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Modeling spatial wholeness in cities using information entropy theory

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Abstract

Descartes states "Divide each difficulty into as many parts as possible and necessary to resolve it." Deconstruction is not a new idea as demonstrated by Descartes quote but a compelling one for understanding the issues behind complex systems especially as vast as cities. Built form is a relational process and the overall spatial form emerges with a sense of wholeness, a certain degree of completeness, in its topologic embodiment. Using Alexander's "*levels of scale*" property of wholeness as a morphologic translation interface, the method developed in this research allows questioning various relative spatial formations. Shannon's entropy theory has been employed for measuring the state of uncertainty, and disorderliness conveyed through the multivariate context of morpho-information across varying scales. This study aims to cross-evaluate mean Entropy-IQR values generated for ten cities using proposed method with the survey results that ten experts, architects, urban planners, and landscape architects have rated for ten cities urban layouts in three aspects of the wholeness. Experts do not have an agreement among each other about the wholeness of case study, inter-raters reliability (Kα) is 0,14 and the correlation coefficient between normalized median expert views and mean Entropy-IQR values is 25%. The results indicate that definition and sense of wholeness even for place making experts is not as intuitive as Alexander claims. These findings help to point out the need for evidence-informed analytical methods that measure the relative degree of wholeness in constantly changing cities.

Keywords
Wholeness, Completeness, Multi-scalar, Information entropy, Measuring.

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1. Introduction

Urban design is an interdisciplinary approach to urban space. Critical role of urban design, between planning and architecture, is to set an order, a feeling of wholeness and a scaling harmony in urban space (Konuk, 1992). The urban design approach in this definition is about concepts of order, hierarchy, and harmony in the process of making robust urban spaces. According to Hanson, the order in its most largely approved definition is a notion of sameness, harmony, repetition, geometry, rhythm, symmetry and grid (Hanson, 1989). The interplay among built elements in various orders, in different size and scales, create the morphology. The order that emerges through such multiplicity of morphologic interplay comes to the front as a measurable notion. Shannon's information entropy, in this study, is being used as a method to measure the "relationship between order and disorder" (Arnheim, 1971). Morphologic interplay at various scale levels is a form of information conveyed through the units of a grid system. Measuring such information using Shannon's entropy is hypothesized to correlate with the degree of the wholeness of the morphologic system. The raw data used in this research is the open street map data land cover vector data in equivalent scale and pixel resolutions belonging to 10 cities, London, New Delhi, New York City, Paris, Rome, Santa Monica, San Francisco, Siena, Tokyo and Washington DC, showing their two-dimensional urban layouts.

Cities are about functions that are perfectly integrated into agglomerated layers of built environment. Layers of different forms of spatial entities are seemingly complex but logically simple ways of scaling (Jiang B., 2012). Cities have their very own scaling patterns embedded in the multivariate morphologic formations. For so many reasons, scaling hierarchy in cities can be deformed through the time. Salingaros states that lively and vibrant cities accommodate unique scaling regimes in touch with all their living systems (Salingaros, 2005). An emergent need for automobile-led 20th-century urbanization and uncontrolled population growth in cities caused a disregard for the scaling-laws in cities and imposed piecemeal lay outs and typological forms. This brought an inevitable change on scaling patterns of spatial formations and thus on the wholeness.

Cities are made of built entities that make the morphologic and symbolic character of spaces, and they create the evaluative and measurable qualities (Nasar, 1994). Large or small, built entities that create the morphologic character in cities are measurable. According to Jiang geographic space is made of far more small things than large ones and the scaling pattern can evoke a certain sense of wholeness (Jiang & Sui, 2014). This kind of wholeness and beauty was initially defined by C. Alexander and compiled in his master work "The Nature of Order" (Alexander, 2002-2005). The concept of wholeness for a spatial context is a relational notion. It is a fragile relationality. Once a single entity that belongs to a built context changes, the configuration and the distribution of the information and thus the entropy, of the system changes. This happens across different scales. Therefore, measuring the entropy of a particular built context requires a multi-scalar approach. Major raw data used for this study is open street map sourced land cover vector data. The multi-scalar approach in this research is being methodized through superimposing a grid with equivalent units upon the raw data. The grid units simply frame equivalent amounts of pixels and generate units of equal size. Each grid unit in each particular grid scale bounds a certain type of morphologic interplay. Changing the grid scale allows creating different size of grid units scanning different built formations exponentially and recursively.

The interplay between the built elements and their overall spatial content is in a continuous process of change. This kind of change in real space is a space compromise ending up in a gradual adaptation. Undoubtedly, if not a natural disaster, this is foremost a human-led process. The human factor, as the decision-maker, builds up the causality about the degree and intensity of the spatial change. Although it mostly occurs in micro scale, the process of change and adaptation gradually remakes the overall urban built context. According to Baynes and Heckber (2009), understanding and modeling the dynamics of spatial change may lead to better understanding and management of the human process that leads to change.

Cullen in "Townscape" (Cullen, 1961) states that space is a meaningful context in its in-situ relationality. The spatial change also embodies and is perceived within such contextual relationality. This kind of relationality requires a site-specific approach considering near and related things that form a geographic context. Tobler, in his influential "First Law of Geography," states that everything is related to each other; yet, the things that are close to each other are more related than the distant ones (Tobler, 1970). Miller on this issue notes that measuring the space does not just generate simple metric or geometric findings, but also develops new spatial attributes considering the nearness and relatedness of various spatial issues. It allows measuring the geographic space through the interplay between diverse urban and environmental phenomena in different scales. Mathematical models in urban planning and design studies can give precise and accurate results by measuring the inputs that embody urban space in an objective way (Nasar, 1997).

This study hypothesizes that morphologic formation in cities is a significant element of spatial signature. Regarding the causation between disorder and law of entropy, an entropy value might define a degree of wholeness for spatial formations. The data used for the case areas in this paper comprises the top view images for 1/5000 scale urban areas' land cover vector data with 1024x1024 pixels resolution. Using the analysis tool developed in this study, case study areas' source data are overlaid by a grid system. In each case area, as seen in Figure 2, an entropy value is generated for each unit that has maximum adjacency, connected to eight surrounding units, throughout the grid. The units by the edges of the grid lack of maximum adjacency and thus they are exempted in the calculation of entropy. The number of units that a grid owns varies depending on the scale of the grid selected for the analysis. Afterward, a statistical method of data measuring –inter quartile range (IQR)- is employed to eliminate the extremes of the generated data set to measure and reduce it to a single value for each case analysis area. The analysis can be applied either for a single particular grid scale or different grid scales for the same analysis. Either case, total sum of entropy-IQR values as a cumulative value implies a degree of wholeness specific for the selected grid scale levels. This study asks whether or not the degree of wholeness in morphologic systems can be mathematically measured. The results of the method are compared with survey results that spatial design experts intuitively rated the case study cities from the strongest to the weakest through their morphologic layouts. This kind of an approach to urban conservation may have significant implications for the built environments that are facing a possible change in different scales.

2. Wholeness of the spatial formations

Alexander (2002-2005) states that natural or human-made, every single identifiable piece of a system is a center and it is unique in its way. The wholeness or life imposed through a system is its very own kind of order. This is an order that arranges a special and adequate mix of decisively nested structures, which both locally and globally interact and reinforce each other. Wholeness, in this respect, is a matter of a vital interrelationship among the elements of any size, shape, and scale in a system. In his own words, Alexander describes this situation as:

> "I propose a view of physical reality which is dominated by the existence of this one particular structure, W, the wholeness. In any given region of space, some sub-regions have higher intensity as centers; others have less. Many sub-regions have weak intensity or none at all. The overall configurations of the nested centers, together with their relative intensities, comprise a single structure. I define this structure as "the" wholeness of that region" (Alexander C. , 2002-2005, p. 96)

One of the critical points in Alexander's definition of wholeness is about understanding what a center is and why it is vital in creating life and wholeness for things or places. Once it is grasped, then the entire Theory of Wholeness and the way in which it is employed in the method used in this study get comprehensible. A center is simply a smallest, identifiable piece, object or part in a system. For instance, the head of the body is a center. At the same time, each of the eyes, nose, forehead, and mouth is a center too. At a subtle level, eyebrows, eyelashes or even the iris of the eye are all centers in their very own way. When the context is a built environment, each single building is an object that can be categorized as a center. Two things are essential to understanding it better: first, a center does not have to be a separate part of the context that it belongs to. A mouth, for instance, is properly located as the continuum of a face itself. Second, centers can exist at different levels of scale. Starting from the globe, the continents, countries, regions, cities, districts, neighborhoods, streets, buildings, apartments, rooms, and even the furniture are all centers in different scales.

The way in which centers interact with each other is the most critical matter in understanding Alexander's overall idea of wholeness. The centers in a system may empower or weaken each other through the way that they exist and interact. The position, size, and shape of each constituent gradually affect the overall degree of the wholeness of the system. At the end of his extensive studies, Alexander defined fifteen properties where the centers exist in diverse morphologic relationships with each other in forming a degree of wholeness. A "property," as a geometric quality, in Alexander's texts, is a fundamentally informative characteristic for "wholeness" (Waguespack, 2010). Either used in a single way or a context of a multitude of patterns, property as Alexander asserts, is critical in forming "life" and generating some level of wholeness.

The concept of wholeness and the life for a spatial setting is a broad notion, and the connection between two concepts is controversial. Building definitive and conclusive analogical bridges between wholeness and life is not always as tangible as Alexander claims in several ways. The entire question of wholeness is a large, flexible and not so clear phenomenon and there is a loose relationship between wholeness and life (Ekinoglu & Kubat, 2017). In other words, beyond strict definitions of "dead" and "alive" life can exist in various degrees in-between for space. Nevertheless, it is hard to construct a direct and determinant relationship between two concepts since different levels of life can exist in space with various degrees of wholeness.

The idea of wholeness and life in space requires a profound and site-specific investigation considering its various cultural, social, symbolic ingredients and architectural attachments. Therefore, reducing the concept of wholeness merely to the relationships of the sub-constituents of a built system's layout might be highly limiting. To avoid this shortfall, in this study, the concept of wholeness that Alexander depicts is being referred as a spatial quality of "completeness" that emerges through the relationships among the sub-constituents of the system across scales. Moreover, Alexander's overall idea of wholeness and life also stands on a firm basis of completeness (Ekinoglu & Kubat, 2017).

Alexander proposed fifteen figurative qualities, which he found similar in things that have a life. These features are "(1) levels of scale, (2) strong centers, (3) boundaries, (4) alternating repetition, (5) positive space, (6) good shape, (7) local symmetries, (8) deep interlock and ambiguity, (9) contrast, (10) gradients, (11) roughness, (12) echoes, (13) the void, (14) simplicity and inner calm, and finally (15) non-separateness" (Alexander C., 2002-2005).

The properties can be described as the syntax rules for spatial translations in examining how centers of an existing built space get together and help each other for evoking life. This kind of process of spatial translation can also be algorithmically coded for each of the properties mentioned above. In this study, the property that has been selected for the spatial translation is "Levels of Scale" since syntactically it is the most general and base property in explaining the most of the other remaining properties.

3. Shannon's entropy approach

The entropy concept was first used as part of thermodynamic systems in the nineteenth century. The second rule of thermodynamics says that every living or non-living system has an amount of free energy, and it always moves towards equilibrium (Bailey, 2015), and the entropy increases towards this realization. In other words, a system spontaneously evolves towards a less ordered state. Nature tends to disorderliness more than order. The probability of a disordered or irregular occasion is higher than an ordered and regular one (Shannon, 1948). This is an act of seeking equilibrium, and maximum entropy is thus what leads to disorderliness. Since the probability of a disordered state is higher than an ordered state, entropy always increases but never decreases. Maximum entropy takes a system to the death. Briefly, energy or substance in nature cannot vanish but evolve from one state to another. Entropy is the measure of this evolution or transformation.

In addition to thermodynamic entropy, statistical entropy was first introduced by Shannon (1948), (2001) as a "basic concept in information theory, measuring the average missing information on a random source" (Jat, Garg, & Khare, 2007). "Shannon's entropy originated from information theory as a measure of uncertainty of conveyed information over a noisy channel" (Bailey, 2015), (Jat et al. 2007). The larger the value of Shannon's entropy, the higher is the uncertainty of information conveyed. Shannon developed the mathematical explanation of the information theory. He focused on how to minimize the loss of information in revealing a message in another point. Entropy (H), in this sense, is a measure of information. H is dependent on the number of information categories, K. Higher, a number of data types, conveyed by a piece of information, lower the probability of the same type of data to gather. It is also the least predictable state (Bailey, 2015). Hence in such a case, the entropy is always towards most probable or most likely state. When the entropy is maximum, the categories of information get to their most random state where the most uncertainty occurs. The high amount of information with diverse information categories is most likely to emerge as high entropy and thus high uncertainty. Bailey (2015), states that Shannon's entropy is content-free and can be applied to measure any information with a multiplicity of data types.

Shannon entropy is a quantity measuring the relations in a data category. Use of logarithm, see Equation 3, makes this quantity growing linearly with system size and "behaving like information." Shannon in his original paper states that the logarithmic measure is more convenient since it is mathematically suitable in measuring the number of possible states in which a system can be found (Ekinoglu & Kubat, 2017). The unit of entropy is a "bit" (Wang, 2016). The information entropy as a method with a rising trend has been employed in diverse design-related disciplines. Krampen (1979) and Stamps (2003) used Shannon's entropy in measuring the data belonging to the façade elements to measure and evaluate their behavior. Bostancı (2009) employed entropy approach in assessing the unique urban skylines from their design quality standpoint. Thanks to the developments in data storing & processing technology, measuring the information is more and more getting one of the central topics in architecture, art, and urban studies that are dealing with multivariate nature of big data and data-intense technologies (Offenhuber & Ratti, 2014). Entropy approach in this sense serves as a device for measuring the visually-diversified information.

4. Method: Measuring the multiscalar and relational entropy levels

"Wholeness and Theory of Centers" (Alexander, 2002-2005) explains that every possible center in a system may empower or weaken another through the way in which they exist and interact in many scales. The way in which built entities exist in a system reveals a high or a weak degree of wholeness. This paper, in the spirit of Alexander's definition of wholeness and life through centers, considers buildings as the fundamental centers in built environment. In brief, the method is simply based on questioning various morphologic formations that the buildings come together to form the built environment. A dynamic grid, as a data-mining interface, acts to translate a particular built context into a digitized equivalent. In other words, grid serves as an instrument that reads the levels of scale blueprint of the built area through the specified grid units.

This study, using Shannon's information entropy theory, develops an alternative quantifiable approach that can measure the contextual nature of completeness for a built environment from the scale levels point of view. To achieve it, a spatial analysis tool has been developed by using two major programming languages; "C#" and "Processing". The tool has two major functions: 1) Data-mining and 2) Data-visualization. The data-mining function has been developed by compiling different image processing algorithms to develop a hybrid feature extraction algorithm, compiling *inrange – edge - canny – color* filter algorithms, (Opencv, 2017) on C# to retrieve data out of land cover vector data. Data-visualization function visualizes the retrieved data sets and illustrates the outcomes of the analysis.

Levels of scale as a parameter in data-mining enables running this investigation reiteratively in a multi-scalar way. This investigation is done at different grid scale levels, so the way each single grid unit interacts with its adjacent units mathematically matters in the calculation of entropy of each max adjacent unit throughout a grid system. As a formulation of the wholeness through the method of this study, it is possible to say that low entropy implies a relatively higher degree of wholeness as it is also theoretically taken both from the definition of entropy (Leibovici, 2009) (Shannon, 1948) and Alexander's thoughts on wholeness in "Nature of Order" (Alexander, 2002-2005, s. 64, 72, 77, 78, 112, 122, 144, 145, 146).

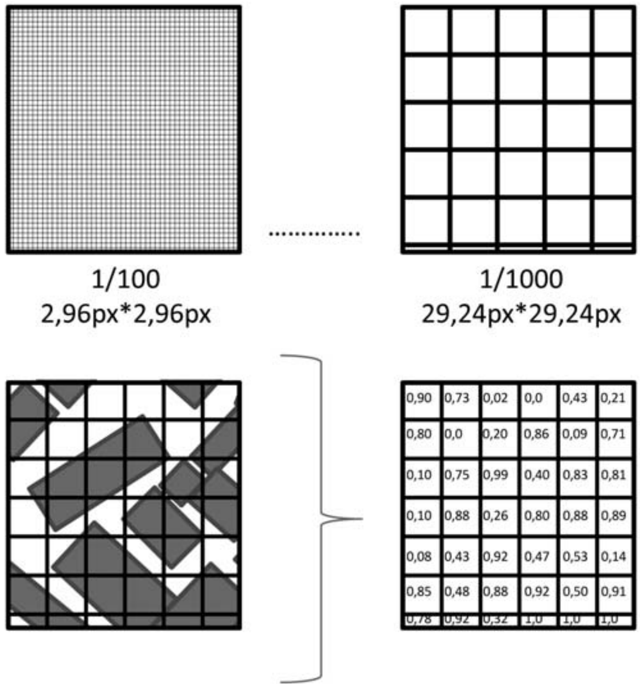

Figure 1. *Changing grid scale levels and the way each unit corresponds to different morphologic interplay in each scale level.*

For the analysis, depending on the selected scale level, the grid gets partitioned into equivalent units of various sizes, as seen in Figure 1. Considering that built entities may exist in a large variety of shapes and sizes in built environment, grid units help to recognize the interplay among the built bodies from an individual scale level. The units allow recognition and translation of corresponding built fabric, see Equation 1, into a numerical scale as in Figure 1. The algorithm generates a G value for each unit. Built probability framed by each grid unit is termed as G. G, and H by definition are two co-dependent spatial measures. G is referred to specific gravity in physics, and it is termed to be the measure of relative scale-based built probability for each grid unit, while entropy(H) is termed to be the measure of uncertainty that each unit holds considering its adjacent units' built probabilities (see Equations 1,2 and 3). G, in this sense, is unit-specific and represents the scale-dependent built probability while H is relational and system-specific and represents the level of uncertainty for a unit considering the eight surrounding-units G values.

Principally according to information entropy a more organized complexity contains less amount of information

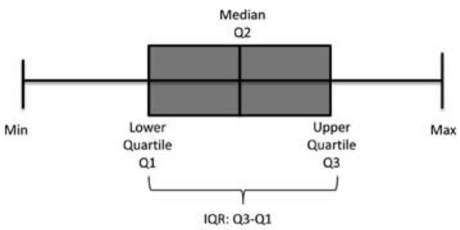

Figure 2. *Generating the IQR values.*

and hence less potential of different probabilities. A somewhat organized but still more random one contains the higher potential of new probabilities and references while a very randomly and diversely organized one contains the most amount of information types and thus the greatest potential for new possibilities. This is no different for built environments. The higher possibility of spatial references in a unit of built area leads to a bigger tendency for new occurrences and a growing potential for change. In brief, the higher the spatial entropy, the more is the uncertainty, and hence a bigger potential of change is there. Higher entropy suggests a lower degree of wholeness.

Depending on the scale of the grid, the analysis tool may generate highly diversified datasets with the different type of deviations along the data depending on the analyzed area. The multivariate nature of the entropy datasets requires discretization to eliminate the extremes and the deviations that exist across the data. IQR (Interquartile Range) statistical data measuring method does the discretization process. It arranges the values from the smallest to the biggest. For discretization of the deviations in the dataset, IQR, as illustrated in Figure 2, plays a role in extracting the "middle fifty" where it draws a new dataset. It is where the bulk of the values falls into, and in statistics is preferred over many other measures of spread (i.e. the average or median) when reporting multivariate data sets e.g. school performances based on the scores of the various tests. Each dataset generated by this analysis tool is scale-dependent, so the ranges of the quartiles change as the scale of the analysis change. In other words, any change in the IQR value for a data set is either about the changing morphologic state of the analyzed area or the changing grid scale.

Leibovici (2009) notes that the integration of specific spatial aspects or adjacency properties into the entropy generation is essential when considering the spatial distributions of geographic entities. In other words, entropy among the interactions of geographic entities requires consideration of multi-scalar proximities and adjacencies systematically. Application of "Levels of Scale" as data-collecting/classifying rule in data-mining process entails the definition of certain proportions between pixels and scale levels, i.e. corresponding metric distances. Scaling via pixels for an image is similar to changing the levels of the camera objective while looking at a particular area from the top view. This kind of changeability sets equilibrium between pixels on an image and metric distances in real space. Any particular change in scale of the grid refers to a certain proportional change for the pixel-area framed by each grid unit as seen in Figure 3. In each scaling level, a grid unit frames a different morphologic occurrence, and thus a new value set for both, G and H states. The scaling levels that have been applied to the case ar-

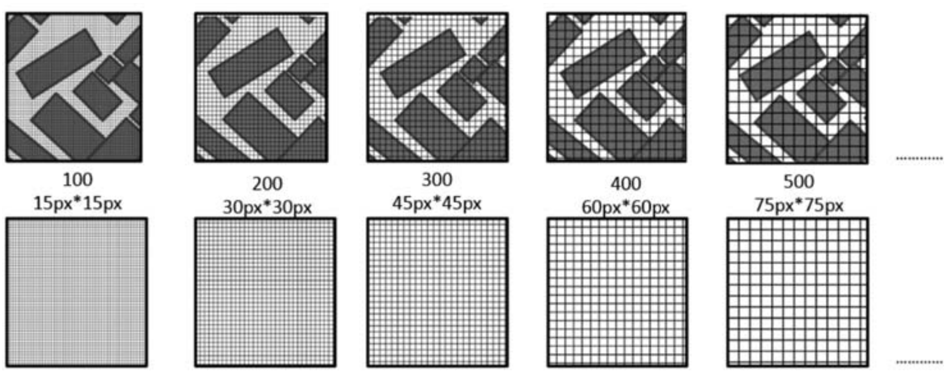

Figure 3. *Scaling the grid via changing number of the pixels framed each time by each grid unit.*

eas in this study range from 1/100 to 1/1000 with 100 intervals of increase.

Before initiating the analysis, the user picks a case area and selects a particular scale for the grid. The scale in this study varies from 100 to 1000 by regular intervals of 100 for the selected ten different case urban areas. A grid system, based on the selected scale level, is superimposed throughout the case area. Referring to Shannon's entropy and using it for built environment as explained in Figure 4, in the i^th^ unit of an n units grid system, G_i is the proportionate of built density, of the i^th^ unit where P_i is the proportion of occurrence considering the G values of the adjacent l, nine in the proposed method, units. H_i is the Entropy for the i^{th} unit. Methodologically, P and thus H is generated as long as the unit is maximum adjacent, meaning it has eight connected units.

$$G_i = \frac{\textit{Built portion of pixel i}}{\textit{Total built pixel area}} \quad (1)$$

$$P_i = G_i / \textstyle\sum_i^l G_i \quad (2)$$

$$H_i = P_i \cdot \log\left(\frac{1}{P_i}\right) \quad (3)$$

Each grid unit as seen in Figure 3, matches a particular built density represented by a (G) value. The algorithm assigns G=0 when the unit is entirely unbuilt, and G=1 when it is completely built up. The units located on the edges of the grid are exempted since they do not have the maximum adjacency. Entropy (H) for the remaining units is calculated as in below Figure 4. Unit number 5, in Figure 4, is being surrounded by eight adjacent units. The entropy for

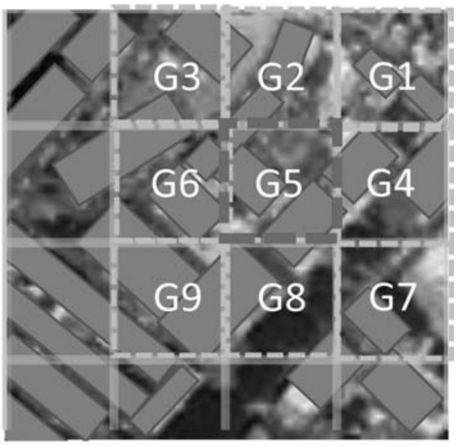

Figure 4. *Unit positions and interactions among the adjacent units in calculation of H.*

the unit with G5 value is calculated by considering the G5 with G1, G2, G3, G4, G6, G7, G8 and G9 values.

In the first round of the study, ten case study urban areas have been specifically selected from densely built areas that reflect the morphologic character of case study cities to analyze using the proposed method. The cities that have been scrutinized in this study are: London (L), New Delhi (ND), New York City (NYC), Paris (P), Rome (R), Santa Monica (SM), San Francisco (SF), Siena (S), Tokyo (T), and Washington DC (WDC). The cities are diversified regarding being old and organically developed vs. being new and geometrically developed and those in-between cities.

As raw data, open street map data, up to date 1/5000 scale, 1024 x 1024 pixels resolution, land cover vector data have been used for the analysis. The case study urban areas have been selected as

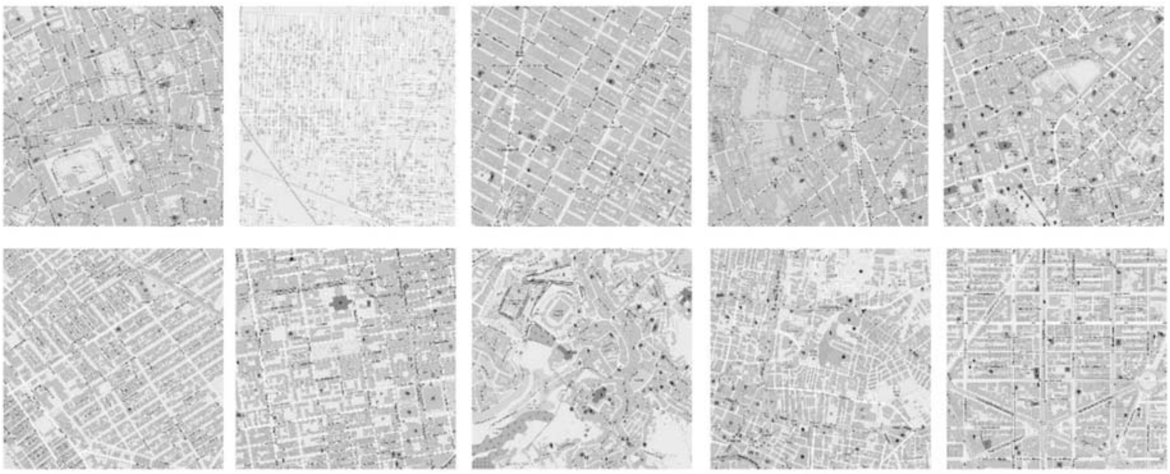

Figure 5. *10 1/5000 scaled case study urban areas: London, New Delhi, New York City, Paris, Rome, Santa Monica, San Francisco, Siena, Tokyo, Washington DC.*

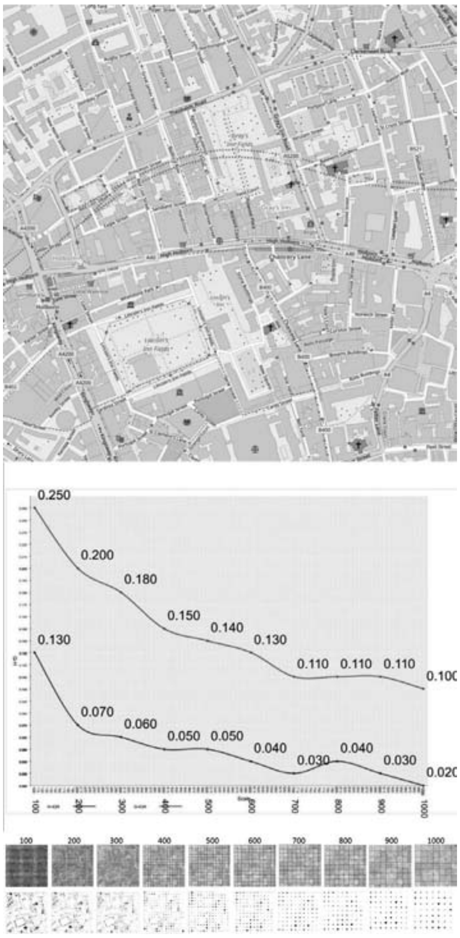

Figure 6. London 1/5000 scaled urban area G-IQR (red curve) and H-IQR (blue curve) values for ten different scales from 1/100 to 1/1000 with regular increases of 100. Bottom; grid-scale dependent G realizations (unit-specific built probability).

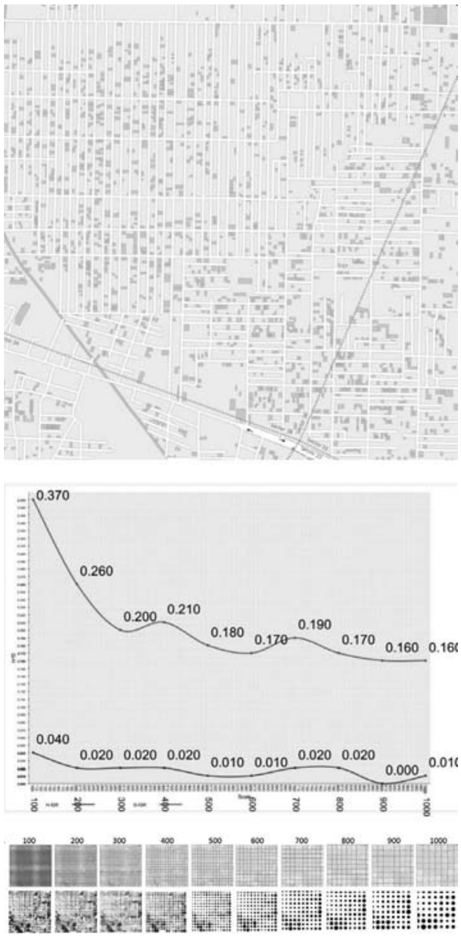

Figure 7. New Delhi 1/5000 scaled urban area G-IQR (red curve) and H-IQR (blue curve) values for ten different scales from 1/100 to 1/1000 with regular increases of 100. Bottom; grid-scale dependent G realizations (unit-specific built probability).

densely built areas showing the unique characteristic and signature-like morphologic lay outs of selected cities. The analyses have been performed using ten types of grid scale, from 1/100 to 1/1000 with regular increases of 100, for the case study cities, in Figure 5, and the results have been created as in Figures 6, 7, 8, 9, 10, 11, 12, 13, and 14.

The H-IQR values generated by the analyses are shown in the multi-scalar analysis graphs in above figures. Each graph shows how each morphologic formation relatively creates its entropy values through varying size & amount of grid units, and varying adjacencies, which gradually redefine a relative state of wholeness. Each H-IQR data is an interval data. Interval data is a numeric data that we know the exact difference between two so that they are equally important. Hence, we can take the mean value of ten H-IQR values as seen in Table below.

5. Getting the experts' views on wholeness for the case study urban layouts

In the second round, in order to compare "measured-wholeness" with "perceived-wholeness" ten experts, consisting of four architects, four urban planners, and two landscape architects & urban designers with minimum ten years of professional experience, have been asked to share their views, a number on a scale of 1 to 10, for ten case study urban layouts. The strongest city takes 10 while the poorest one takes 1 based on the view of the surveyor. The surveyors have not been directed on how to perceive the wholeness and evaluate the case cities' layouts accordingly but fully rely on their own profes-

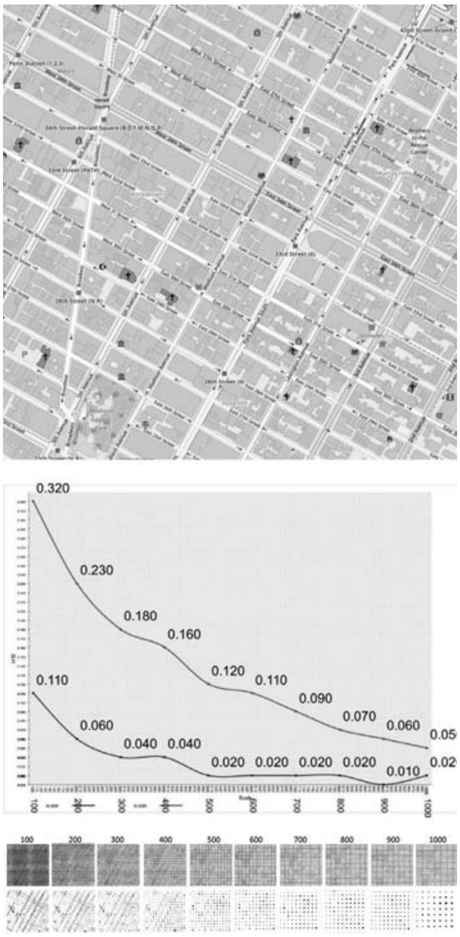

Figure 8. New York City 1/5000 scaled urban area G-IQR (red curve) and H-IQR (blue curve) values for ten different scales from 1/100 to 1/1000 with regular increases of 100. Bottom; grid-scale dependent G realizations (unit-specific built probability).

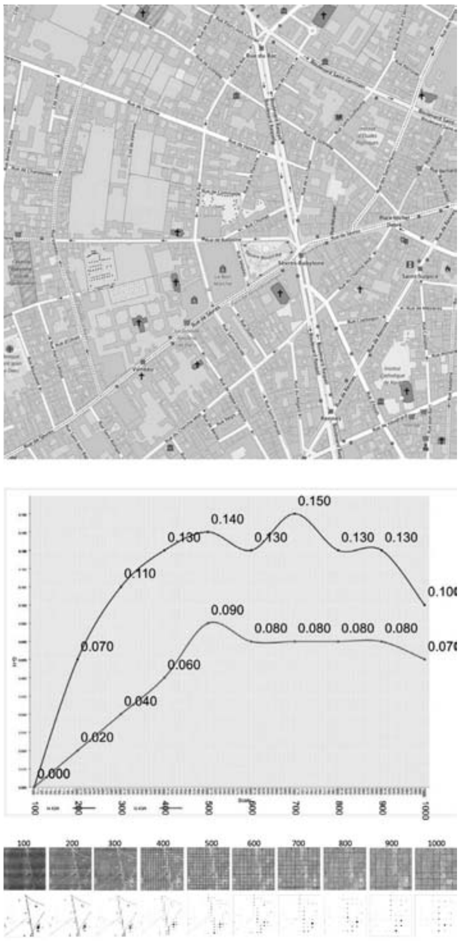

Figure 9. Paris 1/5000 scaled urban area G-IQR (red curve) and H-IQR (blue curve) values for ten different scales from 1/100 to 1/1000 with regular increases of 100. Bottom; grid-scale dependent G realizations (unit-specific built probability).

sional and personal understanding and intuitions. The surveyors have been given 1 hour for rating the ten case study layouts through replying each question in Table 1 below. Briefly, the questions have been asked to see how the sense of wholeness gets shaped in understanding and intuitions of professional place makers.

All the case study cities have potentials to trigger a different sense of wholeness in different aspects. This study does not have an aim to understand the reasoning behind the experts' dissenting views about each parameter of wholeness but the dominant tendency in their understanding of wholeness when compared to the findings of the analytical method developed in this study. The experts have been asked to rate the cities in terms of three aspects of wholeness, in Table 1.

6. Results

The diversity of ratings among the experts' views, in Table 2, make generating of Krippendorff's α (alpha) (10 experts and 10 cities) a consistent approach. "Krippendorff's α (Kα) is a general statistical measure of agreement among observers designed to indicate their reliability." (Salkind, 2017)

Kα for 10 experts and 10 cities is 0.1417. The best alpha value between two experts is 0.4118. These are well below what we expect to see (>70). These findings show that there is no

Table 1: *Survey questions.*

Q1	Degree of wholeness through the solid-void relationships
Q2	Degree of wholeness through the road hierarchy
Q3	Degree of wholeness through the harmony among the adjacent masses

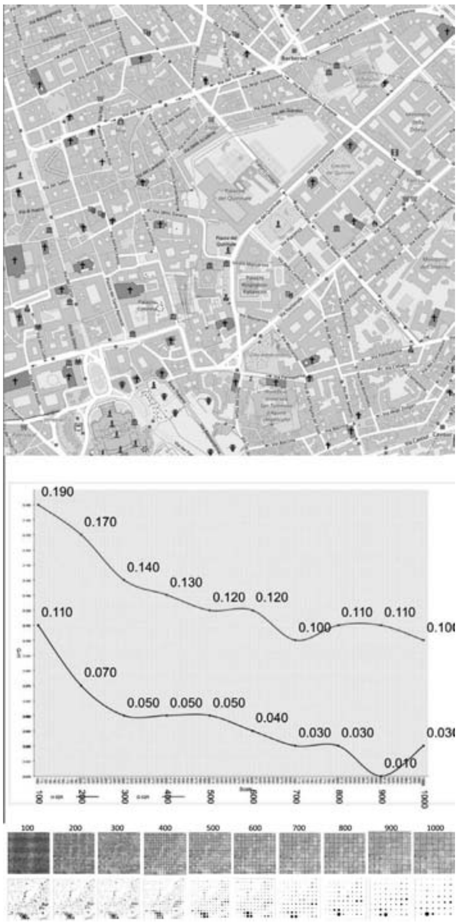

Figure 10. *Rome 1/5000 scaled urban area G-IQR (red curve) and H-IQR (blue curve) values for ten different scales from 1/100 to 1/1000 with regular increases of 100. Bottom; grid-scale dependent G realizations (unit-specific built probability).*

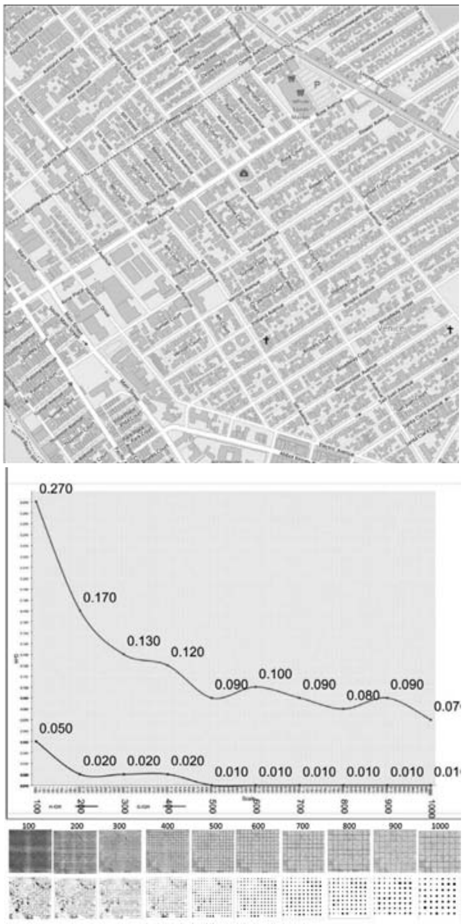

Figure 11. *Santa Monica1/5000 scaled urban area G-IQR (red curve) and H-IQR (blue curve) values for ten different scales from 1/100 to 1/1000 with regular increases of 100. Bottom; grid-scale dependent G realizations (unit-specific built probability).*

agreement among the surveyors about which case study layout creates a stronger sense of wholeness and which one creates a weaker and weakest.

The concept of wholeness in this study is a measure defined by three spatial parameters: i) solid-void relationships ii) road hierarchy iii) harmony among the adjacent masses. The experts' ratings for the analyzed cities show that, even when asked through its three specific aspects, there is no agreement about wholeness. Experts' views indicate that this kind of survey to measure wholeness through three given parameters still shapes a highly subjective assessment and ad hoc definition of wholeness and its components with varying evaluations.

Table 2. *10 normalized (3 parameters merged) experts' reviews for the case Study 10 cities.*

exp	P	NYC	ND	L	WDC	T	SM	R	S	SF
1	8	2	10	11	6	13	7	16	17	9
2	14	9	2	6	14	6	11	16	10	12
3	12	15	14	3	16	5	12	8	3	9
4	12	11	2	7	12	8	10	13	14	12
5	16	11	8	11	13	8	7	11	13	5
6	14	7	2	15	12	5	3	12	15	12
7	8	15	10	8	17	5	14	3	2	13
8	11	12	10	9	13	10	9	10	10	13
9	9	15	9	11	12	11	8	12	4	10
10	12	12	2	11	15	6	12	10	5	14

The finding implies that spatial orders in varying size and scales require an evidence-informed and data-driven analytical method to measure built environment, especially for spatiotemporal investigations.

Scores by the normalized experts' views (N-EV) on wholeness for each

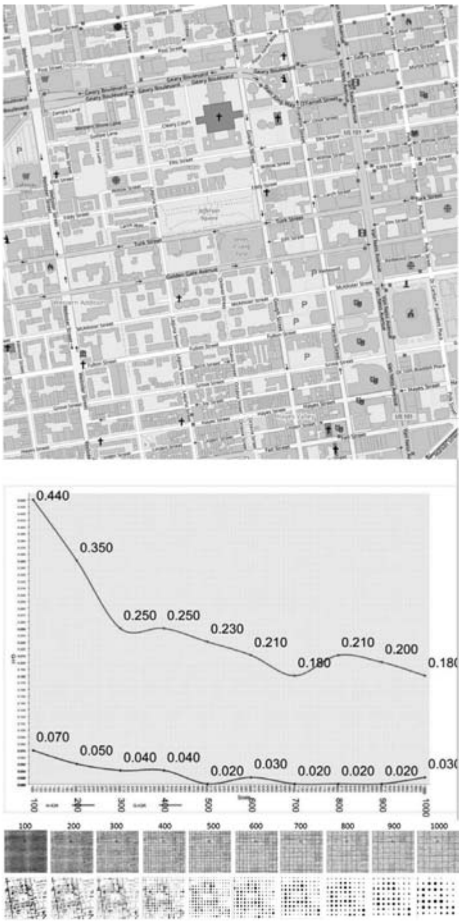

Figure 12. San Francisco 1/5000 scaled urban area G-IQR (red curve) and H-IQR (blue curve) values for ten different scales from 1/100 to 1/1000 with regular increases of 100. Bottom; grid-scale dependent G realizations (unit-specific built probability).

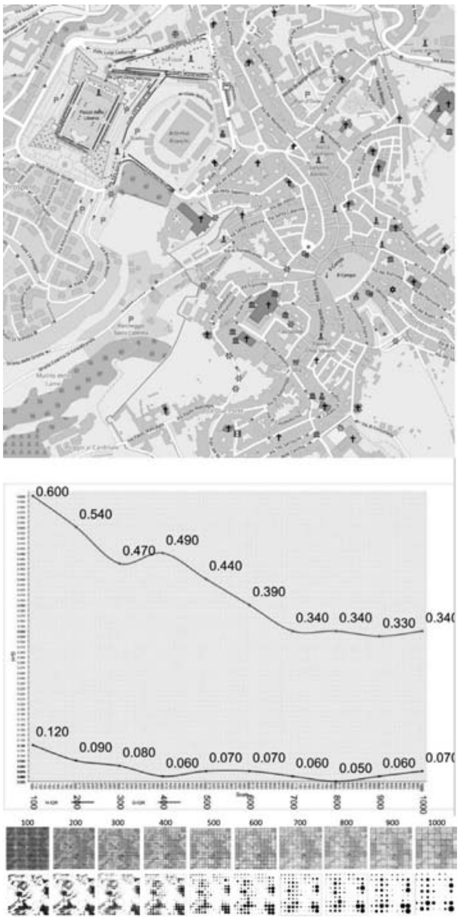

Figure 13. Siena 1/5000 scaled urban area G-IQR (red curve) and H-IQR (blue curve) values for ten different scales from 1/100 to 1/1000 with regular increases of 100. Bottom; grid-scale dependent G realizations (unit-specific built probability).

city is a median value since it is an ordinal scale. Ordinal scales are typically measures of non-numeric concepts like the intensity of a sense for a given situation. We cannot know the difference in the understanding between "very strong" and "strong." Therefore values on the scale are not equal. Thus, we cannot get the mean value of it but the median. However, the situation in H-IQR value data set is different. H-IQR value is an interval scale that are numeric scales in which we know not only the order but also the exact differences between the values. That's why we can get the mean value for the H-IQR data set generated by the analysis of ten different grid scale levels applied for each city.

Two outcomes in this study help to articulate the conclusion. First, the Kα for the 10 experts and 10 cities, is 0.1417. This finding shows that there is no agreement among the experts on the wholeness degrees of the case study cities upon the given parameters. Second; Correlation coefficient between N-EV medians and mean H-IQR values is 25%. Expert views and H-IQRs are supposed to be inversely correlated to verify each other since high expert

***Table 3.** Normalized experts' views (N-EV) and median H-IQR values for the analyzed cities.*

City	N-EV Medians	Mean H-IQR
Paris	12,20	0.109
New York City	11,48	0.036
New Delhi	9,27	0.017
London	8,83	0.052
Washington DC	12,68	0.026
Tokyo	7,54	0.043
Santa Monica	9,16	0.017
Rome	11,74	0.047
Siena	10,24	0.073
San Francisco	11,57	0.034

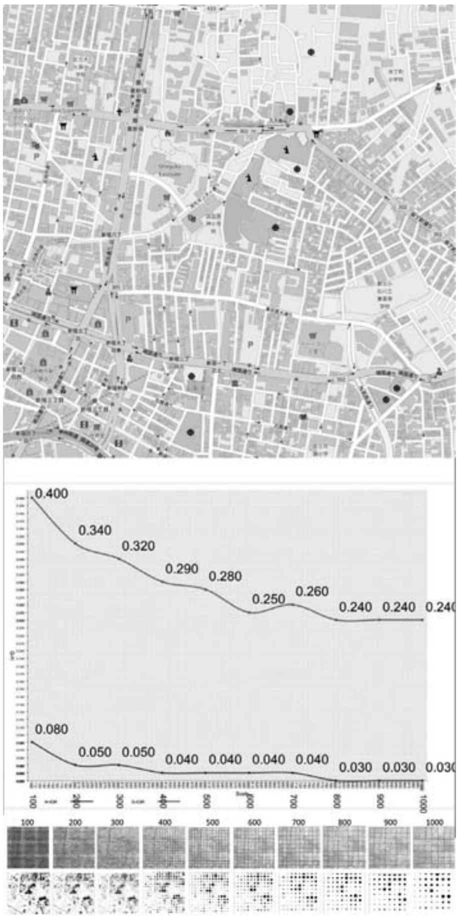

Figure 14. *Tokyo 1/5000 scaled urban area G-IQR (red curve) and H-IQR (blue curve) values for ten different scales from 1/100 to 1/1000 with regular increases of 100. Bottom; grid-scale dependent G realizations (unit-specific built probability).*

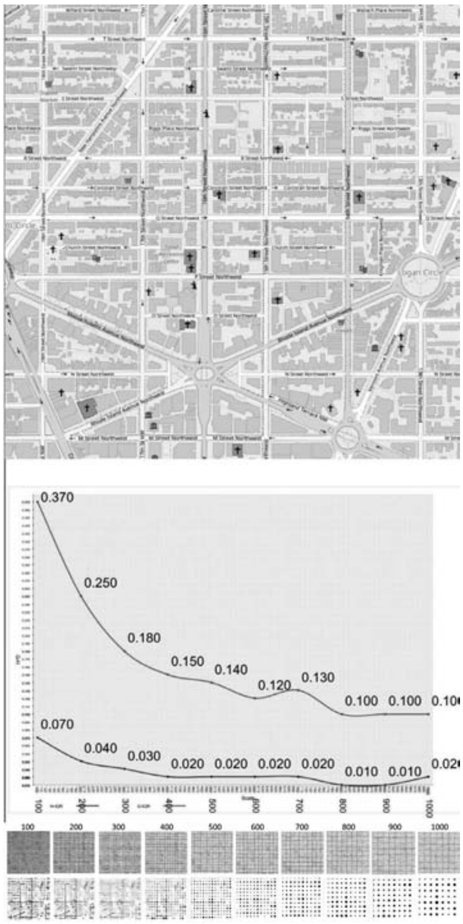

Figure 15. *Washington DC 1/5000 scaled urban area G-IQR (red curve) and H-IQR (blue curve) values for ten different scales from 1/100 to 1/1000 with regular increases of 100. Bottom; grid-scale dependent G realizations (unit-specific built probability).*

rating implies high wholeness which, in entropic scale, is supposed to be low H-IQR and vice-versa. Although 25% is a low enough correlation coefficient and would imply a high consistency with a high Kα, the low Kα value- high disagreement among the surveyors-blocks the way to articulate that the results between two methods are consistent.

Dramatic disagreement, on the idea of wholeness, among the surveyors trigger another significant issue. The idea and sense of wholeness even for place making experts is not as intuitive as Alexander claims but a loose and controversial quality. This finding helps to point out the need for data-driven and evidence-informed analytical methods that measure the relative degree of wholeness in constantly changing urban environments. Such as the method developed in this study.

Results also prove that idea of wholeness, more than perceivable, is a measurable concept. It is neither purely a quantifiable nor an intuitive notion but both of them. This is mostly because the wholeness of the spatial layout is just one of the several other significant factors that trigger an overall sense of wholeness.

Results, using the proposed analytical method indicate that the quality of wholeness embedded in the morphologic layout is a measurable concept more than perceivable. It is not a purely intuitive notion. This might be because the human-eye cognitively tends to the catch simple legible layouts in the most complex systems. Human-eye may neglect many pieces that an algorithm will not.

Results also prove that wholeness, being used for "completeness" in this study, does not necessarily rely on the organic or geometric order of the analyzed layout but the order that reveals a particular scaling hierarchy across scales. The quality of the order is about the success of constituents in making a greater whole and the legibility of morphologic signature that the system reveals at various scale levels.

This study suggests that Shannon's entropy is a convenient theory for measuring the entropy of various morphologic occurrences in built settings from the relationality of scale levels point of view. The results of this study show that urban built layout can be measured. The design is a multi-scalar wholeness-seeking task among various spatial and functional parameters. Design as a wholeness-seeking and life-extending process in built environment requires inspecting and questioning the relational nature of spatial context across scales. Wholeness in this sense is not merely a spatial notion relying on the Euclidian geometric thinking but instead a product of living geometric and fractal thinking. It is, in this study, suggested that wholeness as a qualitative concept can be a measurable spatial quality through the proposed method. The results indicate that wholeness as a space term is not an only an abstract, subjective and intuitive term, but rather a measurable and visualize-able concept.

Briefly;

Information entropy approach allows measuring the multi-scalar behavior of the spatial and geographic entities so that it is convenient to assess the morphologic occurrences.

Information entropy approach gives meaningful and verified findings for the comparative spatiotemporal analysis about the cities (Ekinoglu & Kubat, 2017). Using the proposed method, different parts of the city can be measured by different time periods and grid scales which may have significant implications on the site-specific reasons that alter the degree of the wholeness of the space.

Using the entropy approach, synchronizing GIS datasets, e.g. heat island effect maps can give an alternative way of measuring and better monitoring the consequences of the changing nature of built environment and its irreversible effects on environmental sustainability and urban energy consumption issues.

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