Urban Porosity. A morphological Key Category for the optimization of the CAS's environmental and energy performance.

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***Abstract*—Although there are a lot researches on morphological studies of the city form, very scarce efforts have been applied to systemically comprehend and evaluate urban morphology using reliable metrics able to describe the formal properties of the city. More researches are needed in this direction for better understand the city form's characteristics and its performances. This paper illustrates Porosity seen in IMM as fundamental morphological characteristic of urban systems, integration of two basic components of urban space: Volumes and Voids. It aims to highlight the role of Porosity in the relationship between urban morphology and environmental-energy performances with objective considerations and evaluations of its characteristics based on values and indicators. Hence IMM as systemic methodology presents some key findings in this process to describe it objectively. This paper aims to presents an innovative way to estimate Porosity as a Key Category and anticipates its role in finding a correct balance between level of Compactness, Complexity, and Connectivity in the urban system (CAS). Actually in IMM balancing these determinants (resulting from the interaction of the Key categories) is considered the foundation of a best performing CAS (sustainable urban form) and any of them would not be sufficient on its own to achieve the result. (Abstract)**

Keywords: **Morphology, Urban design, energy, environmental performances, complex adaptive system.**

I. INTRODUCTION

We are living in an era in which cities play the most important role in socio-economic arrangements and the environment is also being affected most dominantly by urban life. Built environment is expanding fast and faster is growing the number of urban inhabitants. Today, more than half of the world's population is living in cities and it is estimated that this ratio will increase to 70 per cent by 2050 [1]. It means that if they are not being tackled now, the challenges we are facing today will be taken to more Intensity tomorrow, and even much more severe environmental risks and socio-economic conflicts are yet to arise. Currently, about 80 percent of the global primary energy is being consumed in urban areas, cities are being responsible of more than 60 percent of the total world's green gas emission [2], and the list of social issues in urban arrangements is endless. Cities are the economic engines of the world though, and by being on average responsible for more than 75 percent of a country's Gross Domestic Product (GDP) [3] their further expansion is an inevitable perspective.

In such situation, and especially in a time that sustainability has become the main development basis for all parts of economic communities, the need for defining sustainable approaches towards built environment is being felt more than ever. However, any attempt at introducing frameworks, tools or sustainable-oriented principals to be applied to developing (or even developed) contexts, demands a sophisticated understanding of the built environment itself. The very first step is to acknowledge the city as a system, and obviously, not an ordinary system but a complex one.

Cities are system zoos composed of numerous architectural, social and functional subsystems (each of them being a complex system itself) twisted with each other in a very complex manner [4].

Naturally, the overall behavior of the city -being the collective functionality of the subsystems- is related to their capacity and more importantly, the way they are connected to each other. The majority of the research carried out with the aim of studying the built environment's behavior considers these subsystems as independent entities; hence neglect the importance of the game changer action-reaction mechanisms inherent in their interconnections.

From an architectural viewpoint, if the scope is limited to the reciprocal form-environmental performance

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relationships, the direct involvement of cultural, social, and institutional systems might be unnecessary. Nevertheless, their footprint on forming processes and their indirect impacts on performing manners could be read easily.

In this framework, most of the urban components could be placed in a certain group of subsets categorized as morphological, typological, and technological systems [5].

Among the mentioned subsets, morphology and form-related systems stand in a particular position.

Morphology is the physical skeleton with which all the other city's subsets and their linkage are defined. It is the semi-solid platform for all the dynamic mechanisms that decide the performance of the city. In this regard, it should not be considered as a passive container, but rather an active ingredient with the most dominant taste.

There are valuable efforts in studying the performance of the urban settlements with regard to their morphology. However, in spite of presenting innovative frameworks of inquiry into the built environment's form, they did not succeed to address the link between urban morphology and the city's behavior in a clear manner [6].

In a profound study Huang and his team, [7] through cluster analysis classified 77 cities from around the word according to their spatial metrics. They have also tried to express the nature of differences in urban forms through comparing socio-economic developmental indicators, and they have concluded with declaring the bold irrelevancy of urban development formulas in developed countries to the developing ones. In another research, Nina Schwartz [8] attempted to sift through the indicators of urban form. In this research, she analyzed 231 European cities, and through correlation and factor analysis identified the most relevant landscape metrics and population related indicators.

The greatest issue associated with the mentioned studies is lacking in systemic view towards the urban settlements. This can be noticed most vividly in scaling and defining the patch areas.

In both cases, as well as in numerous other studies, patches are defined as separated islands, and the form of the city is being defined as the way they are arranged around each other.

Consequently, the inner morphologies of the patches have been studied less accurately, and the global effects of the local systems have been neglected. Whereas, from a holistic point of view, with consideration of links, functionality, and boundaries of the urban systems, patches could overlap with each other in a physically integrated way.

From this perspective, the mentioned studies have practically considered the city merely as an aggregation of the patches and neglected the variety of forms, interconnections and integration mechanisms in smaller scales, inevitably came to generic conclusions regarding the form of the cities [9].

This leads to another fundamental issue that causes the incapability of such research to directly address the relation of the city's performance to its form and through its architectural morphology (shape of the building blocks, the interface of the street networks, and the arrangement of the functions).

In this sense, they lack in morphology related attributes to connect the skeleton of the city to its environmental and socio-economic performances [10].

By focusing on the role of the local morphology in deciding the global performance, the aim of this paper is to present a holistic methodology for studying the form in built environment.

Complementary to analytic methods, this study adopts a systemic approach [11] for breaking down the urban settlements into their morphology generator subsystems, and introduces a synthesis mechanism for understanding the architecture of their links.

The ultimate goal is to find architectural attributes for explaining socio-economic and environmental behavior of the city directly through its morphology.

II. THE ROLE OF POROSITY

In this study, city is being considered as a Complex Adaptive System (CAS) [12], which similar to all other complex systems is decomposable into its consisting parts [13].

In Integrated Modification Methodology (IMM), the morphology generator subsystems of the built environment are recognized as: Urban Built up, Urban Voids, Functional, and Transportation [14] (Fig. 1).

Needless to state that the behavior of the city is more than sum of the functionality of the mentioned parts; therefore, the linkage between parts should be recognized too [15].

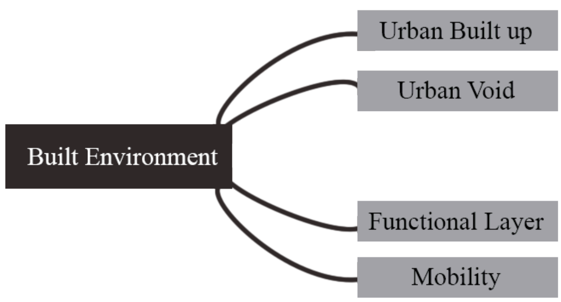

Figure 1. Urban Morphological Subsystems

IMM identifies 6 Key Categories with which the links between the city's primary subsets and ultimately the functionality of the whole system is being investigated.

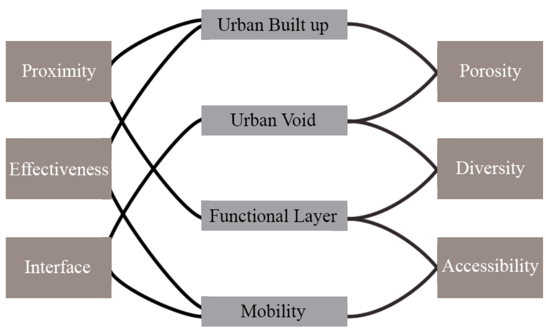

Figure 2. Morphological Subsystems and Key Categories

These Key Categories are basically resulted from the theoretical synthesis of the chief urban subsystems.
They are defined as Porosity, Proximity, Diversity, Interface, Effectiveness, and Accessibility (Fig. 2). Depending on the scope and their theoretical concept, different parameters could be used for studying each of them (table 1).

Table II-1 SYNTHESIS AND KEY CATEGORIES

Synthesis	KC	Explanation	Related Parameters
Void /Built-up	Porosity	The different arrangements between buildings and urban void	Built-up density (FAR), population density, average Size of Household, Block Size, etc.
Void/ Mobility	Interface	The quality of movement through the street network	The geometry of the street network, the boundary of the system, modes of street-level transportation, etc.
Function/ Built-up	Functional Proximity	The horizontal and vertical arrangement of the urban activates	Employment density, walkability, catchment areas, functional classification, distribution of the related functions, urban barriers, etc.
Function/ Void	Functional Diversity	The influence of the functional variety over the streets and public spaces	Employment density, functional time period, walkability, urban barriers, catchment areas, functional classification, etc.
Mobility/ Built-up	Effectiveness	The effectiveness of the public transportation nodes	Geometry of the streets, catchment areas, modes of public transportation, structure of the links, population density, employment density, etc.
Mobility/ Function	Accessibility	The accessibility of the key destinations	The structure of the links, the structure of the nodes population density, employment density, catchment areas, modes of public transportation, etc.

Among the Key Categories, the link between Porosity and the morphology seems to be the most tangible one. Outlining the interconnection of built ups and voids, porosity is the physical skeleton of the city that defines the quality of other syntheses.
The motorized traffic and pedestrian flow, the capacity and the patterns of functional distribution, the paths and the street networks and all the other urban arrangements are affected directly by Porosity.
In other words, the qualities of all the other key categories are decided with Porosity.
Hence, this KC could play the fundamental role in measuring the level of compactness in different urban areas.

III. ASSUMPTION

A. Case Study Selection

Some of the most important provinces of Lombardy have been targeted and in each of them three historically and therefore morphologically different context have been selected as follows:

- The historic City Centre (the historical part originally used to be included inside the urban walls).
- The urban development originated after the wall demolition (the city's expansion in the early modern ages).
- The most contemporary one morphologically characterized by fragmentation and sprawling phenomena as well [16].

B. Study Areas

The spatial limitations of the study cases are defined in accordance with the existing local boundaries within which homogenous morphologies lie.
These boundaries might be the old cities' walls for the historical centers, main roads for the planned cities and municipality limits or the end of the most recent developed parts for the outskirts. The study areas differ in dimension, and they range from 50 to 300ha.
The case study investigation and the 3D model development are based on the information on volumetric units provided by DBTR (Database Territorial Regional) of Lombardy.

IV. METHODOLOGY: DEFINITION AND APPRAISAL

"Porosity or void fraction is a measure of the void (i.e. "empty") spaces in a material, and is a fraction of the volume of voids over the total volume, between 0 and 1, or as da percentage between 0 and 100%".
Urban Porosity is defined variously in the existing literature, and in many cases, these definitions contradict each other [17].
By including the role of the urban density, volume, surfaces, heights, location, and distribution manner of the buildings, this study is trying to define porosity under a broad umbrella.
The chief aim of this study is to present the idea that as a complex morphological attribute, *urban porosity* could be explained only within the linkage of various morphological properties.
Any attempt in defining porosity with a sole numerical value merely reduces its vast qualitative meaning into a meaningless number, hence, leads to a critical loss of the morphological essences through an unnecessary simplification [18].

Rather, assessment of different urban characteristics could come to a fundamental help for simulating the morphological qualities of spatial settlements and elaborate urban porosity in a strong relationship with the complexity of the urban form.
In this study, six spatial assets of the built environment - namely Volume, Surface, Coverage, Distribution Factor, and Number of Buildings- have been studied and urban porosity is being explained through the relationships between them.
In the study cases undertaken by this research, these assets have been evaluated in accordance with their definitions and they are presented in a hexagonal diagram in which their proportional relationships can be compared and interpreted.

1) Volume

Evidently, the volume of the urban built-up and its relationship to urban voids are the decisive parameters of all the definitions that the urban porosity is evaluated based upon. The volume/void arrangement is the most immediate form-related attribute that defines and distinguishes the spatial characteristics.
Therefore, evaluating the relationship between built-up and empty spaces in a proper manner could result to achieve fundamental morphological information.
Similar to studying the Urban Heat Island Effect (UHI), here, the peripheries of the study areas have been decided according to the local Urban Canopy Layer, which is the warm layer of air, near the ground level.

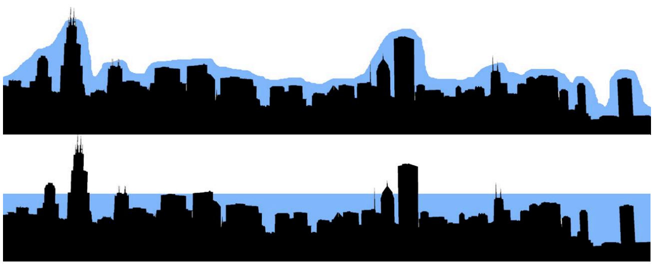

Figure 3. Visualization Of Urban Canopy Layer and Average Heigth

In this study, this evaluation has been carried out by calculating the ratio between the urban volume and urban voids.
In the study cases, the spatial arrangements assumed to be a closed volume containing built-up and empty spaces. For the sake of convenience, the Average Height of the Buildings ($\bar{X}h$) has been considered as the vertical limit of the study areas.
The Average Height of the Buildings, Total Volume of the Selected Site, and Volume of the Built Area are to be obtained as following:

$$X_h = \sum (A \times h) / \sum A \quad (1)$$

$$\sum (A \times h) = V_b \quad (2)$$

$$V_T = A_T \times (\bar{X}_h) \quad (3)$$

Where A, h, and V_b are respectively area of building's footprint, building's height, and volume of the built area.
Hence, Volume of the void area would be:

$$Vv = V_T - V_b \quad (4)$$

Ultimately, the Volume ratio (built-up/voids) can be defined as the following:

$$\text{Volume Ratio (\%)} = (V_v/V_T) \times 100 \quad (5)$$

Because of the sudden level increase in urban canopy layer, the highest of the Urban Volume belongs to the cases where occasional high-rise buildings exist in.
Thanks to the brownfield and rural areas, "Porto di Mare" has a considerable value of 90 percent among the case studies.

2) Surface

The volume ratio offers mostly numeric information and does not reveal much about the spatial forms defined by the layouts of the buildings. On the other hand, the building layouts by itself lacks in spatial information too. In Fig. 3 two alternative building arrangements having the same volume but different footprint are shown.

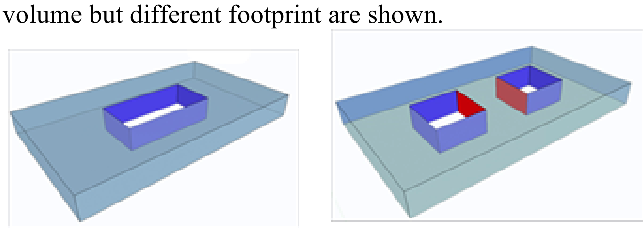

Figure 4. Alternative arrangements of buildings with the same volume

In order to include the shape of the buildings in studying porosity the exposed vertical surface of the buildings has been studied here. The effect of the vertical surface areas could be expressed by a ratio between the total vertical surfaces areas and sum of the vertical surfaces and the total land area of the study area, as follows:

$$S_v = \sum (p \times h) \quad (6)$$

$$A_T = A_b + A_v \quad (7)$$

$$\text{Surface Ratio (\%)} = (S_v / (A_T + S_v)) \text{ x } 100 \quad (8)$$

Where A_b, A_v, h, and p stand for total area of the building's footprint, total area of the void, building's height and building's perimeter respectively.
Alongside the volume ratio, the Surface value could deliver an assessment of the possible collective morphologies shaped by separated volumes. This value can be considered as an inverse shape factor.
The higher number of courtyards, the higher the surface value. Naturally, Milano's City center with an abundance of

central courtyards gains the highest Surface Value of 81 percent among the case studies.

URBAN DENSITY

Urban density is probably the most investigated value to evaluate the quality of built environment for accommodating people and activities.
However, being classically defined as the number of the occupants (residents or employers) in a certain area, it could not be considered as a good indicator of the urban morphology whatsoever [19]. Morphologically speaking, far different contexts could share the same value of urban density (Fig. 4)
In the present study, two different values have been investigated which in some extend could be considered as the morphological interpretations of urban density.
These values are Floor Area Ratio, Building Coverage Ratio, and Building Distribution Factor.

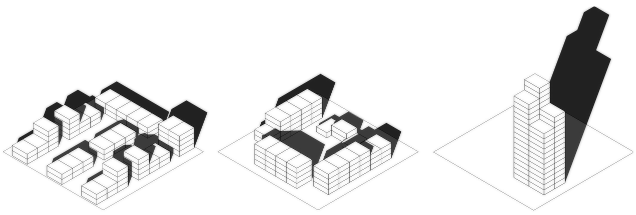

Figure 5. Same density distributed in high, medium and low building footprints

3) *Gross FAR*

FAR is the direct description of the urban density in terms of architectural morphology. It is defined as the ratio of a building's total floor area (gross floor area) to the size of the piece of the land upon which it is built [20].
In this study, the sum of the total floor area of the buildings in the selected site has been considered for the calculation of the FAR.

Figure 6. Tokyo, Black and white plan at different levels

Although it embodies a simple concept, it describes the shape and capacity of the buildings both in horizontal and vertical directions.

$$FAR\ (\%) = [(S_{ground} \times N_{floors}) / (5 \times A_T)] \times 100 \qquad (9)$$

4) *Coverage*

Building Coverage Ratio (BCR) is the size of the constructed buildings' floor in relation to the total size of the plotted land [21]. Similar to FAR, BCR addresses both morphology and density, and quantitatively describes the distribution of the buildings in a certain area.

$$BCR\ (\%) = (S_{ground} / A_T) \times 100 \qquad (10)$$

BCR and FAR are easy to be read and the relationship among them is mainly ruled by buildings' heights.
Milano city center has the highest value in both; considering the high density of historical fabric, this is an expected result.

5) *Number of Buildings*

For demonstrating the role of buildings' distribution on urban morphology, the Number of Buildings is also added to the indicators set presented in this study. Fig. 5 shows a comparison between two relatively extreme cases.
On left, West Bay in Doha with a rather high concentration of units in a few individual buildings offers the huge undecided void spaces; whereas, Venice, on the right side has much smaller buildings containing few units, and defining a myriad of narrow void spaces.

Figure 7. West Bay, Doha (left) and Venice (right)

To highlight this difference, the number of buildings per hectare has been considered which expresses the number of buildings with relation to size of the selected area of analysis.

$$\text{Buildings per hectare} = (N_{build}/A_T) \qquad (11)$$

This value could be normalized and expressed in percentage by considering 50% as the upper extreme for coverage and 100m^2 as the lower extreme for the buildings' average footprint.

$$NB\ (\%) = ((N_{build} / A_T) / 50) \times 100 \qquad (12)$$

Although this value does not reveal much when city scale is considered, it gives important information on the neighborhood and architectural scale, specially, about the quantity, and together with other values, the size of the buildings.
Together with BCR, this value indicates the variety in building facades, the location of the entrances and the morphological patterns of the area.
Interestingly, the Roman and the Modern districts in Brescia, which share the exact same values of FAR, and Coverage, rank reversely in this category.
The contrast between them is as bold as their NB value is 80 percent and 10 percent respectively.

6) Building Distribution Factor (BDF)

As many different urban contexts can contain the same number of buildings, it is obvious that the number of the building alone is not a clear form-related indicator and should be completed with another shape-oriented value. Therefore, in order to morphologically characterize the building arrangement, positions and the distances between buildings should also be considered.

Clustering the buildings with respect to their distances from each other has done in this research.

For each context, an optimum-covering radius has been identified, and the clusters form based on the resulted cover circles overlapping.

These clusters not only reveal the patterns of building arrangements, but also identify the authentic morphological boundaries.

Depended to both covering radius and morphology, the number of clusters may vary from one (in which all the buildings in that context are included) to the total number of the local buildings (in the case that the covering radius is so small that only includes the very building from which it centered.

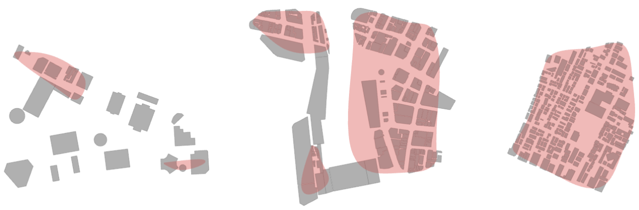

Figure 8. BDF map of different areas of Tokyo

Different values have been tested for the cover radius in this research study cases. When the radius approaches 20 meters, almost each building would be defined as a cluster; and on the other extreme, for the values close to 100 meters, all the building tend to be clustered in one group. Hence, for the sake of convenience, the cover radius is considered 50 meters here.

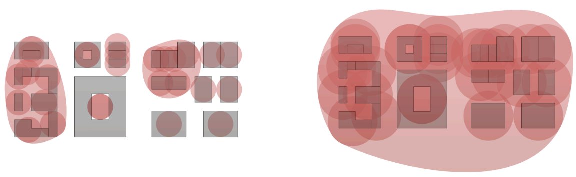

Figure 9. BDF map on same context with different radius value

Based on the mentioned clustering process, the indicator of building distribution used in this study is resulted from normalizing the number of clusters, expressed in percentage, with respect to the local extremes, and subtracted from one. Therefore, this indicator offers a proportional value, which represents the condition of urban built-up rather than the voids.

$$\text{BDF} (\%) = \{ 1 - [(N_{cluster}(d{=}50) - 1) / 100] \} \times 100 \quad (13)$$

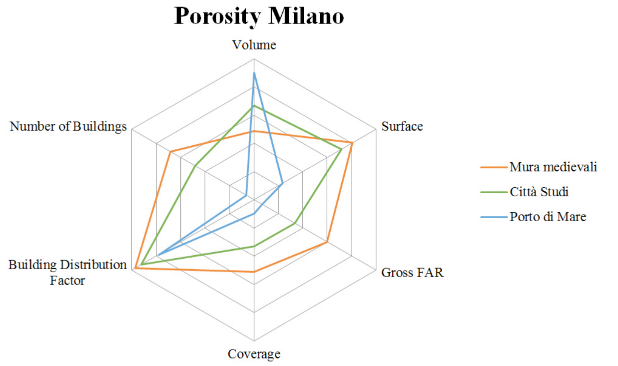

Figure 10. Porosity Investigation, Milano

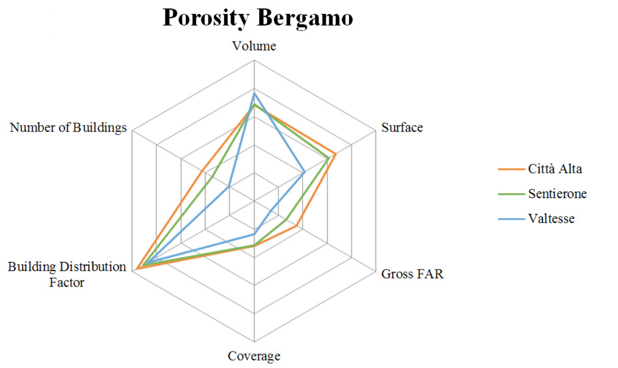

Figure 11. Porosity Investigation, Bergamo

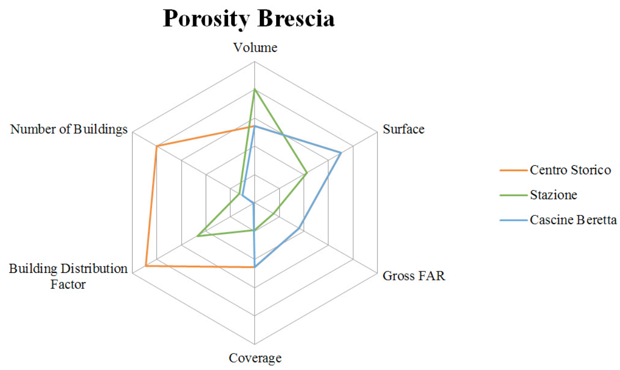

Figure 12. Porosity Investigation, Brescia

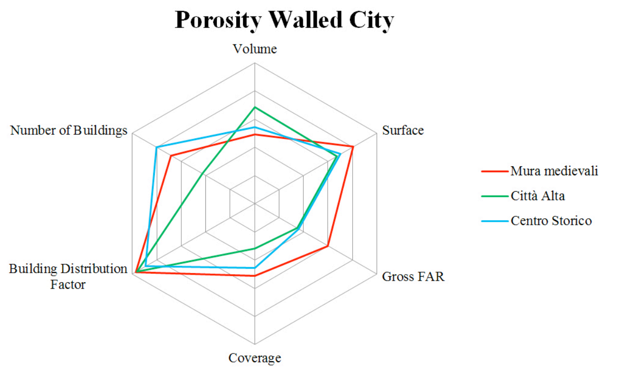

Figure 13. Porosity Investigation, Walled Cities

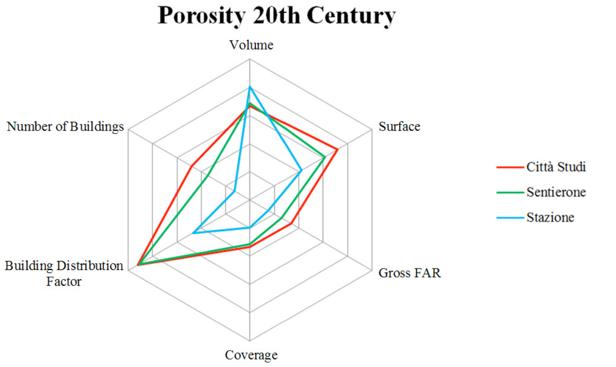

Figure 14. Porosity Investigation, 20th Century Developments

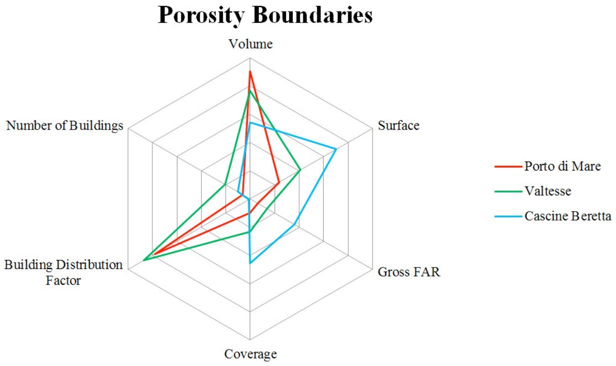

Figure 15. Porosity Investigation, Boundaries

Low values of BDF emerge when regular morphologies are interrupted by bold urban voids like wide streets, roads and parks, or natural elements like rivers and hills. “Cascine Beretta” in Brescia is an extreme case while “Stazione area” can be considered as a filter between compact and modernist city.

TABLE IV-1 POROSITY INVESTIGATION

City	District	Area (ha)	Vol	Sur	FAR	Cov	BDF	NB
MI	Mura M.	269.20	0.49	0.81	0.60	0.51	0.97	0.68
MI	C. Studi	275.30	0.67	0.72	0.34	0.33	0.92	0.48
MI	P. Mare	169.10	0.90	0.23	0.06	0.10	0.78	0.06
BG	Citta Alta	45.35	0.68	0.67	0.35	0.32	0.96	0.43
BG	Sentierone	67.76	0.69	0.61	0.26	0.31	0.91	0.35
BG	Valtesse	84.29	0.77	041	0.14	0.23	0.87	0.21
BS	Centro	177.10	0.54	0.70	0.36	0.46	0.89	0.80
BS	Stazzione	180.10	0.81	0.42	0.15	0.19	0.47	0.13
BS	Cascine B	177.10	0.54	0.70	0.36	0.46	0.01	0.10

V. Discussion

Some of the extremes expressed in the diagrams bear only theoretical meanings.

For example, the value of Coverage can hardly exceed 75% or fail below 10% in practice. In other cases, like in Concentration Factor, to avoid a normalizing process has been applied.

Hence there are mainly two ways to read the diagrams:

First is to morphologically interpret different fabrics within a certain city; as Milano “Mura Medievali” and “Città Studi” clearly represents one city in two historical periods. “Città Studi” presents more void, due to hygienically policies, and all other values decrease in order to achieve it. FAR follows coverage because building height is almost constant, Surface loss from regularization in building shapes is mitigated by an emptying of courts. Larger buildings for a lower Coverage make Building Density value reduce sensibly. The great distance that “Leonardo Campus” holds with the other buildings probably drives BDF loss.

According to the rather medium values resulted from the analysis, these two areas of Milano could be observed as quite compact morphologies with regular shapes.

This regularity is due to the balance between volume and void spaces and the even distribution of the volume in building spaces.

The area of “Porto di mare” is almost divided in two parts, large empty areas in the south and volumes concentrated in quite compact shapes in the northern part of the district. That's why almost all the values may reflect a sprawling-like low-density neighbourhood, while BDF is really close to the values of inner areas.

From a similar viewpoint, other case studies are being read differently through the analysis.

Bergamo seems to maintain a uniform pattern in all the stages of its development and experience a semi-constant rate of reduction in density by distancing from the centre.

The case of Brescia, on the other hand, is much complicated as some of the values of totally different morphologies perfectly overlap each other.

With a much lower number of buildings, “Cascine Beretta” provides as much density as City Centre does. Not surprisingly, these are taller building between which there is a certain distance forming a typical modern layout. Although interpreting the “Stazione Area” is not as straightforward as the other cases, but the existence of larger building units -in comparison with Historical City Centre- is clearly recognizable from its lower density.

Another way to read the diagrams is to compare the urban morphologies of similar historical periods in different cities. Form the historical point of view, three different morphologies have been selected as study cases: The old city centres within the historic walls, areas belonging to the 20^{th} century development, and some settlements of recent development.

All the historical centres reflect the feeling of regularity seen in Milan with differences that may not be directly linked to a geometrical correspondence.

Analogies among them can be the result of being built by the same culture or historical framework, while differences are probably mainly due to the construction sites conformation and properties.

The same can be said for 20^{th} century expansions as “Città Studi” and “Sentierone”, almost perfectly overlapping, while the “Stazione Area” in Brescia is something in between these examples and more sprawled/modern one collected in boundary diagram.

Figure 16. Milano: “City Center, Città Studi, Porto di Mare”
Bergamo: “Città Alta, Sentierone, Valtesse”
Brescia: “City Center, Station, Cascine Beretta”

The difference of polyline shape in the peripherical contemporary areas is the reflection of arbitrary distribution of morphological elements for sprawling fabrics in recent periods. “Valtesse” is a large collection of single-family houses and “Cascine Beretta” is a pure rationalist district. “Porto di Mare” on the contrary is composed by a small compact part, a larger modernist set of blocks and a huge void with few barracks, so the result of the diagram is not so easy to be read.

VI. Conclusion

Unlike the majority of the research in the field of urban morphology, this study does not tend to reduce the Porosity into a sole quantitative meaning, but rather include all the complexities that may shape its concept and describe it through a simultaneous look at them.

Urban Morphology could be interpreted as the DNA code of the City, which dictates the properties of the urban porosity. “Like humans, cities and neighborhoods have their own unique fingerprints.

While genes determine ours, a city’s mark is characterized by the relationship between buildings and open spaces.

That is to think of it as the Spatial DNA, which is typically mapped out in the black-and-white diagrams by the urban designers and the researchers [22]. To investigate Porosity means to do more than just mapping black-and-white spots indicating buildings and open space.

But rather, a comprehensive study demands to evaluate the correlation between the values affecting it.

All the six indicators used here for evaluating the urban porosity are independent form but related to each other.

Due to the complexity of the urban systems, no straightforward relation between them could be pinpointed. However, the hexagonal diagram delivers a visualization platform in which the mentioned values could be seen simultaneously.

The figure resulted from studying an urban system of a particular shape could be interpreted as an abstract morphological characteristic of that specific context.

This could be helpful for categorizing urban areas in the certain visual groups according to their morphological features.

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