Analytical Measuring of Spatial Layouts through Multi-Scalar Adjacencies Lower Manhattan Case Area

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Abstract

Space is a cultural process. It contains various ingredients that affect the degree of liveliness and wholeness, however, these are mostly the qualities that we cannot always measure using conventional methods. In urban design theory, there are normative concepts to explain the link between good urban form and robust urban places that emerges the feeling of wholeness. However, these approaches are mostly objective and require quantifiable methods to test.

This study raises the question of whether or not we can analytically measure Alexander’s definition of wholeness using Shannon’s information entropy. This study develops a mathematical model of wholeness through generating the entropy for particular pixel levels out of building footprints raw data in a systematic and multi-scalar adjacency. Scale, in a dynamic grid interface with equally divisible units, refers to the different spatial formations through the units of a grid overlaid upon the raw data. Eventually, in each pixel level, through varying morphologic formations framed by each grid unit, varying entropy values are calculated throughout the grid.

Various type of figure-ground experiential case studies, through the above-defined method, confirm that it is not only their geographic positions but also the way built entities come together across scales in making larger clusters matters about the degree of wholeness emerged. The method has been applied on a case study with a remarkable change in two periods. World Trade Center Area in Lower Manhattan, before and after 9/11, has been analyzed through ten different pixel levels and the results indicate that the Entropy-IQR, the level of uncertainty, increased from 0,81bit to 1,15bit which means the degree of wholeness decreased regarding the inverse correlation between entropy and wholeness. The method draws a potential in practice of relational measuring built environment that may face a particular change in different portions.

1. Introduction

Understanding the spatial structure and processes of the built environment is a challenging issue in urban planning. Despite extensive investigations on urban complexity, the area of measuring the spatial formations mathematically is still one of the topics with very few advances. According to Kempf, “Although we will never fully comprehend the entire complexity of morphology in one moment, we can understand the urban construct through the interaction of its parts” (Kempf, 2009).

Urban planning long tried to deal with the urban complexity via a ‘general system theory’ strategy. This top-down approaches produced generic and reductionist statements and visions. A growing tendency started to theorize how systems emerge and generated from the bottom-up by a shift towards more decentralized governments. The bigger power at individual and local levels brought up new directions on questioning the urban complexity through a growing control over the spatial information technologies. Conventional urban planning approaches still struggle with the idea of the bottom-up spatial analysis and its insistence on being a reactive power for our inability to understand how the city emerges. Spatial complexity is generated from the ‘local to global’, ‘parts to whole’ or ‘micro to macro’ level. According to scholars, the attempts to fix the parts for making the cities function better is a profound misunderstanding about their nature (Batty M., 2004).

Diverse thoughts are supporting this claim. For example, Anderson (1972, p. 396) states that "quantitative differences become qualitative ones" meaning that the whole is not just 'different' it is 'very different' from its sum of the parts. Jacobs (1961) claimed that the city should be considered as an issue of 'organized complexity' arguing that diversity and variety in towns are their trademarks. She pioneered an influential social movement against destructive effects of the 1950s and 60s post-war American urban planning approaches. Her struggle contributed to systems vs. problems terminology that later inspired the scholars. She categorized the issues as; i) Problems of simplicity; ii) Problems of disorganized complexity and; iii) Problems of organized complexity (Jacobs, 1961). Jacobs, in her influential work "*Death and Life of Great American Cities,*" accepts that her work is pseudo-science. She suggested that the diagnosis of complexity science for the cities is like medical doctors to make scientific studies to develop diagnosis and treatments for the illnesses of the human body. Cities ought to benefit the findings of a science of cities to criticize the current practices and apply the needed changes. Jacobs inserts her claim upon applicable principles and states, "generating an exuberant diversity in a city's streets and districts, these four conditions are indispensable" (Marshall, 2012, p. 261);

i)-The district must serve more than one function

ii)-Blocks must be short

iii)-The district must mix up the buildings that vary in age and condition

iiii)-There must be a sufficiently dense concentration of people

Today diverse urban research methods employ conventional analytical science with measurable data as inputs and outputs. Quantitative data is the legitimate data in confirming or refuting the validity of the claims and hypotheses. Many urban research studies that use different analytical methodologies confirm that urban spaces that promote the efficient social and cultural exchange and productive interaction between people are robust urban areas (Jacobs, 1961), (Seamon, 2013). This review is one of Jacobs' central claims in "the conditions for city diversity" chapter of her book (Jacobs, 1961). According to Russel (2014), the degree and density of urban interactions facilitate and promote the exchange of knowledge.

Another scholar whose ideas shed light on relational quality in the built environment in urban theory is Gordon Cullen. His ideas in his classic book of "*Townscape*" (Cullen, 1961), are established around the importance of contextualized nature of space and non-separateness of structural entities in the built setting. The book explicitly draws hypotheses about the significant effects of the organization and co-existence of the built objects and other urban elements over the user experience and perception. Cullen's one of the most important emphasis in his book is about the art of relational presence, and the dynamism spread throughout the places, which is termed as "synergistic relationality" by Seamon (2014). From the phenomenological point of view, Cullen (1961), defines it as the "art of relationship" in his book. He states, "The critical fact of our place is that the items of the built environment cannot be detached one from another. The human perception and the emotions are revealed by the juxtapositions" (Cullen, 1961). Cullen's core claim focuses on the concept that the individual elements of our physical environments create poor spatial experiences and feeling of wholeness on human cognition and emotions compared to the well-composed spatial compositions.

The concept of "wholeness and the life" for a spatial setting is a broad notion, and the connection between two concepts is controversial. Drawing solid analogies between wholeness and life is not always as clear and direct as Alexander claims in several ways in "*Theory of Wholeness*" Alexander's (2002-2005). 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 et al. 2017). In other words, beyond strict definitions of “dead” and “alive,” the life can exist in various degrees in between those two in 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 wholeness and life as qualitative spatial qualities require a profound and site-specific investigation considering various cultural, social, ideological, 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 theoretically correct yet phenomenologically limiting approach. To avoid this shortfall, in this study, the concept of wholeness that Alexander depicts is being referred as a quality of “completeness in its layout” that emerges through the relationships among the sub-constituents or the parts and whole relationships of the built system. Moreover, Alexander’s overall idea of wholeness and life also stands on a firm basis of the idea of “completeness” (Ekinoglu & Kubat, 2017).

The purpose of this research is to develop an alternative analytical method that can measure and explain the parts & whole-interactions-dependent relational nature of the urban built environment and their larger contexts in various pixel levels. Christopher Alexander’s claims on wholeness in this respect have been studied as reference thoughts. “*Levels of scale*” is the first and most coherent one among Alexander’s (2002-2005) fifteen geometric patterns of wholeness which recurrently appear in things and create life. Starting from there, the proposed method in this research attempts to develop an analysis tool to measure the parts & whole-interactions-dependent morphologic complexity in various pixel levels employing Shannon’s information entropy theory in data-mining function. The method has been applied in the urban area, Lower Manhattan Area a.k.a “Ground Zero” in New York, that has experienced a devastating terrorist attack and following change in overall morphologic layout. The analyses have been conducted based on pre-9/11 and post-9/11 morpho-information.

2. Wholeness of Spatial Formations and the Significance of Adjacencies

There is a constant debate in the agenda of urban design theoreticians and researchers: the struggle between qualitative and qualitative approaches to the urban space in design research and practice. The current state of art knowledge and claims that establish the base of urban design theory argue particular keywords as the criteria for good urban design. For Lynch (1981, pp.109-235) they are ‘vitality’, ‘sensibility’, ‘fit’, ‘accessibility’, and ‘control’ while ‘density’, ‘diversity’ and ‘grain’ for Jacobs (1961) (Caliskan & Mashoodi, 2017). Bentley et al. (1985, p.9) as good urban design indicators, use the keywords of ‘*permeability*’, ‘*variety*’, ‘*legibility*’, ‘*robustness*’, ‘*visual appropriateness*’, ‘*richness*’ and ‘*personalization*’. However, they are flexible, not so clear and mostly intuitive indicators that are in need of scientific validation.

Wholeness as a normative concept has been densely studied by C. Alexander in profound details mostly borrowed from biological, naturally or culturally self-organized and organic systems and textures. However, even in pure spatial perspective, the notion of wholeness is still vague and subjective. Starting from there, the purpose of this research is to develop an alternative analytical method that can measure and explain the parts & whole-interactions-dependent relational nature of the urban built environment in relation to their larger contexts through various levels of investigation. Doing so will allow developing measurable and objective terms in spatial assessment for various purposes. Such measurable and objective terms are promising to help understanding struggles between analytical (quantitative), and synergistic (qualitative) relationalities of space and relevant urban design theory and approaches.

Scholars claim, using the small and large system pieces, every geographic space has a scaling pattern, and when visualized properly, this pattern can extract a unique sense of beauty (Jiang & Sui, 2013). Jiang and Sui (2013) also state that "there is a beauty, a new aesthetic, at a deeper structural level and differs in essence from the intuitive sense of harmony, perceived concerning color, shape, texture and ratio." Christopher Alexander is the one who initially defined this kind of beauty in his masterwork of "*The Nature of Order*" (2002-2005). Alexander wanted to develop a mindset with real-world-based references rather than artistic concerns.

A perfect randomness creates fractal systems, a perfect typicality across scales, in the nature. Clouds, mountains, coastlines, cauliflowers, and ferns are all natural fractals. These shapes have something in common - something intuitive, accessible and aesthetic. The resulting system is built upon a single deterministic rule and using it persistently around one and only developed cell leads to the emergence of a highly systematized system as in Figure 1. It generates a regular and self-similar or fractal pattern across various scales (Batty M., 2004, p. 5). However, fractals as perfect systems are easy to be deformed. When the expansion is not based on the unique deterministic rule at some point of the expansion the morpho-information is altered.

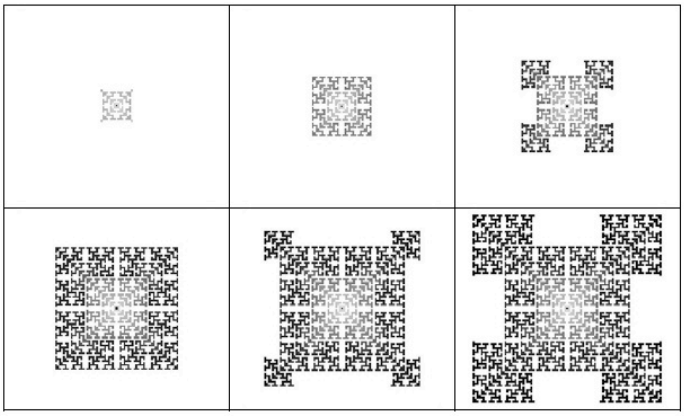


Figure 1 : Idealized development pattern (Batty M., 2004).

According to scholars the perfect symmetry of such town-scaled idealized alignments are highly fragile (Batty M., 2004). The consecutive and random probability of self-positioning makes the city grow upon a complete pattern and non-fragmented way. Thus, there is a great allometric* balance, *(a relative growth of a part concerning a whole body), under the chaotic scheme of the layout as in Figure 1. However, any attempt to turn such perfectly organized layout into a random mode may immediately lead to a self-organizing, organic and amorphous mass, which we see in Figure 2.

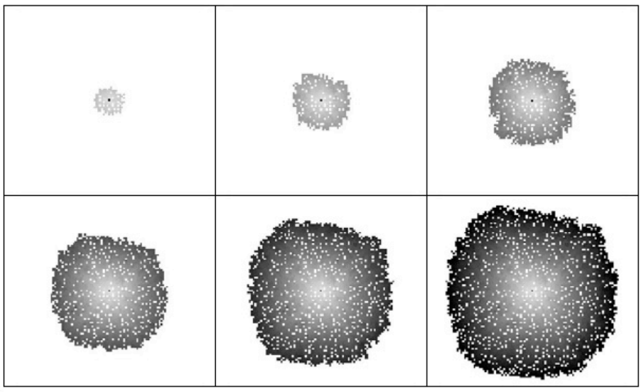


Figure 2 : Random and bottom-up urban development form (Batty M., 2004).

Las Vegas has experienced remarkable growth over the past fifty years (Xian, Crane, & McMahon, 2006) compared to the growth rate of the first half of the last century which was realized at a relatively slow rate. Growth patterns in different periods did not look morphologically diversified and were almost same as in Figure 2. However, the changes occurred dramatically from the inside. The city has assumed the mission of being the entertainment and gambling capital of the U.S. Clark County, in the south of Las Vegas Valley, as of the 2010 census, had a population (United States Census Bureau, 2014) of 1,951,268 while the number was 741,459 in 1990. New employment in the tourism industry accelerated the sharp population growth. Fifty years of steady and continuous growth of Las Vegas exposed relatively similar peripheral expansion patterns in different periods (Batty M., 2004) as in below Figure 3.

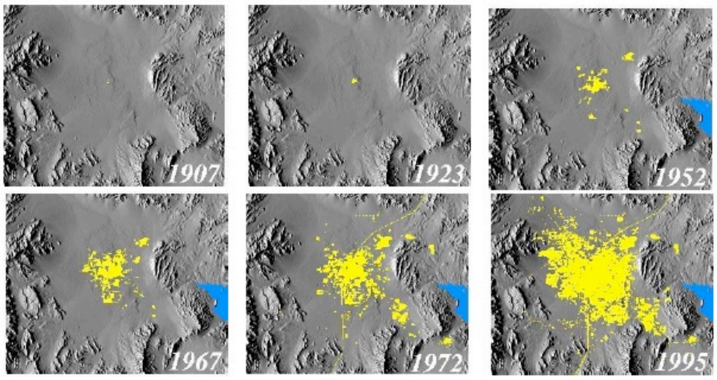


Figure 3 : The growth pattern of Las Vegas from 1907 to 1995 (Batty M., 2004).

Las Vegas' growth experience shows that cities are in fact represented by simple fingerprints-like structural patterns that are repetitive and applicable under different temporal and spatial conditions. This sort of urban development is a type of bottom-up development process where there is a recurring similarity between large and small structures (Batty M., 2004). Briefly, one can say that the way cities experienced a bottom-up no-plan growth, reveal a self-emerging fractal process that implies a degree of wholeness. Entire city starts to grow from a single very first pattern and bodily turns into a complex self-recurring system where the core pattern applied in a vastly diversified structural coalescence.

3. Proposed Method and Data

Alexander's (2002-2005) overall idea of wholeness through the relative position and interaction of the possible centers is figuratively depicted in fifteen properties. Neler onlar? Fifteen properties are the illustrative ways about centers' interactions with each other in embodying a degree of wholeness. In other words, a "property," as a relative positioning, in Alexander's texts, is a fundamental informative characteristic for wholeness (Waguespack, 2010). Either used in a single way or a context of a multitude of patterns, a property is critical in forming a space "life" and generating a "living structure." In another definition, the generative role of a pattern in situating the centers and creating "life" is the process of making a "living structure" (Alexander C., 2002, p. 4). In questioning and defining the ways that the life occurs, Alexander asks: "Can we find any recurrent geometrical structural features whose presence in things correlates with their degree of life?" (Alexander C., 2002-2005, p. 144).

This study suggests that the properties can act like guidelines not only for setting a new order from scratch but also to translate the existing complexities. Through this purpose, each property can be algorithmically coded as the rule of a spatial translation in examining how centers of an existing built complexity come together and help each other for evoking life in various scales. Alexander states that properties make things have a life because they are how centers can help each other in space for making a superior whole (Alexander, 2002-2005).

In this research, the parameter property that has been coded as a data-acquisition rule is the *“Levels of Scale.”* Coding the *Levels of Scale* property in an algorithm as a parameter for data-mining function out of an existing topologic context is simply setting a hierarchy between large and small modules in a system. Considering that centers may exist in a variety of sizes, *Levels of Scale* property explains that a strong center is partly defined by smaller, partly larger centers contained by a composition.

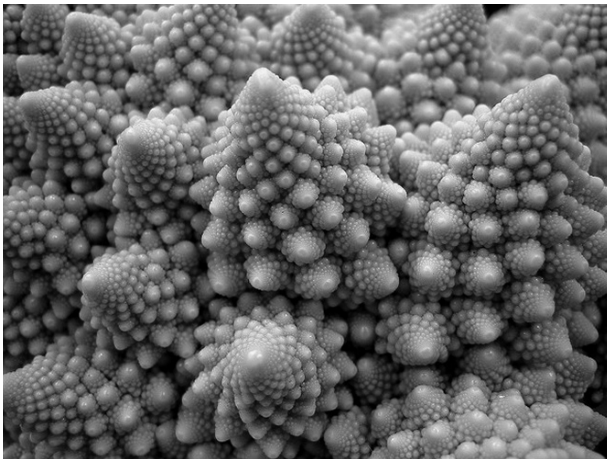


Figure 4 : A romanesco broccoli’s recursiveness in distributing the sub-centers

To understand *Levels of Scale* concept in a comprehensive way, one needs to observe how endlessly a romanesco broccoli is recursive in distributing the sub-centers in making the ultimate form proportionally perfect as in Figure 4. This variant form of cauliflower is the ultimate fractal vegetable. Its pattern is a natural representation of the Fibonacci or golden spiral, a logarithmic spiral where every quarter turn is farther from the origin by a factor of phi, the golden ratio. In such a complex order, there is a great hierarchy. Alexander notes that it is not hard to see that in any systems where there is a good functional order, there is also a degree of wholeness through a good spatial coherence with a legible hierarchy (Alexander, 2002-2005, s. 246). In other words, such complexity suggests a bilateral coherence and hierarchy that makes the spatial and functional space one whole thing.

Starting from this holistic view, proposed method measures and articulates, using Shannon’s Information Entropy (H) as a measure, the degree of wholeness for a particular built context throughout a multi-scalar dynamic grid’s units. Depending on the selected scale level in proposed method, the equivalent units of the grid system will get smaller or bigger each time and scan different size of areas in data-mining. The result is the translation of the built environment using two co-dependent attributes – G (pixel level based built probability) - and – H (maximum adjacency - 9 units - based entropy specific for that pixel level) - generated in the data-mining process and corresponds to the morpho-information of the analyzed area, in other words, translated from one language to another, at multiple pixel-levels. In brief, this method offers an alternative approach for measuring the wholeness of “multi-scalar relationality of multi-adjacencies” for the built environment analytically.

4. Using Shannon Information Entropy in Measuring Spatial Formations

Entropy concept was first used as a term of thermodynamic systems in the nineteenth century. The second rule of thermodynamics says that every living or nonliving system has an amount of free energy, and it always moves towards equilibrium (Bailey, 2015), which the entropy increases to realize. 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 ordered and regular one (Shannon, 1948). There 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 collapse and death. Briefly, energy or substance in nature cannot be vanished but evolve from one state to another. Entropy is the measure of this evolution or transformation as graphically illustrated in Figure 5.

Figure 5 : From the order to disorderliness: a graphic definition of entropy.

In addition to thermodynamic entropy, information entropy was first introduced by mathematician Claude Shannon (1948) as a basic concept in information theory measuring the average missing information on a random source (Jat, et al. 2007). Shannon's entropy, originated from information theory, is 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 and 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 the number of categories conveyed by a particular information, less probability of the same type of categories to gather. High entropy is the most probable, and yet the least predictable state that leads to disorder (Versoza & Gonzales, 2010), (Bailey, 2015). Hence, in such case, the entropy is always towards most probable or most likely state. When the entropy is the highest, the data categories embedded in the information get to the most random state where the most uncertainty occurs.

The same approach is also valid for the urban built environment. Thus, Shannon's entropy is convenient in measuring the uncertainty of morphologic occurrences in urban settings in various scale levels. The use of Shannon's entropy in this research is expected to provide insights into the notions of randomness, typicality, and disorder about the hidden codes of the morphologic occurrences in cities.

In urban built context, employing the entropy concept is expected to find out the state of randomness and disorderliness nested in the relative distribution of built elements of all kind. The method of this research employs the mathematical concept of Shannon's entropy, helps to generate values for each grid unit as spatial attributes. Measuring the built clusters and comparing one to another in changing scales is the basis of the proposed method in understanding the interplay between scale and changing level of spatial uncertainty. Shannon's entropy in this respect has a critical role in translating and reproducing the data and providing a new insight or tendency towards disorderliness, about the nature of the analyzed morphologic co-occurrence. According to Leibovici (2009), use of Shannon's entropy on the bare distribution of a particular number of data categories with different configurations does not help to describe the entropy of each configuration. Scholars in this respect suggest integrating some specific spatial aspects or control definitions into the entropy calculation (Leibovici, 2009). Shannon's entropy was derived from information equation (Wang, 2016).

Information equation is formulated as:

$$I(p) = -\log_b P \tag{1}$$

P is the probability of the event happening

b is the base and the unit of measurement generated by the base 2 in information theory is bits.

An exemplary calculation of the information by tossing a coin:

There are two probabilities for a coin and they are 0,5 head and 0,5 tail. If we toss the coin and get either head or the tail, we get 1 bit of information as in the below equation and graph appears; $I(\text{head}) = -\log_b(0.5) = 1\text{bit}$

Maximum entropy is achieved when all probabilities are equally likely and there is no ability to guess. It is, in other words, the case of maximum surprise. In the case of a coin, the probability is 0,5 both for head and tail. It makes the uncertainty and thus the entropy maximum that is 1bit as appears in below graph in Figure 6. Minimum entropy occurs when one symbol is certain and others are impossible as in the graph. In other words, when there is no surprise, there is no uncertainty.

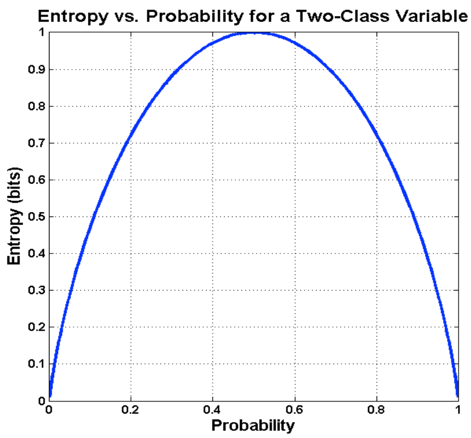


Figure 6: Entropy vs. Probability for a two-class variable in case of a coin toss.

In physics, the word entropy has important physical implications as the amount of "disorder" of a system. In mathematics, a more abstract definition is used. The (Shannon) entropy of a variable X is defined as bits, where $P(x)$ is the probability that X is in the state x, and $P\log_2 P$ is defined as 0 if $P=0$. The joint entropy of variables $X_1,\dots\dots\dots Xn$ is then defined by

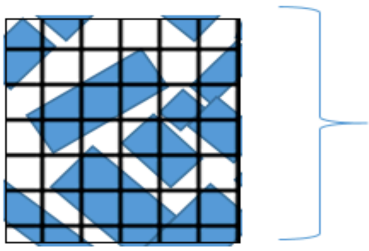
$$H(X) \equiv -\sum_x P(x)\log_2[P(x)]$$

$$H(X_1,\dots,X_n) \equiv -\sum_{x_1}\cdots\sum_{x_n} P(x_1,\dots,x_n)\log_2[P(x_1,\dots,x_n)].$$

Certain information with plenty of information types is most likely to lead to high entropy and thus a high level of uncertainty. Bailey (2015) states that Shannon’s entropy is content-free and can be applied to measure any data type with a multiple information. Entropy concept with a rising trend has been employed in diverse design-related disciplines. Krampen (1979) and Stamps (2003) used entropy method in measuring the data belongs to the façade elements to measure and evaluate their behaviors. Measuring the information, thanks to the developments in big data storing & processing technology, is becoming one of the central topics in architecture, art, and urban studies that are dealing with multivariate nature of big data and data-intense technologies (Ratti & Offenhuber, 2014). Entropy approach in this sense serves as a device for measuring the visual-diversity-related information.

According to Allen (2008), field conditions in the built environment are relational and yet they are based on interval measures. From the relational wholeness point of view, using Shannon’s entropy, through a multi-scalar grid, is convenient in measuring the uncertainty embedded in various morphologic possibilities. Shannon’s entropy in this sense is expected to provide insights into the wholeness of these spatial possibilities across scales. The novelty in this proposal is about making this kind of questioning via considering the immediate proximities or contiguities systematically. This kind of relative investigation is performed by a grid as a data-mining interface. The grid acts as a data-translation interface in translating the vector data into digitized data.

Gravity models in spatial studies owe its name to the analogy between the gravitational interaction among the planetary bodies that rely on two fundamental factors: scale and distance (Haynes & Fortheringham, 1984). In this study, built density falling into each unit area throughout a grid is termed as G referring to the specific gravity in material science (Wardlaw, G; McAllister, A. S., 1933) and in the science of spatial relatedness (Beenstock & Felsenstein, 2012). In other words, it is the ratio of built density to a specific area and thus the pressure and the compress created within a grid unit in this study as shown in Figure 7. Beenstock and Felsenstein (2012) state that gravity in spatial interaction studies simply sets upon a logic of bilateral flow of spatial push and pull factors based on scale and distance.



0,82	0,72	0,03	0,00	0,49	0,22
0,82	0,0	0,20	0,86	0,09	0,62
0,02	0,75	0,99	0,40	0,83	0,42
0,05	0,88	0,26	0,80	0,88	0,52
0,03	0,43	0,92	0,47	0,53	0,32
0,80	0,48	0,88	0,92	0,50	0,90
0,42	0,82	0,72	1,00	1,00	1,00

Figure 7 : G values, unit-based built probabilities, throughout a grid.

“G” as unit-based built probability and Shannon’s Information Entropy (H) by definition are two co-dependent spatial terms in the proposed method. G is termed to be the measure of scale-based built density for each unit as illustrated in Figure 8 upper row and formulated in the below equations. Entropy, on the other hand, is the measure of uncertainty that each grid unit holds considering connected units as illustrated in Figure 8 lower row G for a built context implies scale responsiveness and is generated for every particular grid unit area while H is generated for any unit area that is a neighbor to eight connected equivalent units. It is simply the entropy emerged through the relative interaction among a particular unit area and its adjacent neighbors and is formulated in the equations (1), (2), and (3) in below.

Referring to Shannon’s entropy as formulated in below equations (1), (2), and (3),

Given *i* is a central unit adjacent to 8 equivalent units, *n* is the 9 adjacent units that form square sub-regions throughout the grid system. G_i, for the i^{th} unit of the *n* units of a sub-region in grid system, is the unit-specific built portion. P_i is the built portion by the unit *i* divided by the total built portion of the nine units sub-region where *i* is the central unit. For instance, as in Figure 3.2, the entropy (H) for the 9-units sub-area where G5 it the central unit with G5 value. P_i is that G5 is divided by G1, G2, G3, G4, G5, G6, G7, G8 and G9 values. P_i multiplied by logb(1/P_i) where the base for the logarithm is 2. H_i is calculated by taking the sum of each of the nine P_i values in the 9-units system.

Maximum adjacency in Figures 8 and 9 refer to the rule that for each unit that is adjacent to 8 connected units can only be calculated P. In other words, the units by the grid edges are exempted in entropy calculation as illustrated in Figure 9 since they do not meet this criterion.

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

$$P_i = G_i / \sum_i^n G_i \qquad (2)$$

$$H_i = \Sigma P_i \cdot \log(\frac{1}{P_i}) \qquad (3)$$

Each grid unit in Figure 8 matches a particular space and thus a particular portion of a morphologic occurrence represented by a G value. If a unit partially frames a building or a group of buildings, the algorithm as in equation 1, assigns a ratio for the area of the built part divided by the total unit area depending on the scale of the grid. It assigns G=0 when the unit area is totally no-building, and G=1 when it fully frames a building or group of buildings.

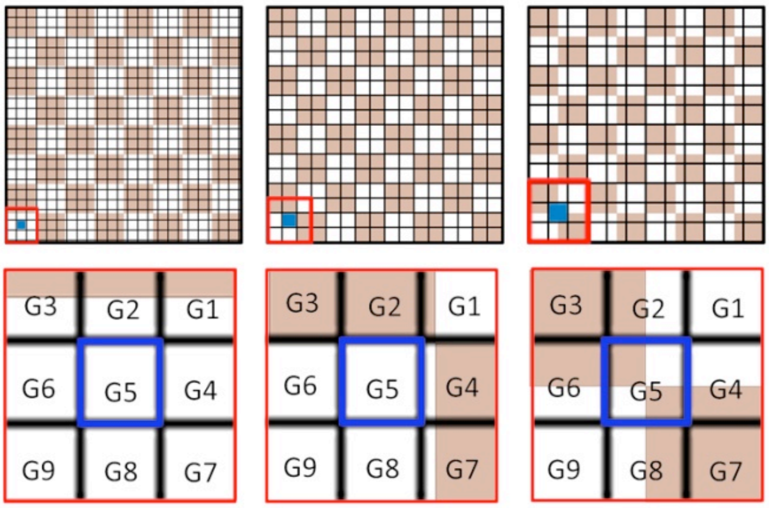


Figure 8 : Unit positions and their interactions with adjacent units in the calculation of G, P and H values.

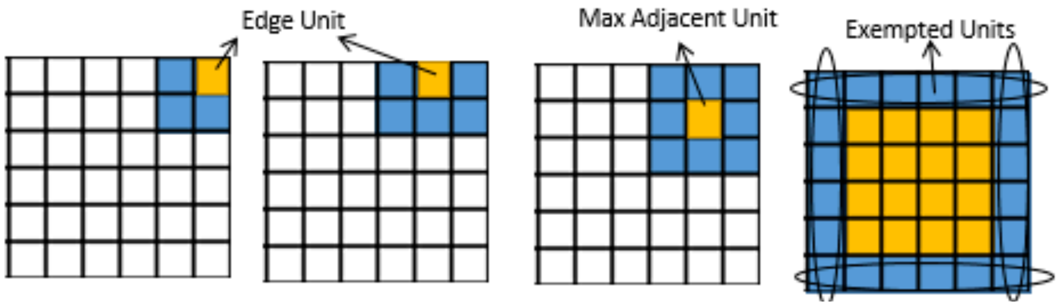


Figure 9 : Exempted units since they do not meet the maximum adjacency rule in calculating the P values.

IQR (Interquartile Range) is a statistical data measuring method that does a discretization for the data with different spreads. It arranges the values from the smallest to the biggest. For discretization of the deviations along the data, IQR plays a role in extracting the “middle fifty” where it draws a specified data as graphed using the Box and Whisker Plot in Figure 10. The extremes of the data eliminated, and it is where the bulk, middle fifty, of the data falls in. It is preferred over many other measures of spread in statistics when reporting about multivariate data sets. Because each output is scale-dependent, the ranges of the quartiles change as the scale of the analysis changes. In other words, each IQR for a specific scale relies on the changing morphologic states that are framed by different size of grid units. By the IQR method, each output dataset is reduced to a single value. Multiple analyses for varying scales allow generating multiple IQRs.

The total sum of Entropy-IQRs that have been generated for various scale levels gives the outcome of the study. Knowing the values of quartiles, Q1 and Q3, has critical importance. The position of the quartiles, between 0, 00 and 1, 00, can be highly distinct, somehow close to each other or juxtaposed which at the end explains how the IQR is created in fact. When the quartiles are located distinctly far from each other, IQR gets a higher value. This also points to the deviations that exist along the entropy dataset. The remarkable deviations in the dataset point to the remarkable differences among the morphologic formations framed by the grid units, in other words among the G values, unit based built probability. The differences gradually affect the P as mentioned in above equation (2) , the relational probability of total nine adjacent units as seen in above, and thus the entropy (H) value in equation (3) explained above.

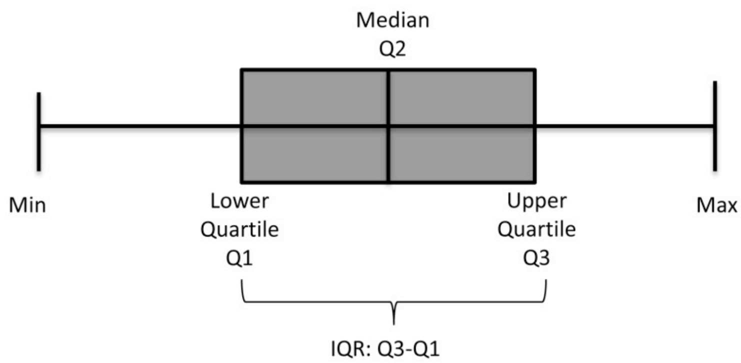


Figure 10 : Generating of IQR statistical value for a multivariate dataset.

Case Study Area: World Trade Center Area in Lower Manhattan, layouts before and after 9/11

A 14.6-acre (59,000 sqm.) built area in Lower Manhattan in New York City has experienced a major spatial change due to devastating terrorist attacks on September 11, 2001. The attacks destroyed and changed the entire morphologic structure of the area. The area which is bounded by Vesey Street to the north, West Highway to the west, Liberty Street to the south and Church Street to the east belongs to the Port Authority except the World Trade Centers. In 2002, the Lower Manhattan Development Corporation (LMDC) announced a competition for a master plan to redevelop the 16 acres area (libeskind.com, 2016). Studio Daniel Libeskind, with various stakeholders, developed a master plan revitalizing the historic grid and increasing the number of public spaces reinforcing the place memory for a mixed-use vibrant urban area characterized with high-tech office towers (libeskind.com, 2016). Revitalization of a 200-foot continuance of street and sidewalk along Greenwich Street which did not exist since the 1960s is a significant urban intervention reshaping the street layout of the area and its vicinity. As shown in Figure 11, the entire redevelopment brought a remarkable change in the urban layout of the area, and it will be completed soon (libeskind.com, 2016). A larger area, approx. 130 acres (500,000 sq. m), that has been selected for the analysis includes WTC buildings, memorial park, and the new train station.

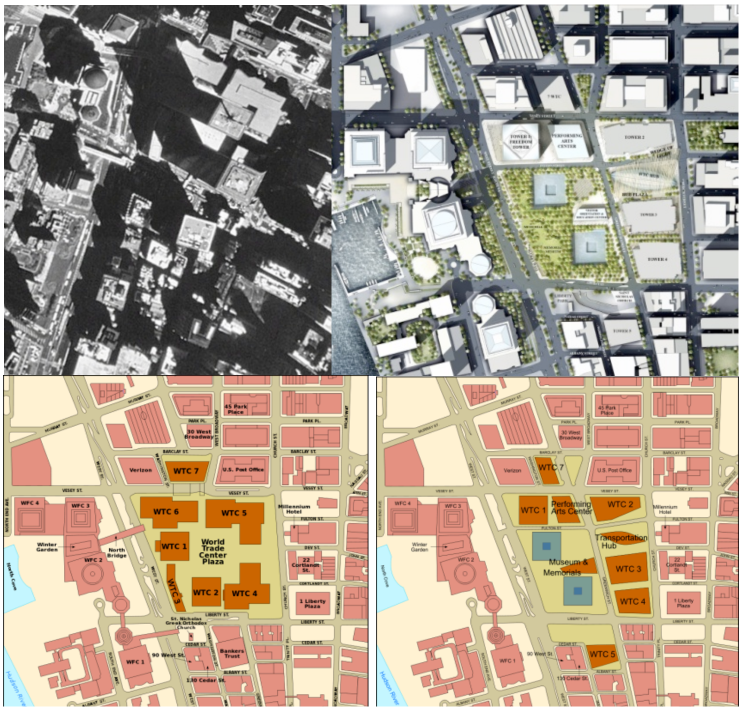


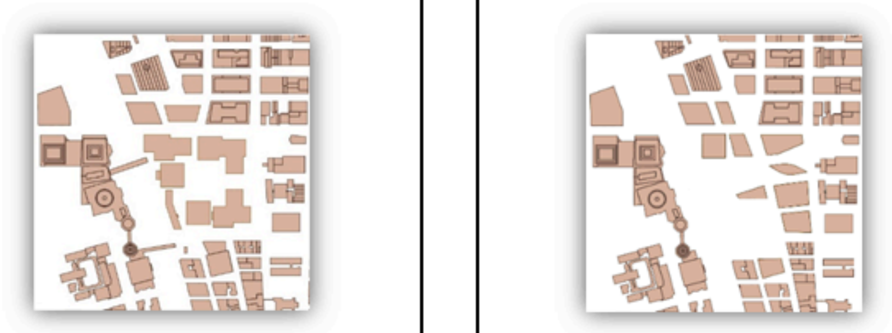
Figure 11 : Left 2: WTC are and its vicinity in Lower Manhattan before 9/11. Right 2: Ground Zero and its vicinity with New WTC master plan (Url-5).

The spatiotemporal analysis has been performed upon the morphologic states of (1) Before the 9/11 and (2) The spatial layout based on the Libeskind’s master plan, in Figure 11, to be completed soon. The case area, approx. 130 acres (500.000 sq. m), has been analyzed using 1024 x 1024 pixels with 1-meter pixel resolution building footprints vector data as seen in Figure 12.

For both case analyses, ten types of grid scales, with regular increases from 1/100 to 1/1000, have been used in generating datasets for varying pixel levels as seen in Figure 13. Results, as shown in below are used to generate unit-specific G color-coding visualizations as seen in Figure 14 and

Multi-scalar Analysis (MSA) graphs that helped to generate H-Min & H-Max graph, H-Median & H- Min Graph and H-IQR graphs as in Figure 15.

H-IQR graphs indicate that the Mean H-IQR for the pre-9/11 case is 0,81bits while it increases to 1,15 bit for the new spatial layout. The entropy of the site has increased. Two types of spatial intervention recreated the entire site: a new spatial order and the volumetric relationship among the buildings, and the revitalization of the Greenwich Street between Fulton and Liberty Streets. The area is predominantly characterized as a dense high-rise urban area configured by the skyscrapers. Considering that proposed method performs the analysis using two-dimensional spatial layout, the area’s outstanding high-rise character remains disregarded. This situation puts the results into question in the sense of whether or not the dominant character of the area is its spatial layout and the new street network or the entire 3D character in developing the sense of wholeness from the users’ perspective. Applying Shannon’s Entropy via considering the three dimensionalities of the area requires a new methodological approach using additional input data such as building floor areas and building heights. When comparing to the perfectly systematic grid-iron street plan in the north of the Houston Street, Lower Manhattan’s irregular and the cramped street system is due to the uncontrolled development and a decade of public health epidemics (Jaffe, 2011). Nevertheless, Lower Manhattan is a densely built urban area. Considering the relative positions, size and shapes of the buildings in pre-9/11 layout, one can comfortably tell that not only the entire configuration but also the overall built density of the area has decreased in the new master plan. Such kind of complete change obviously affected no matter positively or negatively, the scaling hierarchy of the area and thus the nature of the quartiles, Q1 and Q3 for before and after situations, generated for the analysis. This is quite relevant and supporting the hypothesis of ‘even one single entity can change the overall level of wholeness in the entire connected built context across the scales.’ The diameter of the change of the wholeness is about the scale of the investigation. In other words, the scale of the analysis determines if the effect of the change in adjacent units is significant or insignificant. Looking at the quartiles in Tables 1 and 2 in a closer inspection, one can easily say that there is a slight decrease in Q3 values that lead to a small increase in H-IQR mean value for the master plan based layout. Such amount of increase is no significant change. However, the overall morphologic system of the area has been re-characterized through a new architectonic order.



Case Study 13-3
Pre 9/11

Case Study 13-4
Post 9/11

Figure 12 : A 14.6-acre (59,000 sqm.) built area in Lower Manhattan in New York City has experienced a major spatial change due to 9/11 terrorist attacks.

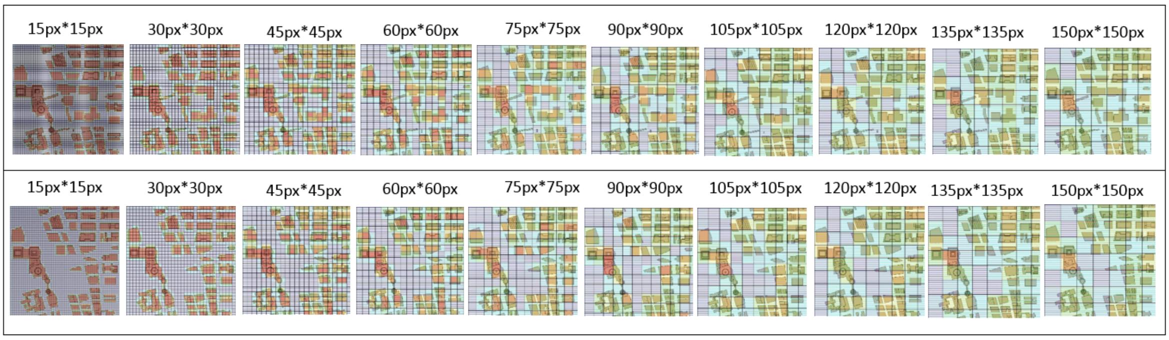


Figure 13 : Grids for varying scale levels superimposed upon the pre-9/11 (Up) and post-9/11 (down) morphologic formations of the same urban area.

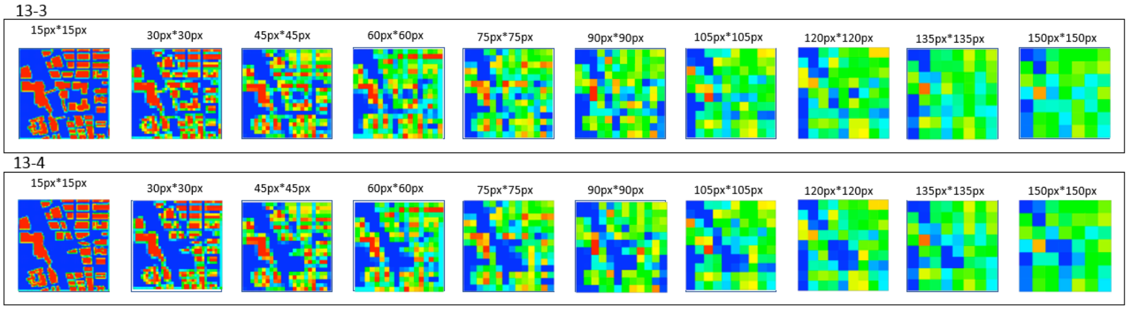


Figure 14: Unit-specific G color-coding visualizations for pre-9/11 (up) and post-9/11 (down) layouts.

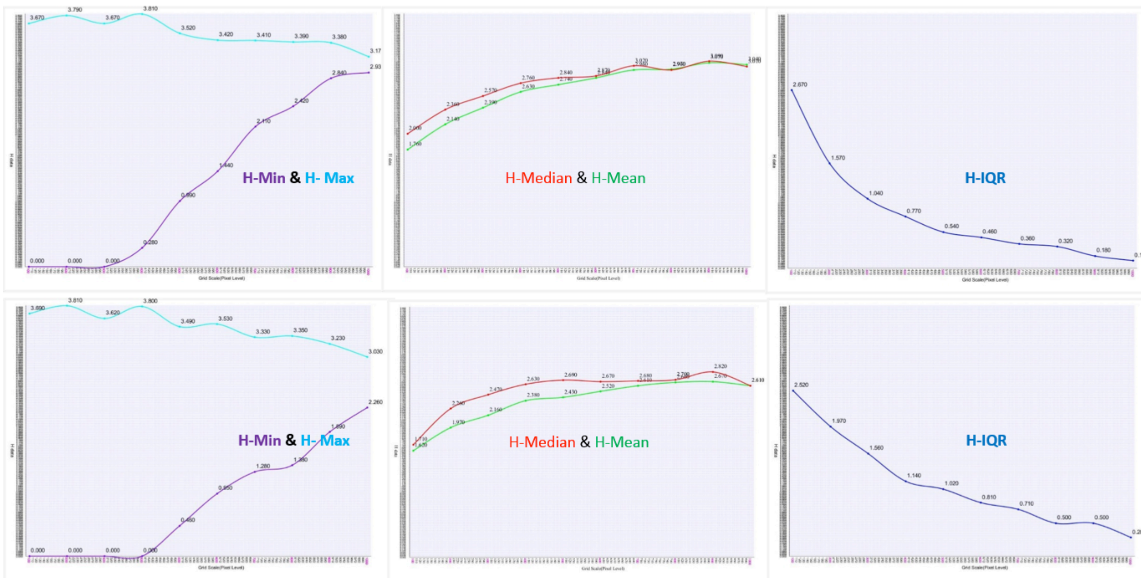


Figure 15 : Graphs for h-min & h-max, h-mean & h-median and h-iqr values generated through the analyses by multiple pixel levels for pre-9/11 (up) and post-9/11 (down) morphologic formations.

Table 1 : Graphs for h-min & h-max, h-mean & h-median and h-iqr values generated through the analyses by multiple pixel levels for pre-9/11 morphologic layout.

Grid Scale	Pixel Level	Total Cell	NA Cell	G-IQR	Q1	Q3	H-Mean	H-Median	H-IQR	Q1	Q3	H-Max	H-Min
100	15*15	4761	272	1.000	0.000	1.000	1.760	2.000	2.770	0.300	3.070	3.680	0.000
200	30*30	1225	136	0.860	0.000	0.860	2.140	2.360	1.550	1.450	3.000	3.800	0.000
300	45*45	529	88	0.695	0.030	0.725	2.390	2.570	1.040	2.000	3.040	3.670	0.000
400	60*60	324	68	0.510	0.155	0.665	2.630	2.760	0.770	2.340	3.110	3.800	0.280
500	75*75	196	52	0.465	0.180	0.645	2.740	2.840	0.540	2.550	3.090	3.520	0.990
600	90*90	144	44	0.490	0.150	0.640	2.840	2.870	0.460	2.680	3.140	3.410	1.430
700	105*105	100	36	0.360	0.220	0.580	2.960	3.020	0.360	2.820	3.190	3.390	2.100
800	120*120	81	32	0.330	0.250	0.580	2.970	2.960	0.310	2.860	3.170	3.410	2.430
900	135*135	64	28	0.280	0.280	0.560	3.070	3.090	0.180	3.000	3.170	3.380	2.850
1000	148*148	49	24	0.320	0.260	0.580	3.040	3.010	0.110	3.000	3.110	3.170	2.930

Table 2 : Graphs for h-min & h-max, h-mean & h-median and h-iqr values generated through the analyses by multiple pixel levels for post-9/11 morphologic layout.

Grid Scale	Pixel Level	Total Cell	NA Cell	G-IQR	Q1	Q3	H-Mean	H-Median	H-IQR	Q1	Q3	H-Max	H-Min
100	15*15	4761	272	0.960	0.000	0.960	1.620	1.710	2.970	0.000	2.970	3.680	0.000
200	30*30	1225	136	0.790	0.000	0.790	1.970	2.260	1.960	0.990	2.950	3.800	0.000
300	45*45	529	88	0.670	0.020	0.690	2.160	2.470	1.560	1.420	2.980	3.610	0.000
400	60*60	324	68	0.540	0.085	0.625	2.380	2.630	1.140	1.890	3.040	3.800	0.000
500	75*75	196	52	0.595	0.045	0.640	2.430	2.690	1.020	2.030	3.050	3.500	0.460
600	90*90	144	44	0.565	0.060	0.625	2.520	2.670	0.810	2.240	3.050	3.530	0.950
700	105*105	100	36	0.410	0.170	0.580	2.610	2.680	0.690	2.380	3.070	3.330	1.290
800	120*120	81	32	0.410	0.180	0.590	2.660	2.700	0.520	2.510	3.030	3.350	1.360
900	135*135	64	28	0.365	0.210	0.575	2.670	2.820	0.510	2.500	3.010	3.240	1.900
1000	148*148	49	24	0.345	0.195	0.540	2.610	2.610	0.280	2.580	2.860	3.030	2.270

Results and Conclusion

The method developed in this research, as an explorative approach reveals the bottom-up multivariate nature of morphologic emergence that unearths and articulates, in its terms, the hidden order throughout a multi-scalar grid's faces. The resulting cartographic language is not for idealized models but instead a highly varied topography for two attributes - G and H - that expose several morphologic co-occurrences at multiple-scales and diverse part-whole expansions. In brief description, this method offers an alternative approach for decoding bottom-up morphologic behaviors of cities for scientific measuring and testing of spatial change from the relational wholeness points of view.

The proposed method is innovative in two aspects: 1) Performing a data-classifying process based on a particular rule upon the targeted data category (buildings) and generating two co-dependent attributes 2) Translating the findings into a cartographic language specified by the distribution of described characteristics. - G -, scale-based built probability and H, entropy, scale-dependent spatial uncertainty. The ultimate purpose of this research, parallel to Alexander's assertions on the concept of wholeness, is to define the way in which G and H relatively behave in shaping a degree of wholeness for a certain built area. In doing so, it becomes possible to test and expose how the level of wholeness might be formed differently when the parts change in a grid system of different scale level.

Briefly, below outcomes have been obtained from the World Trade Centre Area case study:

Results, as shown in MSA graphs in Figure 15, indicate that the H-IQR mean value for the pre-9/11 case is 0,81bit while it occurs as 1,15 bit for the new spatial layout. The entropy of the site has increased. Two types of spatial intervention recreated the entire site: a new spatial order and the volumetric relationships among the buildings, and the revitalization of the Greenwich Street between Fulton and Liberty Streets. The area is predominantly characterized as a dense high-rise urban area configured by the skyscrapers. Considering that proposed method performs the analysis using two-dimensional spatial layout, the area’s outstanding high-rise character remains disregarded.

Nevertheless, Lower Manhattan is a densely built urban area. Considering the relative positions, size and shapes of the buildings in pre-9/11 layout, one can comfortably tell that not only the entire configuration but also the overall built density of the area has decreased in the new master plan. Such kind of complete change obviously affected no matter positively or negatively, the scaling hierarchy of the area and thus the nature of the quartiles, Q1 and Q3 for before and after situations, generated for the analysis. This is quite relevant and supporting the hypothesis of even one single entity changes the overall level of wholeness in the entire connected built context across the scales. The diameter of the change of the wholeness is about the scale of the investigation. In other words, the scale of the analysis makes the effect of the change in adjacent units significant or insignificant. Looking at the quartiles in Tables 1 and 2 in a closer inspection, one can confidently say that there is a slight decrease in Q3 values that lead to a small increase in H-IQR mean value for the master plan based layout. Such amount of increase is no significant change. However, the overall morphologic system of the area has been re-characterized through a new architectonic order. This fact, by all means, implies that the overall visibility of the area changed.

The assertion of low entropy implies a high degree of wholeness is being supported by the findings derived from the analyses. Spatial change is relational and it mostly occurs and immediately affects the degree of entropy, as a quantitative state, and thus the level of wholeness, as a qualitative state, that the built area hold in its very own spatial formation.

The findings plotted through the MSA graphs for the case areas reinforced the outcome that any spatial change occurs in a particular built area alters the level uncertainty for each unit of area and its connected units of areas depending on the intensity of change. This co-affection gradually changes the degree of wholeness throughout entire grid system. The co-affection first occurs mostly by the connected units of built context and continues wave by wave over the continuing units in varying degrees

Considering that, there is a repetitive self-recurring or similar degrees of irregularity over successive scales in cities (Salingaros, 2005). Such morphologic occurrence is fragile and easy to be deformed. As an inference, in particular cases of Beyazit Square and Ground Zero Area, findings prove how spatial change altered and deformed the inner scaling laws and thus the cumulative degrees of wholeness in both areas.

Parallel to the hypothesis of the study, the outcomes prove that any change within the topologic body of any particular spatial formation deforms its scaling pattern in various scale levels and thus alters the entropic states. This causation gradually affects the degree of the wholeness of the system for the scale levels that the analyses performed. For both case studies, as shown in the Tables 1 and 2 and the graphs in Figure 15, the maximum H and H-IQR values occur at lowest grid scale levels (100 grid scale or 15px*15px) in another word at the lowest resolution. This outcome indicates that the relations between the units and their immediate 9-units context that they exist has the highest scale jumps and most varying G and thus P values. In another word, an investigation in most possible micro level leads to the highest entropic state since it is the degree where relatively the highest number of units capture the built entities, empty areas, and those transition areas. Such multiplicity creates a remarkable tension and it brings higher H values for the maximum adjacent sub-regions.

Briefly, similar to the method develop in this study, the science of cities requires analytical and data-driven methods that will consider the urban morphology as various information types and relationally measure it across scales from a perspective of parts & whole interactions. In doing so, we will not only visualize the way urban built form changes and the effects of these changes on other urban issues but also measure and calculate the value of this relational change mathematically.

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