology (Erin, Araldi, Fusco, & Cubukcu, 2017; Moudon, 1997).

Spatial information (and in turn information management) plays a central role in this space as nearly all urban and human processes are spatially-situated. In particular, this paper reflects on user-contributed big data about spatial infrastructure that allow us to examine the physical substrate that constrains and shapes the flows of people, goods, and information through urban space (Batty, 2013). Street networks are the paradigmatic example of such infrastructure. Researchers have explored these networks in recent years to model trips and traffic, to uncover fundamental patterns in city organization, and to explore urban planning and design histories. OpenStreetMap (OSM) – a worldwide mapping community and online geospatial information system – has played an increasingly key role in these streams of scholarship as it provides a freely available, high quality source of data on street networks and other urban infrastructure worldwide (Barrington-Leigh & Millard-Ball, 2017; Jokar Arsanjani, Zipf, Mooney, & Helbich, 2015).

This paper builds on recent work by Crooks et al. (2016) – who argued that big data is an underexplored, emerging frontier in urban morphology – to introduce and review examples of analyses that help to reveal and explain the urban form. In particular, it focuses on a motivating question: how can user-contributed big data be collected, organized, and modeled to explore the various spatial logics resulting from urban planning, design, and evolution? It takes up Crooks et al.'s call to develop workflows that integrate both data-driven and qualitative (i.e., interpretive or narrative) methods of urban morphology in today's era of ubiquitous urban big data. Situating this theoretical work in the visual culture of planning, this paper presents a visualization-mediated interpretative process of urban morphology.

This paper is organized as follows. First it situates analytical cartography within the theoretical framework of the visual culture of planning, which has traditionally sought to visualize urban space to understand city presents and futures (Gage, 2009; Gissen, 2008; Jacobs, 1984; Shanken, 2018; Söderström, 1996; Tobler, 1976) – from Nolli maps (Hwang & Koile, 2005; Verstegen & Ceen, 2013) to figure-ground street diagrams (Jacobs, 1995) to rose diagrams (Mohajeri & Gudmundsson, 2014). Then it discusses an information management workflow for collecting, modeling, analyzing, and visualizing OSM big data using open source tools like OSMnx and computational methodologies. Finally, it considers what these data-driven techniques reveal about different places and modes of urbanization before discussing implications for the Smart Cities paradigm of monitoring and understanding cities. It argues that such historically- and culturally-informed quantitative methods are essential for understanding the patterns and forms resulting from urban processes.

## 2. Spatial information and urban form

Much like the broader field of information management, many of the former central challenges in collecting, storing, and sharing spatial data have now evolved into commonplace processes and standardized platforms to largely alleviate technical burden. Today, greater emphasis belongs to the role that spatial information systems play in shaping urban patterns and processes from travel behavior, to housing markets and gentrification, to the ways in which planners, designers, and citizens engage with spatial information (Batty, 2005; Evans-Cowley & Griffin, 2012). This engagement is critical both for evidence-based city planning as well as for collaborative community-building in an era of ubiquitous technology. In particular, the Smart Cities paradigm today aims to quantify and measure urban patterns and processes in a positivist approach to understanding, controlling, and improving cities through information technology (Angelo & Vormann, 2018; Kitchin, 2016; Krivý, 2018; Townsend, 2015; Watson, 2015). As an epistemological project, Smart Cities research and practice take many diverse forms (Albino, Berardi, & Dangelico, 2015; Ismagilova, Hughes, Dwivedi, & Raman, 2019; Lytras & Visvizi, 2018; Stone, Knapper, Evans, & Aravopoulou, 2018; Visvizi, Lytras, Damiani, & Mathkour, 2018).

One such subject of urban morphology research today intersects Smart Cities, computational geometry, and network science to explore the patterns of urban form and circulation through large, harvested, user-generated data sets. Scholars have investigated this to explore travel behavior, public health and safety, and residential sorting (Ewing & Cervero, 2010; Hajrasouliha & Yin, 2015; Levinson & El-Geneidy, 2009; Marshall, Piatkowski, & Garrick, 2014; Porta et al., 2012; Southworth & Ben-Joseph, 1995; Xiao, Webster, & Orford, 2016; Zhong, Arisona, Huang, Batty, & Schmitt, 2014). Spatial information plays an important role in urban simulation for community visioning (Vanegas, Aliaga, Benes, & Waddell, 2009; Waddell et al., 2018), streetscape quality analysis (Shen et al., 2018), and predicting urban attributes from street imagery (Arietta, Efros, Ramamoorthi, & Agrawala, 2014). Another research stream examines the spatial ordering of cities' configuration and orientation through circulation network patterns (2014,

Barthelemy, Bordin, Berestycki, & Gribaudi, 2013; Barthelemy, 2017; Boeing, 2019; Buhl et al., 2006; Chan, Donner, & Lämmer, 2011; Courtat, Gloaguen, & Douady, 2011; Gudmundsson & Mohajeri, 2013; Louf & Barthelemy, 2014; Mohajeri & Gudmundsson, 2012; Mohajeri, French, & Batty, 2013). Various spatial logics and ordering principles exist in planned, unplanned, formal, informal, gridded, and organic urban patterns (Kostof, 1991; Rose-Redwood & Bigon, 2018; Smith, 2007) – and a city without one single, formal, geometric ordering logic may have well-defined, high-functioning physical and social structure (Hanson, 1989).

Data-driven urban morphology seeks to explore urban form and spatial order – modeling spatial data to trace histories, configurations, and orientations in physical space – but requires a grounding in narrative and interpretative approaches to truly reveal the nuances of local planning context and history. The urban design historian Spiro Kostof (1991, p. 10) said: "Form, in itself, is very lamely informative of intention. We 'read' form correctly only to the extent that we are familiar with the precise cultural conditions that generated it… The more we know about cultures, about the structure of society in various periods of history in different parts of the world, the better we are able to read their built environment." That is, urban spatial data must be contextually interpreted to become meaningful information. Kostof (1991, p. 11) continues: "There is no point in noticing the formal similarities between L'Enfant's plan for Washington and the absolutist diagrams of Versailles or Karlsruhe… unless we can elaborate on the nature of the content that was to be housed within each, and the social premises of the designers."

Here we specifically situate such visual thinking within the theoretical frameworks developed by Söderström (1996); Gissen (2008), and Shanken (2018). Söderström traces the distinct histories of cartography, geography, and postmodernity, arguing that the visual representation of urban form undergirds the scientific mode of studying cities. This visual thinking renders abstract spatial information legible to planners and citizens. Gissen explores the historical and still evolving visual-analytical links between architecture and geography, arguing that datascapes and visualization mediate the differences between empirical research traditions and the creative process of urban design. Shanken argues that urban planners have employed a constellation of visual methods to analyze spatial information and represent the city. This representational visual culture was historically exemplified by Giambattista Nolli's eighteenth century ichnographic study of Rome, producing the famous figure-ground Nolli Maps of the urban fabric (Hwang & Koile, 2005; Verstegen & Ceen, 2013). Two centuries later, this particular methodology was explored anew by Allan Jacobsö (1995) comparative visual study of dozens of urban street networks around the world.

This paper takes up where these traditional manual workflows left off to explore new computational, automated, big data methods through three demonstrative questions important to urban morphology research. 1) How do street networks embody specific spatial logics to organize city dynamics? 2) How do their orientations and configurations vary across places accordingly? 3) How can we visualize these complex patterns to render their information legible to planners and citizens using modern computational workflows and spatial big data?

## 3. Working with OpenStreetMap data

This paper explores these questions using case studies in a small set of cities and building models of urban street networks from OSM raw data using OSMnx, a Python package to automate and streamline OSM spatial data acquisition and analysis (Boeing, 2017). Alone, OSM's spatial information system and its various APIs can be challenging to synthesize and work with in nuanced and theoretically-sound ways (particularly for planning practitioners): its raw data do not lend themselves automatically to urban form/network analysis and its custom query languages can be cumbersome for scripting. OSMnx

allows researchers and practitioners to easily download street network, building, and amenity data for any study site in the world, then automatically construct them into street network graphs or spatial data frames for built-in visualization and statistical analysis. This empowers new ways of engaging with this massive repository of global spatial information.

These models are nonplanar directed multigraphs, where graph nodes represent intersections and dead-ends, and graph edges represent the street segments linking them (Barnes & Harary, 1983; Cardillo, Scellato, Latora, & Porta, 2006; Lin & Ban, 2013; Marshall, Gil, Kropf, Tomko, & Figueiredo, 2018; Trudeau, 1994). OSMnx allows users to download spatial data from OSM for any study site boundary in the world, automatically construct it into a model that conforms to urban design and transportation planning conventions, and then analyze and visualize it (Boeing, 2017). OSM is a valuable source of geospatial data as it has worldwide coverage, generally high quality, and an active collaborative user community (Barron, Neis, & Zipf, 2014; Basiri et al., 2016; Corcoran, Mooney, & Bertolotto, 2013; Girres & Touya, 2010; Haklay, 2010; Jokar Arsanjani, Zipf, Mooney, & Helbich, 2015; Neis, Zielstra, & Zipf, 2011; Over, Schilling, Neubauer, & Zipf, 2010; Zielstra, Hochmair, & Neis, 2013).

This paper employs two visualization methods to illustrate urban morphology through street patterns. First, it uses OSMnx to produce figure-ground diagrams of street networks and building footprints to compress urban form complexity, illustrate urban design, and communicate planning decisions and histories. These are inspired by Allan Jacobs's (1995) classic book on street-level urban form and design, which featured dozens of hand-drawn figure-ground diagrams in the general style of Nolli maps, depicting built versus open space to illustrate street network patterns. We adapt this cartographic methodology to a computational, big data workflow to likewise depict one square mile of multiple cities' street networks, considering similarities and differences. Plotting cities at the same scale provides a revealing spatial objectivity in visually comparing their street networks and urban forms.

The second method uses rose diagrams of street orientations to visualize the spatial ordering of urban circulation infrastructure (2012, 2013b, Gudmundsson & Mohajeri, 2013; Mohajeri & Gudmundsson, 2014; Mohajeri, French, & Gudmundsson, 2013). First we calculate the compass bearings of all the street segments in 25 world cities, then visualize them with a rose diagram in which the bars' directions represent 10° bins around the compass, and the bars' lengths represent the relative frequency of street segments that fall in each bin (Boeing, 2019). This produces a visual representation of the extent to which a street network follows the spatial ordering logic of a low entropy grid versus having streets oriented more evenly in all compass directions.

## 4. Urban circulation systems and spatial logics

Fig. 1 shows one square mile figure-ground diagrams from 12 cities around the world. At the top-left, Portland, Oregon and San Francisco, California typify the late nineteenth century American orthogonal grid (1995, Cole, 2014; Marshall, Garrick, & Marshall, 2015; Southworth & Ben-Joseph, 1997). Portland's famously compact, walkable, 200-foot × 200-foot blocks are clearly visible but its grid is interrupted by the Interstate 405 freeway which tore through the central city in the 1960s (Mesh, 2014; Speck, 2012). In the middle-left, the business park in suburban Irvine, California demonstrates the coarse-grained, modernist, auto-centric form that characterized American urbanization in the latter half of the twentieth century (Hayden, 2004; Jackson, 1985; Jacobs, 1995).

In stark contrast, Rome has a more fine-grained, complex, organic form which evolved over millennia of self-organization and urban planning (Taylor, Rinne, & Kostof, 2016). Representing each of these street networks here at the same scale – one square mile – it is easy to compare the qualitative urban patterns in these different cities to one another. Contrast the order of the nineteenth century orthogonal grid in

San Francisco and the functionalist simplifications of twentieth century Irvine to the messy, complex mesh of pedestrian paths, passageways, and alleys constituting the circulation network in the ancient center of Rome.

At the top- and middle-right, we see New York, Paris, Tunis, and Atlanta. Midtown Manhattan's rectangular grid originates from the New York Commissioners' Plan of 1811, which laid out its iconic 800-foot × 200-foot blocks approximately 29 degrees off true North (Ballon, 2012; Koeppel, 2015). Broadway weaves diagonally across it, revealing the path dependence of the old Wickquasgeck Trail's vestiges, which Native American residents used to traverse the length of the island long before the first Dutch settlers arrived (Holloway, 2013; Shorto, 2004).

At the center of the Paris square mile lies the Arc de Triomphe, from which Baron Haussmann's streets radiate outward as remnants of his massive demolition and renovation of nineteenth century Paris (Hall, 1996). The spatial signatures of Haussmann's project can clearly be seen via network analysis through the redistribution of betweenness centralities and block sizes (Barthelemy et al., 2013). At the center of the Tunis square mile lies its Medina, with a complex urban fabric that evolved over the middle ages (Kostof, 1991; Micaud, 1978). Finally, Atlanta is typical of many American downtowns: coarse-grained, disconnected, and surrounded by freeways (Allen, 1996; Grable, 1979; Jackson, 1985; Kruse, 2007; Rose, 2001).

The bottom row of Fig. 1 shows square miles of Boston, Dubai, Sacramento, and Osaka. The central Boston square mile includes the city's old North End – beloved by Jane Jacobs (1961) for its lively streets, but previously cut-off from the rest of the city by the Interstate 93 freeway. This freeway has since been undergrounded as part of the "Big Dig" megaproject to alleviate traffic and re-knit the surface-level urban fabric (Flyvbjerg, 2007; Robinson, 2008). The Dubai square mile shows Jumeirah Village Circle, a master-planned residential suburb designed in the late 2000s by the Nakheel corporation, a major Dubai real estate developer (Boleat, 2005; Haine, 2013; Kubat, Guney, Ozer, Topcu, & Bayraktar, 2009). Its street network demonstrates a hybrid of the whimsical curvilinearity of the garden cities movement and the ordered geometry of modernism. The Sacramento square mile depicts its northeastern residential suburb of Arden-Arcade and demonstrates Southworth and Ben-Joseph's (1997) "warped parallel" and "loops and lollipops" design patterns of late twentieth century American urban form.

Finally, the Osaka square mile portrays Fukushima-ku, a mixed-use but primarily residential neighborhood first urbanized during the late nineteenth century. Today, the freeway we see in the upper-right of this square mile infamously passes through the center of the high-rise Gate Tower Building's fifth through seventh floors (Yakunicheva, 2014). This peculiar intermingling of street network and edifice arose when transportation planners were forced to compromise with private landowners seeking to redevelop their property, despite the prior designation of the freeway's alignment (Isaac, 2014).

To qualitatively compare urban spatial forms in different kinds of places, these visualizations depict a mix of modern central business districts, ancient historic quarters, twentieth century business parks, and suburban residential neighborhoods. The cities they represent are drawn from across the United States, Europe, North Africa, the Arabian Peninsula, and East Asia. Yet street network patterns also vary greatly within cities: Portland's suburban east and west sides look different than its downtown, and Sacramento's compact, grid-like downtown looks different than its residential suburbs – a finding true of many American cities ((Boeing, 2018a)). A single square mile diagram thus cannot be taken to be representative of broader spatial scales or other locations within the municipality. These visualizations, rather, show us how different urbanization patterns and paradigms compare at the same scale, using automatically harvested user-generated data. This can serve both as a practitioner's tool for comprehending the physical outcomes of planning and informal urbanization, as well as a tool for
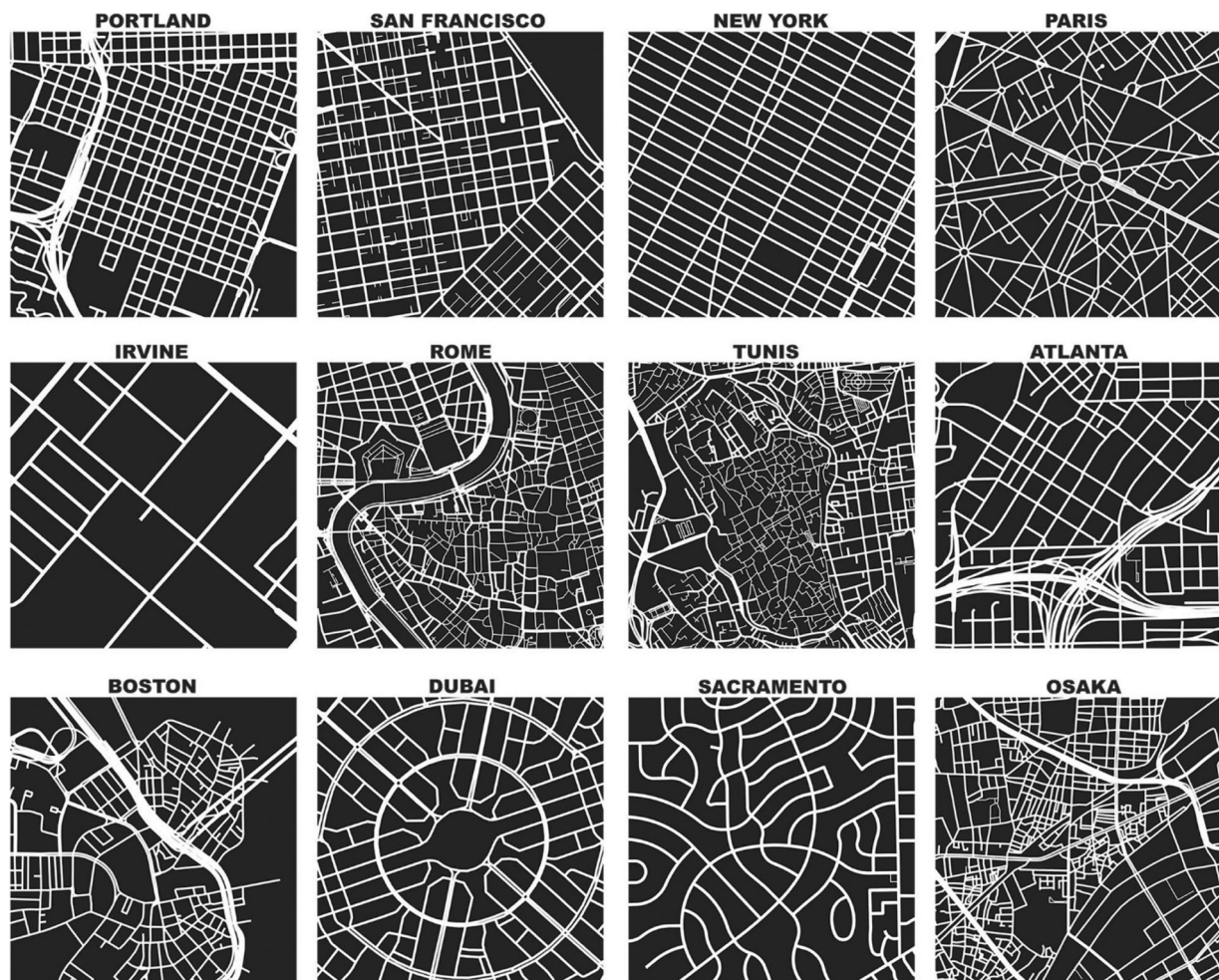
**Fig. 1.** One square mile of each city's street network. The consistent spatial scale allows us to easily compare different kinds of street networks and urban forms in different kinds of places.

communicating urban planning and design in a clear and immediate manner to laymen – leveraging spatial information to improve political collaboration and multi-level co-governance.

These uses can be seen perhaps even more clearly when we use OSMnx to visualize street networks along with OSM building footprints, as shown in Fig. 2. At the top-left, we see the densely built form of midtown Manhattan, with large buildings filling most of the available space between streets. Within this square mile, there are 2237 building footprints with a median area of 241 square meters. At the top-right, we see the medium-density perimeter blocks of San Francisco's Richmond district, just south of the Presidio. Here the building footprints line the streets while leaving the centers of each block as open space for residents. Within this square mile, there are 5054 building footprints with a median area of 142 square meters. The bottom two images in Fig. 2 reveal an entirely different mode of urbanization by visualizing the slums of Monrovia, Liberia and Port-au-Prince, Haiti. These informal settlements are much finer-grained and are not structured according to the orderly, centralized planning of the American street grids in the top row. Monrovia's square mile contains 2543 building footprints with a median area of 127 square meters. Port-au-Prince's square mile contains 14,037 building footprints with a median area of just 34 square meters.

OSM data and OSMnx provide planning practitioners an easy-to-use tool to visualize and examine street networks and building footprints as a planning and communication tool. The data in Fig. 2, for instance, could help planners and residents in Monrovia and Port-au-Prince collaboratively study how to percolate formal circulation networks into

these informal settlements with minimal disruption to the existing urban fabric, homes, and livelihoods (Brelsford, Martin, Hand, & Bettencourt, 2018; Brelsford, Martin, & Bettencourt, 2019; Brelsford, Martin, Hand, & Bettencourt, 2015; Masucci, Stanilov, & Batty, 2013; Zook, Graham, Shelton, & Gorman, 2010).

Visualizing spatial information can also reveal the state assertion of power and modernism's inversion of traditional urban spatial order (Holston, 1989; Vale, 2008). In pre-industrial cities, the figure dominates the ground as the diagram displays scattered open space between buildings, as seen in Fig. 3. But in modernist cities, the ground dominates the figure as only a few scattered buildings are positioned as sculptural elements across the landscape's void. The modernist paradigm sought to open up the dense, messy, and complex urban fabric with towers-in-the-park, spacing, highways, and functional simplicity ((Boeing, 2018b); Fishman, 2011). This phenomenon is clearly seen in Brasília, the modernist capital of Brazil, designed as a planned city in the 1950s by Lúcio Costa, Oscar Niemeyer, and Roberto Burle Marx (Fig. 3). The structural order of the city also suggests "an ordering of social relations and practices in the city" (Holston, 1989, p. 125). These figure-ground diagrams provide a spatial data-driven method to in turn qualitatively interpret and study the urban form and circulation networks that structure human activities and social relations.

The rose diagrams in Fig. 4 offer another perspective on visualizing this structural ordering of the city. Each polar histogram visualizes the orientation (compass bearing) of the borough's street segments, with bins representing 10-degrees around the compass and bar lengths representing relative frequency (for complete methodological details and
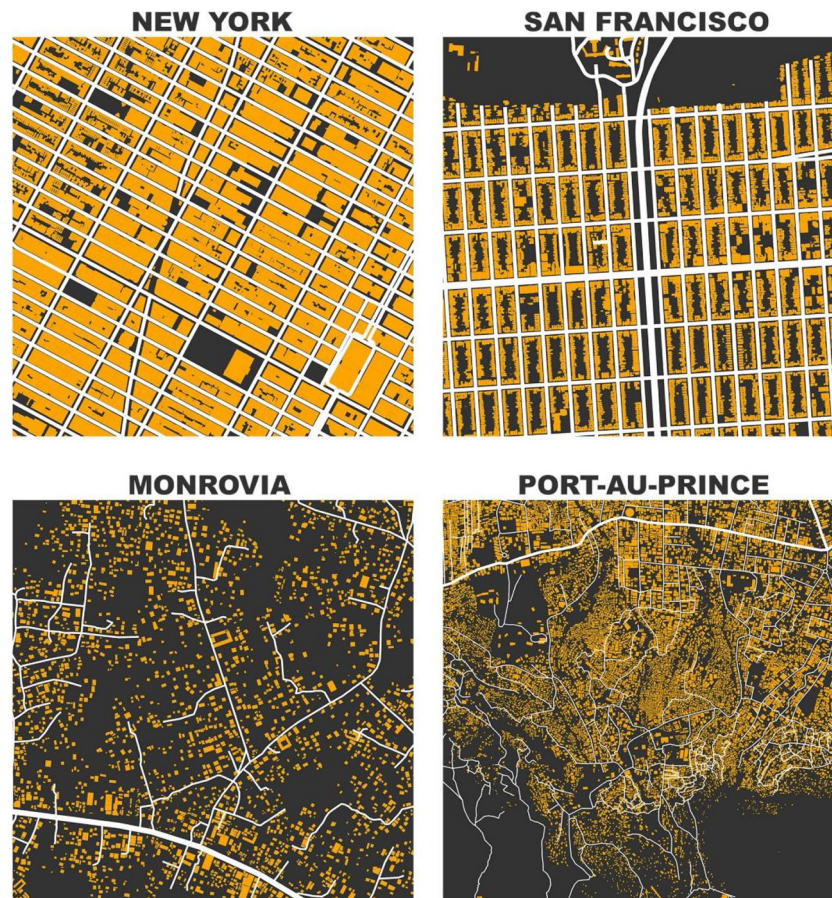
**NEW YORK**     **SAN FRANCISCO**

**MONROVIA**     **PORT-AU-PRINCE**

**Fig. 2.** One square mile of each city's street network and building footprints, comparing US cities to informal settlements in the Global South.

theoretical development see Boeing, 2019). For example, in Manhattan's rose diagram we can see the spatial order produced by its dominant orthogonal grid (cf. Fig. 1) as its street bearings are primarily captured in four bins, offset from true North. Higher entropy street orientations can be seen in the other boroughs as they do not adhere as strictly to the ordering logic of a single grid. Such an analysis can be performed with tools like QGIS or ArcGIS, but OSMnx helps to streamline the workflow by automating the process of downloading the raw data, building the model, and then allowing easy directionality analysis using Python libraries like geopandas and matplotlib and the interactivity afforded by the Jupyter environment.

In Fig. 5 we see rose diagrams of 25 cities (municipalities) around the world. This study scale aggregates heterogeneous neighborhoods into a single analytical whole, but offers the benefit of capturing the scale of city planning jurisdiction to tell us about the spatial ordering that the circulatory system provides. While some street networks in modern cities in Canada, Australia, and China demonstrate similar low-entropy grids, far more of these cities show higher entropy. That is, their streets are oriented more evenly in all compass directions rather than following the spatial ordering logic of one or two consistent grids. The spatial signature of the street grid is clearest in cities like Toronto and Beijing, while cities like Rome and Rio de Janeiro demonstrate more-organic and less-orthogonal patterns. The patterns in Beijing are interesting as they deviate from many of its Asian neighbors, instead conforming more to the rationalist, centrally planned gridirons of Western cities like Toronto, Melbourne, and Manhattan and suggesting a certain spatial logic undergirding its massive and rapid urbanization in recent years.

## 5. Discussion

Through the tools of urban morphology and computer science, spatial information allows us to see how urban planning, design, and millions of individual decisions shape how cities organize and order space according to various spatial social logics and cultures. In the 1990s, Allan Jacobs adapted the style of Nolli maps to manually illustrate figure-ground diagrams of cities to explore their urban form. Today, OSM provides a worldwide data set to perform these analytical cartographic workflows automatically and computationally in the Smart Cities mode of analyzing and understanding cities through user-generated big data.

This paper operationalized OSMnx's figure-ground diagrams and rose diagrams as methods of hybrid quantitative-qualitative analysis of urban patterns. These visualizations reveal the texture, grain, and spatial-ordering logic of different cities around the world. Compressing the dense spatial complexity inherent in cities, they offer a streamlined and legible window into the urban fabric and how the circulation system's infrastructure percolates through it. These figure-ground diagrams allow us to compare across places at the same scale to better understand similarities and differences particularly in texture, grain, and connectivity. The rose diagrams compress the complexity of street network orientation entropy into simple plots that immediately reveal the spatial ordering of the city's streets and its underlying spatial logic.

These visual urban morphology methods and OSMnx workflows can help planners convey comparative urban form to laypersons. They can destigmatize density and explain how connectivity and urbantexture vary across cities. They simplify complicated urban planning and urban data science concepts to make them more approachable for practitioners, community advocates, and other members of the public to engage in citizen science. Future research can further operationalize
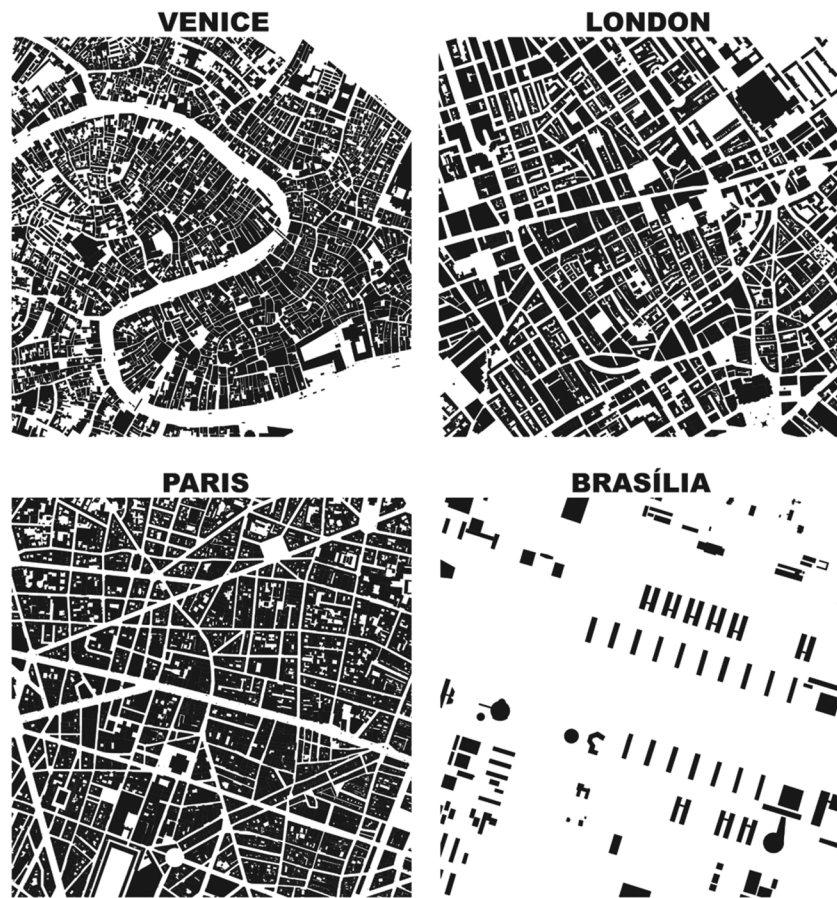
**Fig. 3.** One square mile figure-ground diagrams of building footprints in the centers of Venice, London, Paris, and Brasília reveal the modernist inversion of traditional urban spatial order.
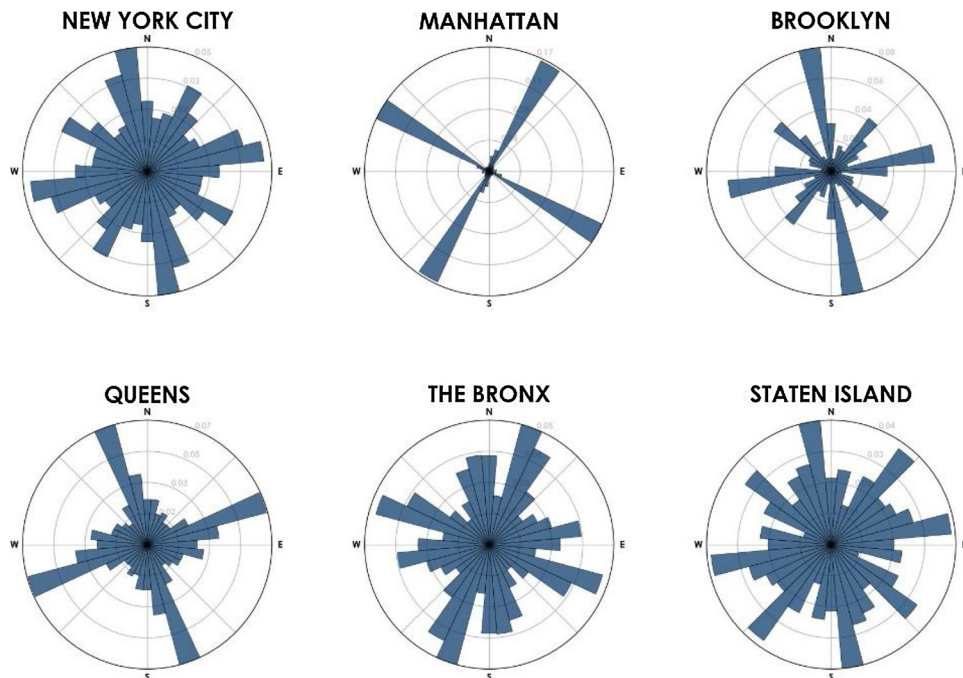


**Fig. 4.** Rose diagrams of the street orientations in New York City and its five constituent boroughs.
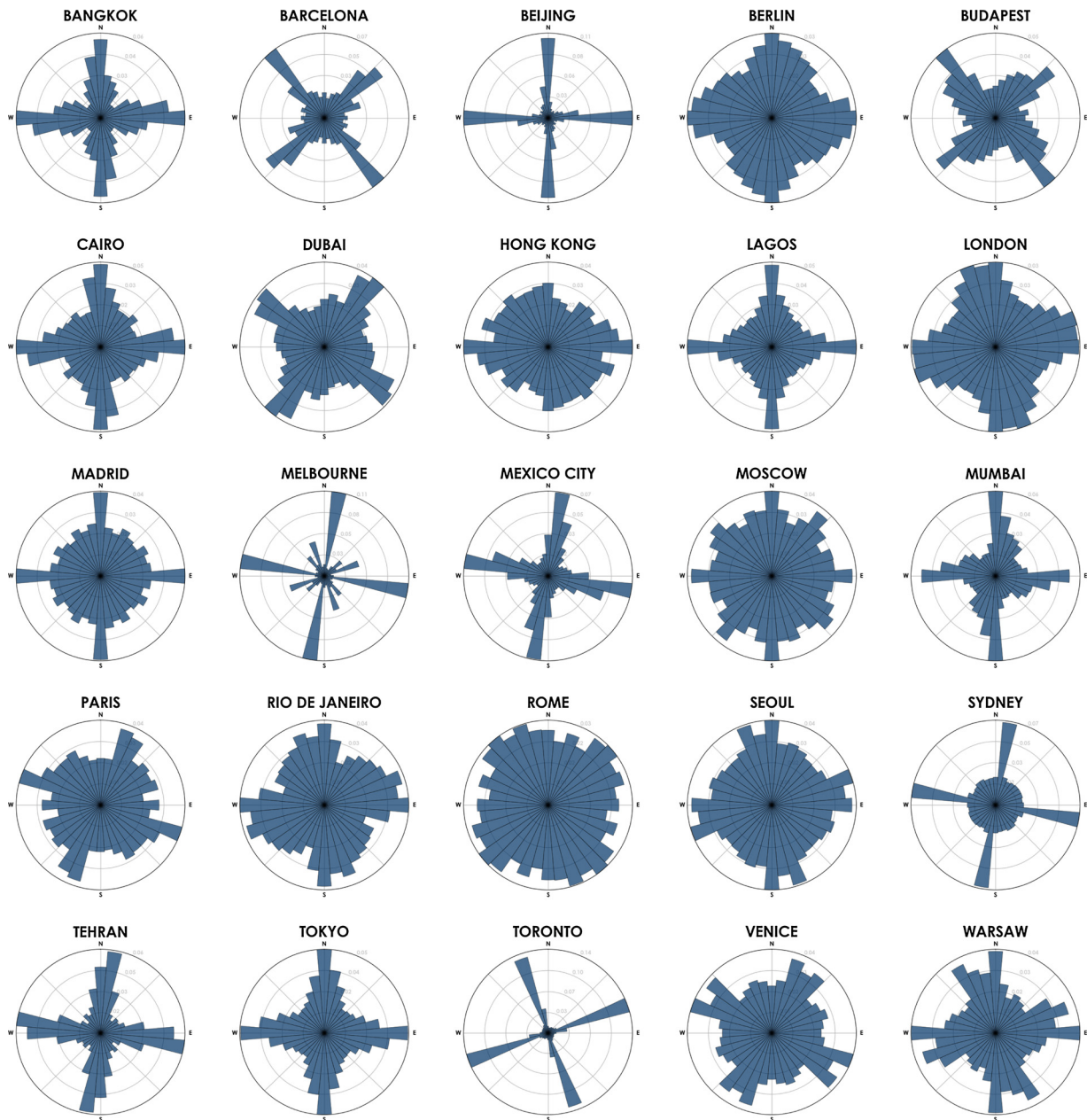
**Fig. 5.** Rose diagrams of the street orientations in 25 cities around the world.

these techniques to quantify circulation system connectivity and griddedness, and measure how street network design has evolved across the United States. This can provide a comprehensive understanding of a city's morphological trajectory through time and, in turn, help planners collaboratively shape that trajectory.

## 6. Conclusion

This paper explored information management processes of data acquisition, transformation, modeling, interpretation, and dissemination for understanding and communicating urban form. It took up Crooks et al.ös (2016) call for developing workflows that meld both data-driven and interpretive approaches to urban morphology in the burgeoning era of user-generated big data. It discussed the OSMnx toolkit for modeling, analyzing, and visualizing street networks from morphological perspectives, advancing techniques such as Jacobsös (1995) figure-ground diagrams and rose diagrams into reproducible, computational workflows. It situated this theoretical work in the visual

culture of planning – adopting a visually-mediated narrative approach of exploring the urban form and in particular demonstrating how OSM data can be modeled to explore the spatial ordering that results from urban planning and design.

In doing so, it made three primary contributions to urban planning/ morphology at the intersection of Smart Cities and information management. First, it presented an urban data science workflow for collecting, modeling, and interpreting user-contributed big data to research how cities' street networks embody different spatial logics and organize complex human dynamics through urban space. Second, it demonstrated a big data-driven approach to modeling and evaluating street network orientation and configuration in different places. Third, it extended these quantitative streams of Smart Cities/information management scholarship in a complementary qualitative direction by describing how planners can visualize these complex patterns to make them legible to citizens in collaborative planning processes of comparing alternative scenarios. This communicative data-driven decision-making sits at the heart of the intersection of urban planning,

morphology, and information management.

Throughout, this paper operationalized a narrative approach, following Kostofös (1991) emphasis on social premises and cultural conditions, to interpret urban morphology qualitatively through data-driven quantitative analysis and visualization. This sets up two key next steps for future urban morphology research in the Smart Cities paradigm. First, from a big data perspective, developing richer interactive visual functionality is critical to empowering analytical reasoning in these planning and engagement processes. Some interaction was discussed in this paper, but this remains an important emerging frontier at the intersection of information management and urban planning. Second, future research at the intersection of information science and urban morphology can further develop the rose diagrams in the context of information entropy to explore street network orientation-order and develop new indicators of griddedness to see how planning and design paradigms have evolved over time in different cities and countries. In tandem, information management and urban morphology will further converge to provide comprehensive understandings of city pasts and presents and empower planners and community members in collaborative data-driven decision-making processes.

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