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Measuring the Influence of Functional Proximity on Environmental Urban Performance via Integrated Modification Methodology: Four Study Cases in Milan

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***Abstract*—**Although how cities' forms are structured is studied, more efforts are needed on systemic comprehensions and evaluations of the urban morphology through quantitative metrics that are able to describe the performance of a city in relation to its formal properties. More research is required in this direction in order to better describe the urban form characteristics and their impact on the environmental performance of cities and to increase their sustainability stewardship. With the aim of developing a better understanding of the built environment's systemic structure, the intention of this paper is to present a holistic methodology for studying the behavior of the built environment and investigate the methods for measuring the effect of urban structure to the environmental performance. This goal will be pursued through an inquiry into the morphological components of the urban systems and the complex relationships between them. Particularly, this paper focuses on proximity, referring to the proximity of different land-uses, is a concept with which Integrated Modification Methodology (IMM) explains how land-use allocation might affect the choice of mobility in neighborhoods, and especially, encourage or discourage non-motived mobility. This paper uses proximity to demonstrate that the structure attributes can quantifiably relate to the performing behavior in the city. The target is to devise a mathematical pattern from the structural elements and correlate it directly with urban performance indicators concerned with environmental sustainability. The paper presents some results of this rigorous investigation of urban proximity and its correlation with performance indicators in four different areas in the city of Milan, each of them characterized by different morphological features.

***Keywords*—**Built environment, ecology, sustainable indicators, sustainability, urban morphology.

I. INTRODUCTION

SEVERAL reasons such as diseases, accidents, natural disasters, … cause millions of deaths. Annually about 4.6 million people die due to urban pollution-related diseases worldwide [1]. This statistic exceeds the number of mortalities due to accidents, which itself is related to cars chiefly. Although a fraction of urban pollution is associated with indoor contaminations, cars are easily the primary source of pollution in the cites. Non-motorized traffic would play the most prominent role in mitigating the catastrophic effects of air pollution and increase the healthiness of the citizens. Non-motorized means of mobility, moreover, positively change the overall social health by encouraging the urban inhabitants to boost their physical activities. Much research examined the direct relations between the convenience of urban environments for non-motorized modes of mobility and the overall health of society [2], [3].

Besides individual intentions, specific characteristics of the urban environment can strongly encourage people to walk or ride bicycles for transportation or recreational reasons and break the tedious habits of long sittings, which have become a typical feature of modern life [4], [5]. Furthermore, non-motorized traffic, mainly walking, benefits social life at many levels. Safe and favorable streets that host walking traffic can hugely increase the chance of social interactions. Appropriate urban form and intelligent distribution of urban function can actively stimulate the non-motorized modes of mobility that directly affect the social interactions in the urban contexts [6]. From the standpoint of sustainability, thus, the chief importance of non-vehicular mobility is its potential to be a practical alternative to car-based transportation. In this sense, by reducing air pollution, providing healthier habits, creating social-friendly environments, reducing fuel consumption, and many other consequential feedbacks, non-vehicular mobility effectively makes enhancements in all three pillars of sustainability.

This paper makes a scientific inquiry into the ways that the morphological structure of the urban settlements might influence non-motorized mobility. The angle from which this study views the mentioned quality is the concept of Proximity defined by the IMM. In IMM, the emergence process of interaction between elementary parts to form a synergy is named Key Category. The Key Category concept in IMM refers to Emergence one in Complex System Theory [7]. It describes a process whereby parts interact to form a synergetic integration adding value to the system. Hence, it gives rise to the emergence of a new system level as the product of the synergies between the single parts and not simply the properties of the parts themselves.

There are types of emergence that show how elements come to self-organize or to synchronize their states into forming a new level of organization [8]. Emergence is something new

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that cannot be adequately represented by the description of the parts. Key Categories are then the products of the synergy between elementary parts. In IMM Key Categories are namely: Porosity, Permeability, Proximity, Diversity, Interface, Accessibility, Effectiveness [9]. It is vital to note that the Key Categories simultaneously affect one other and drive the performance of the whole system in a complex manner. Hence, an appropriate way to model them together is an artificial neural network as shown in Fig 1. However, before modeling such a system, it is essential to gain a proper systemic understanding of the individual Key Categories.

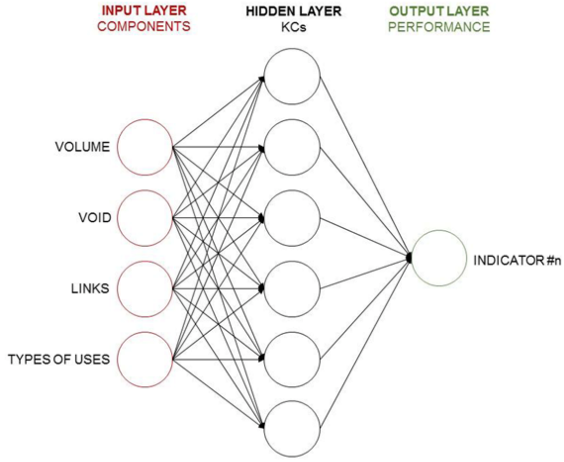


Fig. 1 The connection of components, structure (IMM's Key Categories), and performance of the built environment in a simplified artificial neural network

II. The Role of Key Categories in IMM

IMM aims at providing quantitative measures (metrics) that can pinpoint significant features of the spatial organization of the urban elements to characterize the concept of Key Categories. For this purpose, it assigns a set of quantitative metrics to each Key Category. Each proposed metric has a quantification procedure that is reproducible and easily exportable to any case study of interest.

The six metrics for each Key Category are typically illustrated through Kiviat (or radar) diagrams. This manner allows for expressing the influential factors in an easily readable illustrative system. The Key Categories can then be characterized, quantified, and discussed by reading the metrics together and concerning each other. Metrics in IMM are structural properties of the built environment, which are to be correlated with the performance indicators. They introduce a more accurate way of studying the functioning mechanisms of the urban systems, which are conventionally expressed by a single numerical value. This set of quantitative parameters is usually accompanied by a synthetic map to deliver in-depth resolutions of different structural characteristics. This representation not only allows us to investigate the different facets of every property and offering a better comprehension of the urban systems but also provides practical measures to size the influence of structure on the performance.

III. Functional Proximity

According to IMM's definition, Proximity is the morphological quality that the urban context offers for walking through the arrangement of primary types of uses. The primary types of uses are vital urban services, which might differ from context to context.

Concerning specific studies that measured the walking preference, the authors have chosen the convenient walking duration between five to ten minutes that roughly corresponds with 400 to 800 meters [23], [24]. Non-motorized traffic is a function of many other variables [4], [10]-[14].

In addition to types of uses, population density, the street profile, mixed-use level, and human comforts are decisive parameters profoundly affecting non-motorized transport. Modeling of Proximity should consider these factors both in numerical measurements and graphical representation. Within the boundary of urban organizations, the functioning mechanisms are influenced by spatial systems, links and mobility patterns, and land-use characteristics. In this direction, the attempts should be made at providing a framework in which different functioning manners -influenced by the city's morphological environment are pictured. It seems that these functioning processes can be categorized in and between the following categories [15]:

1. Spatial arrangements;
2. Street systems interface; and,
3. Distribution quality of types of uses.

This study aims at providing quantitative measures that can pinpoint significant features of the spatial organization of the urban elements to characterize the concept of urban proximity. Hence, following the IMM approach already applied to the other key categories description, the complexity of urban proximity can be better rendered by a set of metrics instead of one single value.

In this study, six spatial assets of the built environment- Length Share; Width Share; Mixed-use Share; Surface Share; Thermal Comfort Ratio; Simultaneous Proximity - have been studied to cover the mentioned functioning processes and Urban Proximity is explained through the relationships between them. For the selected case studies, these assets have been evaluated and presented in Section IV, utilizing spectrum diagrams that allow direct comparison of the different metrics [16]. They are respectively:

- *Length Share* measures the length of walkable/cyclable links compared to the total length of the streets in each context. This parameter provides a proportional measure for the share of non-motorized links and their level of interruption compared to the rest of the street network. Higher values in this parameter indicate a more connected and continuous local network.

$$Length\ Share = \frac{Non\text{-}vehicular\ Links\ Length}{Vehicular\ Links\ Length} \tag{1}$$

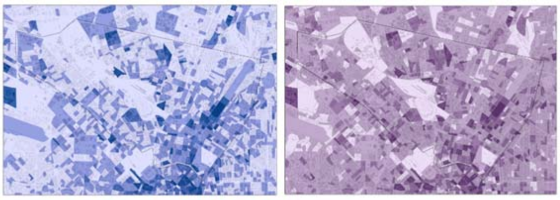
- *Width Share* measures the proportion of the non-motorized verge width to the total width of the streets. This parameter, too, measures the share of non-vehicular paths thought from users' preference viewpoint. Higher values in this parameter represent safer and preferable walkable/cyclable links.

$$Width\ Share = \frac{Non{-}vehicular\ Links\ width}{Vehicular\ Links\ Width} \tag{2}$$

Fig. 2 Non-motorized and motorized streets, motorized streets represented in black

- *Mixed-use share* measures the overall density distribution for global and intermediate-scale; the ratio between employment density and total density gives a grade for the level of the land-use mix in each area. According to the literature, the more mixed the land-use, the higher the chance of walking or cycling for transport reasons [17], [18], [4].

$$Mixed - use\ Share = \frac{Number\ of\ employees}{Number\ of\ residents{+}employees} \tag{3}$$



(a) (b)

Fig. 3 (a) Number of employees in Farini, (b) Sum of residents and employees in Farini

More diverse neighborhoods, because of natural shorter distances, are likely to host higher walking flow. This quality also makes them safer for walking and cycling because non-vehicular flow increases surveillance in the neighborhoods.

- *Surface Share* measures the existence of commercial activities at the street level.

The parameter for measuring this quality would be the ratio between the surfaces with window-shops, and the total surface area on the street level. Higher values in this parameter indicate the existence of commercial bases, and if the other parameters agree, it can positively affect non-motorized traffic.

$$Surface\ Share = \frac{Surface\ of\ windowshops}{Total\ street\ level\ surface} \tag{4}$$

- *Thermal Comfort Ratio* measures the outdoor human thermal comfort that influences the choice of transportation mode [19], [20].

The metric for measuring it is represented by the proportion of the length of comfortable links, in specific periods of the year, over the total length of the street network. The higher values in these parameters show the comfort potential for the users to walk or cycle.

$$Thermal\ Comfort\ Ratio = \frac{Length\ of\ Comfortable\ Streets}{Length\ of\ total\ street\ network} \tag{5}$$

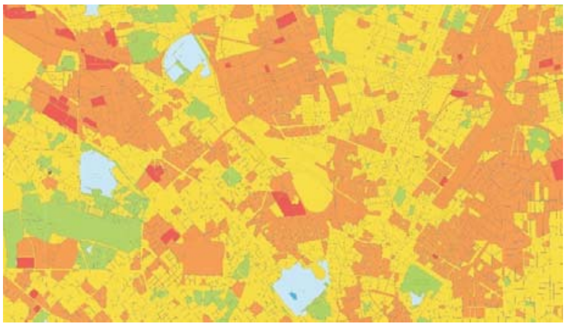
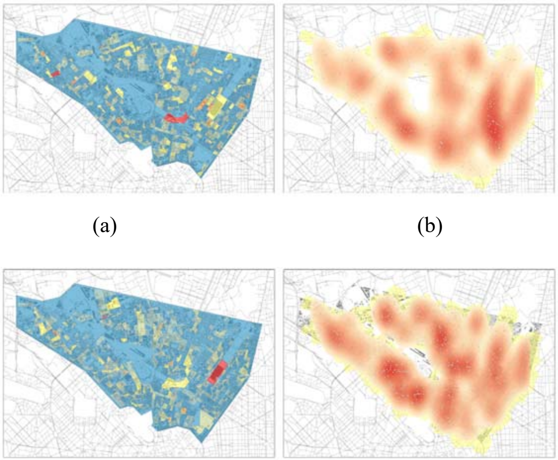


Fig. 4 Streets by temperature, warmer colors indicate higher temperatures

- *Simultaneous Proximity* measures how close the population is to different types of primary functions, each of which covers different daily needs.

$$Simultaneous\ Proximity = \frac{Residents\ in\ proximity\ area}{Total\ residents} \tag{6}$$

This metric provides information on the distribution and mix of types of uses in each context, reducing motorized mobility.



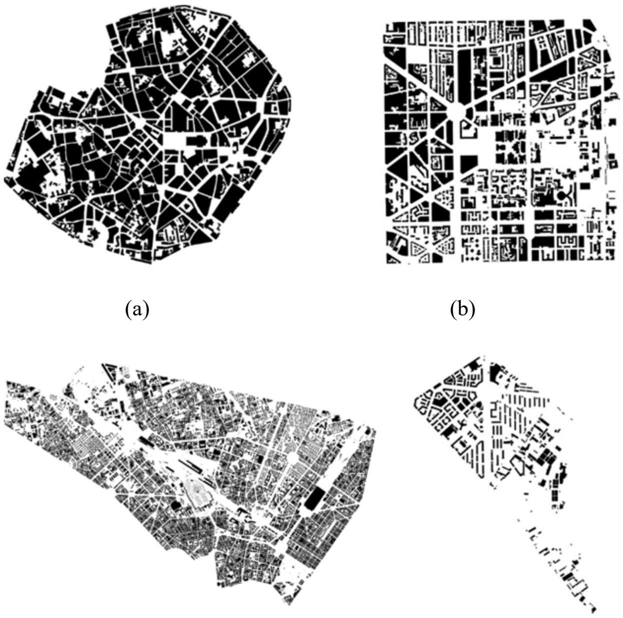
(a) (b)

(c) (d)

Fig. 5 (a) Number of primary functions for residents in census tracts, (b) Distribution of primary functions for residents in relation with pedestrian isochrones in the Walled City, (c) Number of primary functions for employees in census tracts, (d) Distribution of primary functions for residents in relation with pedestrian isochrones in the Walled City

IV. CASE STUDIES

This section aims to demonstrate the ability of the proposed metrics to characterize the morphological features of specific urban areas in Milan.



(a) (b) (c) (d)

Fig. 6 (a) The Walled City, (b) Citta Studi, (c) Farini, (d) Porto di Mare

The city of Milan has been studied, selecting four contexts with different historical periods and therefore exhibit various morphological features:

- *The Walled City* is the old part of Milan, now corresponding to the core of the city.
- *Città Studi*, as representative of the areas, developed after the wall demolition as the first city's expansion in the early modern ages.
- *Farini area*, with the abandoned railway yard in the center, is currently under development by the Municipality of Milan.
- *Porto di Mare*, as representative of the most contemporary outskirt areas morphologically characterized by fragmentation and sprawling phenomena.

These analyses are performed based on DBTR (Topographic Regional Database) of Lombardy [21] and SIT (Territorial Information System) [22] of the Municipality of Milan, to be specific; the most used data are Street Network (L010107), Street Area (A010104), Street Nodes (P010108), and Volumetric Units (A020101). Additionally, Daytime Surface Temperature Hotspots by SIT is used as preliminary data to obtain Street Discomfort. Regarding the demographic data used, the source is ISTAT (National Institute of Statistics), both for residents and employees.

The spatial limitation of the study cases is defined following the existing local boundaries within which homogenous morphologies lie.

The study areas differ in terms of dimension. A comprehensive view of all the results can explain trends in urban development and, eventually, other phenomena not so directly to the ascribable physical arrangement of volumes and voids.

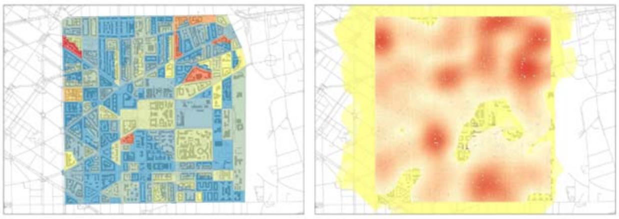
Simultaneous Proximity metric is represented graphically in Figs. 7-10. These maps illustrate not only locations of related types of uses but also their distribution in the area. Since pedestrian isochrones overlap them on street networks, it is visible how easy it is to reach them. They are the sum of primary functions for residents and employees that are considered separately.

(a) (b)

Fig. 7 (a) Number of primary functions in census tracts, (b) Distribution of primary functions in relation with pedestrian isochrones in the Walled City

(a) (b)

Fig. 8 (a) Number of primary functions in census tracts, (b) Distribution of primary functions in relation with pedestrian isochrones in the Farini area



(a) (b)

Fig. 9 (a) Number of primary functions in census tracts, (b) Distribution of primary functions in relation with pedestrian isochrones in the Città Studi area

The final radar graphics (Figs. 11-15) show how the different areas located in the same city could be different and similar by considering these analyses. The six mentioned metrics have a significant role in understanding and interpreting the existing structure about functional proximity and urban morphology.

(a) (b)

Fig. 10 (a) Number of primary functions in census tracts, (b) Distribution of primary functions in relation with pedestrian isochrones in the Porto di Mare area

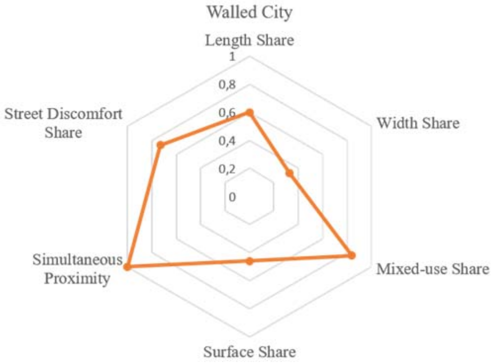


Fig. 11 Spectrum of Walled City

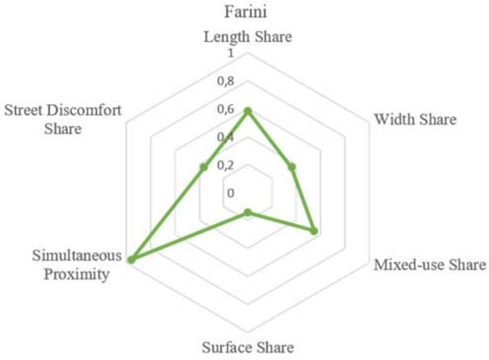


Fig. 12 Spectrum of Farini

The spectra differ for all cases as expected since they have different performances for related parameters. For instance, the balance between the number of employees and residents is one of the themes.

The historical center has quite diverse activities and offers several job opportunities in comparison with the rest of Milan. So, Walled city has the most significant value for mixed-use share and Farini, Città Studi, Porto di Mare follow it respectively.

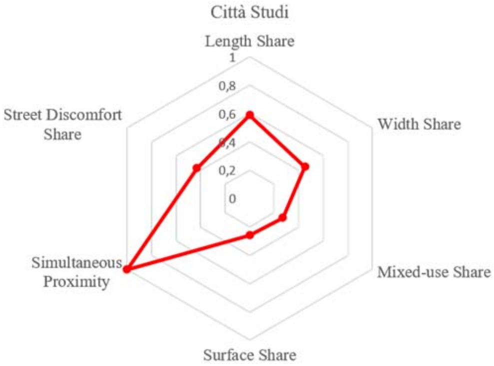


Fig. 13 Spectrum of Città Studi

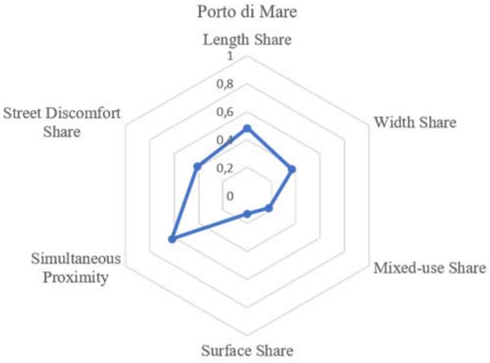


Fig. 14 Spectrum of Porto di Mare

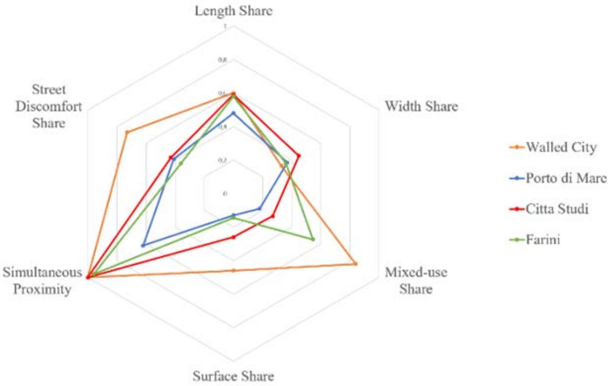


Fig. 15 Spectrum of four cases

V. PERFORMANCE EVALUATION

The key categories are only structural attributes. No values within them or a single key category alone can offer enough information about the performance of the system. Key categories only reveal how specific parameters arrange the system, and together, they show a much complete vision of the systemic structures. In IMM, like most of the scientific methodologies, the tools for performance evaluation are indicators. IMM examines scientific methods to find correlations between the structure and performance. Hence the performance of the system has the indicators of its own.

A multi-final system like the built environment, naturally, demands many indicators to cover different aspects of its performance. Cities are economic, social, and environmental systems with many associated subsystems.

Each aspect of performance is also encompassing more other aspects. For evaluating the behavior of the urban systems, one needs an accurate set of indicators. For example, non-motorized mobility, which IMM intends to address with proximity, can associate with many performance aspects with coherent value loads.

In general, the grade of a system in supporting non-vehicular modes of transportation can be shown by indicators like length of biking roads, car free or minimal car traffic streets, Pedestrian street paths – walkways, etc. as listed on the Table I. 20 indicators have been calculated for each of the study cases in order to understand how they perform. With this methodology, they could be compared by considering different parameters. For instance, the Walled City's performance is better than any other three on these indicators: Number of buildings per hectare, Job/housing ratio, Number of bike parking spots, Physical permeable footage, Sidewalks that are lined with continuous ground-floor activity, and Number of public transportations noticeably. This situation comes from its morphological characteristics and organization of diverse activities. On the other hand, it is evident that Porto the Mare is underperforming compared to three other cases in many indicators (see Table I).

For measuring the impact of proximity on transportation performance, walkability, and energy use, in the four areas, indicators will be added to size the concentration of particles (PM_{10}, $PM_{2.5}$, NO_2, CO_X), and its related pollution.

TABLE I
PERFORMANCE INDICATORS

Indicators	Inputs	Farini	Walled city	Citta Studi	Porto di Mare
Number of buildings per hectare	Number of buildings/total land area	11	34	24	3
Block Density	Number of blocks in a given area/total area (ha)	0,56	2,58	7,19	0,95
Heatmap street indicator	Global Temperature (in C°), Length-Temperature product (mXC°), Total Length (in m) *100	3,515	3,511	3,519	3,617
Ratio between numbers of residents and activities	Number of residents/number of activities	139,77	9,25	43,07	161,98
Job/housing ratio	Number of jobs in a given area/ Total number of employed who live in the same area(total workable res.)	1,81	8,4	0,59	0,37
Ratio of place dedicated to Innovation and Knowledge	Number of IK activities/total activities	3,24%	3,36%	2,42%	0,00%
Percentage of Residents within Walking Distance of a Recreation Area %	Residents live in in a 400 m distance from recreation areas/total population	79,20%	78,78%	93,63%	44,11%
Length of biking roads	The amount of roads dedicated to bike.	21,51km	4,91km	0,84km	1,41km
Number of bike parking spots	Number of parking spots/total residents (*1000)	1,37	5,65	2,38	0,22
Bike Sharing	Total number of bike sharing points	92	37	12	0
Number of key functions in a walking distance from residential buildings	The number of key functions located in a 400 meters distance from the residential area	890	512	295	33
Car free or minimal car traffic streets	The km of street dedicated to minimal car traffic or car free street	78,4km	25,92km	17,58km	2,46km
Pedestrian street paths - walkways	Total pedestrian street area/total street area	35,70%	40,39%	38,73%	27,27%
Number of people that are within walking distance of frequent transit stops	Population within 5 min catchment area from public transport stop/total population	45,07%	66,14%	63,47%	15,41%
Physically permeable frontage. Number of entrances per 100 meters of block frontage	Number of entrances/numbers of 100*100 blocks	45,6	93,43	74,76	9,83
Sidewalks that are lined with continuous ground-floor activity	Length of sidewalks face with activities/Total length of sidewalks	14,40%	58,75%	35,17%	7,03%
Shade and shelter	Area of canopy of trees+area of shadow elements/total area	4,36%	1,98%	3,76%	6,58%
Number of public transports operated	Total transportation routes	14	19	15	5
Spatial Integration	Number of active platforms at the interchange	7	8	5	1
Access to community gardens	Population within 400 m to community gardens/total population	5,07%	0%	0%	0%

VI. CONCLUSION

The result shows that the city center of Milan, not surprisingly, stands higher than all the other areas. Although Farini and Città Studi both rank the same as the city center in Simultaneous Proximity and Length Share, the morphology of the city center shows more flexibility to support non-vehicular traffic through Mixed-use Share and Street Comfort Ratio. The suburb-like Porto di Mare is the weakest among the four due to the natural disarrangement of its form and its distance from the activity centers. The sharp unbalance between the proximity metrics in Farini-compared with the city center-might highlight the difference in historical purposes and evolution courses of these two areas.

Unlike the majority of the research in the field of urban morphology, this study does not tend to reduce proximity into a sole quantitative meaning, but rather includes all the complexities that may shape its concept and describe it through a single look at them. The results achieved, even if new metrics might be added in the future, deliver a new practical tool for urban proximity investigation, applicable by researchers, designers, and stakeholders in all urban existing contexts, capable of measuring the impact of proximity on transportation performance, walkability, energy use, and more. Moreover, as urban arrangements are complex systems, the interactions between all the key categories must be investigated. By taking these steps, however limited, science can finally bridge between the structure and performance of the city as a complex adaptive system.

Here, there is a critical lesson; the performance is the result of the structural arrangements, not the individual quality of components. Hence in the future, if one gathers enough actual structural models of all key categories and enough performance indicators of the same contexts, the chance of accurately predicting the potential performance of given design scenarios concerning their structure will increase.

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