Multi-Scale Modelling Approach for Urban Optimization:

Compactness Environmental Implications

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To measure

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Preface

May we work with something that we don't precisely know? May we know something that we can't precisely define?

Once finished my master studies in architecture I felt as I was not completely aware of the subjects of my discipline. After designing buildings, public spaces, blocks and entire neighbourhoods and tutoring other students for doing the same I realised that my knowledge of architecture and urban environment was still partial and incomplete. More precisely I couldn't demonstrate in an objective and measurable way some concepts that were absolutely clear in my mind. I overcame this limit with students thanks to my storytelling skill but fortunately or unfortunately I'm not as good in listening as in speaking, so I couldn't totally convince myself.

My research journey started looking for a definition of the concepts I was used to deal with but I immediately realised that before I needed a definition of "definition", the true meaning of this word. Definition has a double meaning. The first is "the exact statement or description of the nature, scope, or meaning of something", while the second is "the degree of distinctness in outline of an object, image, or sound".

The first meaning didn't surprise me a lot but gave me some hints for a further reflection. The word "exact" stresses the fact that the semantic bounds of the investigated objects should be clear and agreed. It follows that the only possibility to disagree on a topic is to start from a different definition of it. The definition of architecture are countless and more than axioms, cold but stable, they look like aphorisms, warm but vague.

The second meaning immediately suggests me a connection between this word, the concept of scale and its relevance in our discipline. An architect, during its studies, has to deal with objects of very heterogeneous dimensions ranging from detail to regional planning, from a screw to an ecological corridor or a highway. Even trying to reduce the field to just design/composition, excluding construction and planning, the domain is still wide. Its bounds could be approximately identified in walls and rooms on the bottom and districts on the upper extreme.
Theory of representation suggests some conventions at the different scales defining a minimum size for an object to be considered. This operation is similar to a progressive zoom out with a consequent loss of information. Discrete elements become continuous, shapes simplify, figures merge and the result of each iteration is not always easily associable to its constituents.

"To know" means being aware of through observation, inquiry, or information. It has different levels of depth from the mere awareness of the existence of an object to the full cognition and understanding of its being. Architects are, or should be, master of observation and their knowledge is mainly based on their ability of formal synthesis.

Inquiries and interrogations are less common words and imply a deeper investigation of the object also from inside trying to explicit all those properties that were already evident by observation, but not easily transferable.

Thanks to these definitions the picture became clearer. The scalar interconnection of urban element was not controlled by a unique body of knowledge, instead many specialisms or sub-categories of studies defined own boundaries around a specific scale as the building, the plot or the neighbourhood. We could compare it to a company having its offices in a tower with no connection among the floors. The results are very advanced but disconnected horizontal bodies of knowledge.

The vertical connection is not simply a matter of communication, it also gives the possibility to understand the mechanisms of that previously mentioned zoom allowing the emergence of inter-scalar properties of objects making them evident.

So, I focused on urban morphology, structure, fabric, design and all those words that refer to the relation between volumes and voids, black and white, positive and negative (or vice versa). I extracted all the already existing information that were left aside and tested if they could help us understanding and describing the object of our study. I tried to understand before judging, leaving all prejudices and the hurry of finding solutions. I entered the jungle of terms and metrics of urban studies trying to trace some safe and recognizable path for new visitors. I found few answers and many new questions. I realised that love is attention and attention is love. I get lost there, but I'm still alive and even more in love with that jungle that is the city.

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Introduction

The research objective is to develop and implement a multi-scalar and multi-metrics methodology capable of objectively representing some morphological properties of the city considered as a Complex Adaptive System investigating in particular Porosity and Permeability, how they concur in the definition of the Compactness of an area and their environmental implications.

Thesis is organized in eight chapters that progressively reveal the reasons that drove the research into this direction starting from a critical issue of contemporary society, crossing almost every disciplinary field: climate change.
Chapter 1 contextualise the research within the actions to fight climate change working on the urban environment. It quantifies the urgency of this issue by examining current urbanization trends and the challenges that cities are sked to face because of that. The scenario is heterogeneous and complex and no ready-made solution can be used as a panacea for sustainable development.

Chapter 2 is devoted to the construction of a comprehensive framework about cities and the methodologies used to deal with them. The relationship between definition, representation and approach is elucidated bringing many opposed examples. Among the myriad of existing approaches, three are selected and deeply investigated as considered the most appropriate to address the urban environmental issue. The key relationship between urban structure and its environmental performances is targeted starting from rating systems, starting from the good results already achieved at the building scale, exploring the efforts to apply them to the neighbourhood one and understanding the limits of the most popular existing systems (BREAM, CASBEE, LEED). The relationship to the context and the ability to quantify some morphological qualitative features appeared as the weakest part of those methodologies. For this reason, the field of urban form, closer to the author's architectural background, has been explored to find principles able to fill this gap. A profound investigation on urban morphology and architectural typology is conducted, coherently with the tradition of the architectural school of Politecnico di Milano, stressing the importance of classification. Finally, system theory is faced as considered able to match the two previous approaches taking the best from them. Considering the city a Complex Adaptive System (CAS) allows to work on it in a holistic way exploiting the knowledge transfer from other disciplinary fields working in a systemic way.

Once assumed the research reference city definition and approach, chapter 3 is dedicated to understand how it affects and drive the study of an urban system and to the research of an existing reference methodology, coherent with research assumptions, that could support its development. Here comes the importance of Compactness (together with Complexity and Connectivity), a system Determinant able to match structural and performance aspects. Reviewing the existing literature, both its impact on city performances and the lack of a theoretical framework for its qualitative measurement and representation emerged.
At this point of the research two already latent questions became clear and urgent:

- How to demonstrate the relationship between urban form and environmental performances?
- How to characterise urban morphology?

Integrated Modification Methodology (IMM), among the existing operative methodologies, resulted the most appropriate to answer these questions, especially the first one. Compactness is actually defined as the result of the integration of Porosity and Permeability Key Categories (KC), which, in their turn, are seen as the integration of

Volume and Void Components. This methodology, to be considered a CAS on its own, was the perfect room for the practical implementation glimpsed by the author. Its theory, phasing and elements are introduced in order to contextualise the research contribution to its functioning, based on a data-oriented reconceptualization of IMM Components.

Chapter 4 describes the desired complex modelling approach moving from literature gaps and most promising affine researches. Multiplicity under many aspects (scale, disciplinary, metrics) is one of the main drivers to defy simplistic approach and increase modelling capability to describe complexity. A synergy of maps, numerical values and the resulting pattern radar diagram are proposed to investigate morphological features and a set of GIS operations automatize the whole process. Aldo Rossi sentence “Non vi è nulla di più vario di un meccanismo ripetitivo” (there’s nothing more diverse than a recurring mechanism), inspired the development of a methodology applicable to any urban context solve the global/local debate giving the proper importance back to the context.

Chapter 5 enters into the details of the previously mentioned methodology exploring the state of the art in terms of spatial metrics, representation techniques and measurement tools and proposing for each category a series of implementations. The most consistent part is the metric one where dozens new metrics based on the interaction of Volume and Void Components are introduced and a selection of 60 metrics (including existing ones) is tested on a very large sample to extract the most complete, valid, consistent and non-redundant one. In addition, the selected metrics have been assigned to one or more IMM KC, even the ones out of this research investigation like, i.e., diversity. The maps section benefits from new metric-related geometries that offer synthetic representation of complex morphological phenomena. The tool part makes a lucid picture of the empty space existing in between GIS and BIM, analysis and simulation, developing a set of algorithms in between GIS and 3d modelling that will hopefully represent the first step of City Information Modelling (CIM) software thanks to an international partnership with a software house.

In chapter 6, this improved morphological investigation method is used to define a calculation and a representation method for Porosity and Permeability Key Categories as a first step for Compactness understanding. Both properties are approached justifying their right to be considered systemic properties, reviewing existing definitions and measurement methods, proposing a set of heterogeneous metrics able to describe them from both quantitative and qualitative aspect and validating this method on a sample of nine case studies from three different cities. Then, the performance side is taken into account starting from indicators in general as an instrument able to assess performances, moving to researches already demonstrating the correlation between performance indicators and quantitative simple spatial metrics, to finish by explaining IMM indicators logical structure and accepting them as the tool for assessing performance within the research framework in accordance to United Nations Sustainable Development Goals (SDGs). Finally, we arrive to Compactness confronting with literature definitions and discussing its optimization based on the integration between the structural aspects and the performance one. An application to 88 district-like areas in Milan is performed to verify the proposed approach and discuss the first results.

Last part is dedicated to the thesis case study. As evident from the previous chapter, the presented approach doesn’t require a specific case study as they could, and should, be tested on the highest possible number of difference contexts in order to be fine-tuned. By the way, despite the importance given to the diagnostic phase up to now, we should remember that is only a preliminary stage for design and transformation. Accordingly, the main purpose of IMM and other methodologies is to compare an urban system before and after a transformation. For this and other convenience reasons the area of Porto di Mare in Milan has been selected as the case study for the design of an Eco-District. Chapter 7 begins with the reasons in support of working at the district scale and deepening Eco-district approaches and experiences through a huge number of case studies from USA and Europe, with an additional focus on Italy and Milan. Following IMM phasing it explains the characteristics of the area and the origin of the project. The final masterplan is compared with the initial configuration and with an alternative transformation scenario with the same techniques used in chapter 6 for the Milanese neighbourhoods' analysis. This to demonstrate the effectiveness of the proposed methodology for both these complementary purposes. In conclusion the dissemination activity to promote the Eco-District project is presented. The project is not an original independent contribution of the author but has been developed during a research activity involving three universities during two international workshops. That to say that it shouldn't be judged in terms of architectural quality but only considered as a test to assess the modelling capacity of the proposed methodology.

Abbreviations

Due to the huge number of acronyms included in the thesis they have been divided in three sections. The first one contains all the acronyms cited in the text. They can be of various nature including institutions, countries, geometries, software and technologies. The second section is dedicated to metrics found in literature while the third one contains only the metrics introduced by the author. This last section must be used to read the results from chapter 6 to the conclusion while the previous one can be useful to orient in chapter 4 and the beginning of chapter 5. All the acronyms are also explicated inside the text.

Section 1 Various acronyms and abbreviations

ACRONYMS	MEANING	TRANSLATION
A	Area	
AD2Y	Architectural Design 2nd Year	
ANCE	National Association of Building Contractors	Associazione Nazionale Costruttori Edili
ATU	Urban Transformation Area	Ambito di Trasformazione Urbana
AUDIS	Abandoned Urban Areas Association	Associazione Aree Urbane Dismesse
AWCS	Automated Waste Collection System	
AWMPFD	Area Weighted Mean Patch Fractal Dimension	
AWMSI	Area Weighted Mean Shape Index	
B	Building	
Bds	Building Dissolved	
Bf	Buffer	
BIM	Building Information Modelling	
BL	Block	
BREAM	Building Research Establishment Environmental Assessment Method	
CAD	Computer Aided Drawing	
CAS	Complex Adaptive System	
CASBEE	Comprehensive Assessment System for Building Environmental Efficiency	
CCC	Compactness Complexity and Connectivity	
CH	Convex Hull	
CIM	City Information Modelling	
CMYK	Cyan Magenta Yellow Black	
CNU	Congress of New Urbanism	
CSTB	French Centre for Building Science	
CT	Court	
DBT	Topographic Database	
DOE	Department of Energy	
DOP	Design Ordering Principles	

DS	Dissolved	
EC	European Commission	
ECC	EarthCraft Communities	
EEA	European Environmental Agency	
ER	Entity Relation	
ESRI	Environmental System Research Institute	
F	Diffusive Flux	
FCC	False Colour Composite	
FH	Reference Diffusive Flux	
GBC	Green Building Council	
GDP	Gross Domestic Product	
GIS	Geographic Information System	
GML	Geography Markup Language	
GSV	Google Street View	
H	Height	
HK-BEAM	Hong Kong Building Environmental Assessment Method	
HQE2R	Haute Qualité Environmentale dans la Réhabilitation des bâtiments et le Renouvellement des Quartiers	
IMM	Integrated Modification Methodology	
INSPIRE	Infrastructure for Spatial Information in Europe	
ISUF	International Seminar on Urban Form	
IT	Information Technology	
ITACA	Institute for Contracts Innovation and Transparency and Environmental Compatibility	Istituto per l'Innovazione e Trasparenza degli Appalti e la Compatibilità Ambientale
IUMAT	Integrated Urban Metabolism Analysis Tool	
KC	Key Category	
LEED	Leadership in Energy and Environmental Design	
MBG	Minimum Bounding Geometry	
MIP	Mercury Intrusion Porosimetry	
MIT	Massachusetts Institute of Technology	
MM3	Milanese Metro 3	Metropolitana Milanese 3
ND	Neighbourhood Development	
NIL	Local Identity Nucleus	Nucleo di Identità Locale
NSF	National Science Foundation	
NYC	New York City	
NZEB	Near Zero Energy Building	
NZED	Near Zero Energy District	

OD	Origin Destination	
OR	Oriented Rectangle	
OSM	Open Street Map	
P	Perimeter	
PET	Physiological Equivalent Temperature	
PhD	Doctor of Philosophy	
PSD	Pore Size Distribution	
PV	Photovoltaic	
QSAS	Qatar Sustainability Assessment System	
RGB	Red Green Blue	
S	Surface	
SCR	Sheffield City Region	
SD	Sustainable Development	
SDG	Sustainable Development Goal	
SMDP	Sustainable Multidisciplinary Design Process	
SOA	State of the Art	
STC	Solar Thermal Collectors	
TCPA	Town and Country Planning Act	
UBEM	Urban Building Energy Modelling	
UCL	University College London	
UD	Urban Development	
UK	United Kingdom	
ULM	Urban Landscape Model	
UMEP	Urban Multi-scale Environmental Predictor	
UMI	Urban Modelling Interface	
UN	United Nations	
UNA	Urban Network Analyst	
USA	United States of America	
UV	Volumetric Units	Unità Volumetriche
V	Volume	
VBL	Virtual Block	
ZEDA	Zero Energy District Accelerator	

Section 2 Metric and Indicators from literature

ACRONYM	MEANING
AwaP	Area Weighted Average Perimeter
AWMPFD	Area Weighted Mean Patch Fractal Dimension
AWMSI	Area Weighted Mean Shape Index
BCR	Building Coverage Ratio
BD	Built Density
BH	Building Height
Bh	Building Height Limit
BVD	Building Volume Density
C	Coverage area
C	Form factor
Cbottema	Bottema Compactness
Cd	Discrete Compactness
Cdcm	Digital Compactness Measure
CI	Compactness Index
CI	Compactness Index
CILP	Compactness Index of the Largest Patch
Cipq	Osserman Compactness
CMI	Compactness based upon MI
Cndc	Normalized Discrete Compactness
D	Density
El	Elongation Index
FAD	Floor Area Density
FAD	Frontal Area Density
FAI	Frontal Area Index
FAR	Floor Area Ratio
FSI	Floor Space Index
FSId	Building Intensity
GC	Ground Coverage
GSI	Ground Space Index
GSId	Ground Space Index
H/W	Aspect ratio / Urban Canyon
Hc	Canopy Height
Hm	Absolute Rugosity
IC	Interface Catchment
MI	Moment of Inertia
MR	Metric Reach
ND	Network Density
P/A	Ritter Compactness
PCR	Pedestrian Catchment Ratio
PD	Population Density
Po	Porosity

R	Relative Rugosity
RA	Relative Asimmetry
ROS	Ratio of Open Space
RRA	Real Relative Asimmetry
Sq	Sinuosity
SVF	Sky View Factor
VAR	Volume Area Ratio
VD	Volume Density
VMT	Vehicle Miles Travel
VTD	Vehicle Traffic Density
μ	Cyclomatic number

Section 3 Metrics introduced by the author

ACRONYM	MEANING
BBVR	Building Built Volume Ratio
BchAR	Convex Building Area Ratio
BchmbgAR	Building Convex to box area ratio
BchPR	Convex Building Perimeter Ratio
BDSR	Dissolved Building Ratio
BFR10	Cluster / Buffer Building Ratio
BFR5	Cluster / Buffer Building Ratio
BLBDSR	Dissolved Building Block Ratio
BLBP	Block Built Perimeter
BLBPLmean	Block Built Perimeter mean length
BLBPLR	Block Built Perimeter frequency
BLBR	Building Block Ratio
BLmbgAR	Block Box Area Ratio
BLmbgC	Block Box Compactness
BLmbgO	Block Box Orientation
BLmbgPR	Block Box Perimeter Ratio
BmbgAR	Building Box Area
BmbgC	Building Box Compactness
BmbgO	Building Box Orientation
BmbgPR	Building Box Perimeter
BptD	Building Centroid Distance
BSAR	Building Surface Area Ratio
BSR	Building Surface Ratio
BUVR	Building Volumetric Unit Ratio
BVR	Built Volume Ratio
CAR	Canopy Area Ratio
CTAR	Net Courts area ratio
CTBDSPR	Courts Block Perimeter Ratio
CTBDSR	Courts to Dissolved Building Ratio
CTBLBPR	Courts to Block Built Perimeter Ratio
CTBR	Courts to Building Ratio
CTchAR	Convex Court Area Ratio
CTchPR	Convex Court Perimeter Ratio
CTD	Courts Density
CTmbgAR	Court Box Area Ratio
CTmbgO	Court Box Orientation
FSD	Front Surface Density
UBR	Unique Building Ratio
VBLAR	Virtual Block Area Ratio
VBLPR	Virtual Block Perimeter Ratio

1 City and sustainability

This chapter draws a picture of the urgency and relevance of the environmental issues raised by climate change. Built environment is identified as the most promising sector to fight this problem because of the actual impact of cities on both global consumptions and economy. The role of citizens in determining urban consumptions is made explicit as well as the global awareness of the current scenario. A quick overview of existing reports and city initiatives in this direction in given. The attention is moved to urban form and its capability to directly affect citizens' behaviours and indirectly play a role on environmental, economic and social performances. District scale is identified as the most appropriate to test initiatives oriented towards achieving a more sustainable urban environment as complex enough but more manageable than the whole city scale. In the second paragraph, the reasons for an inevitable continuous city growth are reminded giving also an ideal environmental perspective. Different urbanization patterns around the world are examined to understand the complexity of the existing framework and the need of developing context-based solution instead of exporting existing practices from developed counties into developing one. The phenomena of megacities, shrinking cities, metropolitan areas, new town and ghost towns are presented in a perspective of uneven growth of population and urban areas.

1.1 Cities and Climate change

1.1.1 The role of cities

Climate change has raised concerns about the future of the world's environment and its resources. This attention has been accompanied by expressions of good intention by governments worldwide. There has been wide ranging discussion about the importance of achieving inter- and intra-generational sustainability (M. (Michael) Jenks, Burton, and Williams 1996). All the sectors are asked to reduce their environmental impact but not all of them have the same impact on global scale and the same possibilities to put in practice some consistent changes. International programs and policies have indicated that the built environment is the most promising sector for a rapid transition to sustainability (Ghaffarianhoseini et al. 2013)

In the last two centuries, the progressive and intense urbanization process has reshaped the role of cities: from simple human settlements, cities have become complex systems with multiple functions and nowadays they constitute the core of human activities and economy.

This attention to the built environment is due to energy consumption and greenhouse gas emissions, which, in developed countries, represent 30 and 40 percent of the total quantities, respectively (Berardi 2013). Currently about 80 percent of the global primary energy is being consumed in urban areas and cities are being responsible of more than 60 percent of the total world's green gas emission (World Bank 2010). Today, cities are major consumers of resources and producers of waste having extended their ecological footprints far beyond their official borders (Lenzen and Peters 2009; Næss 2001). Concerns about the quality of the environment, rates of natural resource consumption, and impact on the global environment have generated a new interest in cities' environmental quality and performance. Today, virtually all cities share concerns for the state of their environment (Alberti 1999) and the need for defining sustainable approaches towards built environment is being felt more than ever. A secure plan for future global development will require cities to evolve into more sustainable ecosystems.

This transition towards a reduction of environmental impact passes not only through policies and high level decisions but also from everyday people behaviour. Over 50 % of the world's population currently lives in urban areas, a figure expected to rise to 70 % by 2050 (UN 2014) and this makes the largest part of world inhabitants not only humans but citizens. This makes a lot of difference considering that more than 70% of people environmental impact is due to the energy consumption of houses, mobility and food chain (ANCE 2013). Cities are so also asked to face issues concerning the sustainability and quality of life. This concerns aspects such as food security, mobility, logistics, energy, the availability of water, dealing with raw materials and waste, health and well-being. Considering that 883 million people live in slums today and more than half of urban population were exposed to air pollution levels 2.5 higher than safety standards (UN.org 2019), the need of solutions is pretty urgent.

Fortunately, the most powerful venues for transformative solutions are cities themselves. Cities contain the fundamental ingredients to enable innovation: talent, capital, technologies and networks. City has advantages like choice, services, facilities, intellectual challenge, workplace and education (Hildebrand 1999). We can imagine city as an engine, converting propellant into work, and to reduce the impact of this transformation it is necessary to improve its efficiency and to feed it with clean energy.

Cities are so 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) their further expansion is an inevitable perspective. Sustainable urban development is an important challenge that needs to be faced to support the continuous growth of cities and reduce their environmental impact (James et al. 2015).

1.1.2 Cities in action

Many reports (Agenda 21 1992; Bruntland report 1987; European Commission (EC) Green paper on urban environment 1990) already pointed out the main urban problems as well as the need for an integrated and multidisciplinary approach to urban planning and management and the need for environmental assessment and monitoring within cities (EEA 2002).

City governments are aggressively targeting cities to reduce energy waste and cut carbon emissions developing world-wide ambitious long-term GHG emission reduction targets such as 40 and 60 percent by 2025 (San Francisco and London) or 80 percent by 2050 (New York City and Boston)(NYC Gov. 2014; Walsh 2014). Other programs involve many cities around the world with the same target and are guided by private foundations as Resilient Cities from Rockfeller (Mitroliou et al. 2018), international institutions or groupings of municipalities or local bodies ("C40 Cities" 2014).

These optimization strategies are not only related to a technological implementation of urban elements or infrastructures as means of transport, buildings components and renewable resources. "These elements work as a dressing on cake" (Vahabzadeh Manesh 2012) represented by the urban structure, the arrangement of its components or constituents part. Urban form influences daily life and is an important factor for both quality of life and environmental impact (Nijkamp and Finco' 2009). It is also commonly accepted that environmental sustainability has an effect on the social dimension of well-being (Berardi 2013).

We inevitably affect this phenomenon every time we are asked to intervene on an urban fabric through a modification process. "Just as all acts of urban design are embedded in their local contexts, they are also inextricably embedded in the global context" (Carmona et al. 2003). It means that as local actions have global impacts and consequences, also global actions have local impacts and consequences. For this reason global warming, climate change and pollution are important considerations for architects and planners, no matter the size of their projects.

To contribute to a sustainable development, they need take into account social, environmental and long term economic impacts (Schwartz 2008).

Even if the goal is clear the problem is not so easy to be tackled and solved. Due to their large size, socioeconomic structures and geopolitical attributes the patterns of change in cities are very complex (Mostafavi, Farzinmoghadam, and Hoque 2014). A comprehensive analysis of the dynamic of urban resource flows is critical to understand and address ecological challenges in the path towards a sustainable urbanized planet (AKIMOTO et al., 2008; Vera, & Langlois, 2007)

Working on sub-system of cities, as districts, makes everything more manageable without losing complexity and leaves the possibility of achieving more results than working at the building scale. Previous considerations show that communities are nowadays considered as a proper scale to assess sustainability of the built environment (Mori and Christodoulou 2012). Unfortunately, the best spatial entity to tackle environmental issue lacks in data and requires complex simulation to overcome this limit (Howard et al. 2011). In fact the actual top-down model for energy and more generally performance monitoring extrapolate values from the status quo and is hence less suitable when more integrated energy supply-demand scenarios are being investigated or when an analysis focuses on a specific neighbourhood (Reinhart & Cerezo Davila, 2016). The district scale would benefit of a bottom-up approach based on buildings as data collectors, aggregable to need in different spatial units.

In this framework, is clear that there's a growing market demand for environmentally friendly and energy efficient approach that can be labelled as *green design* (Schwartz 2008). This label synthetizes awareness, respect for nature and reduction of negative human impacts in every process. It may also be defined as the art of designing physical objects and the built environment according to the principles of economic, social, and ecological sustainability.

1.2 Urbanization framework

1.2.1 The city paradox

Even if we have just seen how cities are responsible for the current environmental situation, we should also remember how cities are usually seen as more energy efficient than surrounding areas (Boyko and Cooper 2011). Burchell & Listokin (1982) suggest the following reasons:

- Urban buildings consume less energy because of their density and compactness.
- Cities benefit from good transportation and commuting travel.
- Cities can easily capitalise from more efficient energy systems.
- High-density developments and mixed land uses may contribute to better efficiency.

Also for this reasons the United Nations estimates that the number of city-dwellers worldwide will grow until 2030 at a net rate of about two million per week (UN 2014). The other side of the coin is that urban dwellers have higher individual consumptions as their basic necessities are more than countryside inhabitants. The presence of more services, alternatives and opportunities pushes people to perform many activities not strictly essential that in the end balance the above mentioned advantages.

It's clear that the positive effects of these principles in support of urban agglomeration vary incredibly from city to city. The consistence of the urban components and their ligands determine the level of performance of an urban system. In fact, even if built with the same elements (buildings, streets, transportation system, services and activities), urban areas around the world present huge differences among them.

1.2.2 Urban forms and challenges

Currently, debates over urban form have generally focused on the contrast between the "sprawl", often seen as typical of the United States, and "compact" urban forms, found in parts of Europe. Although these debates are presumed to have implications for developing worlds as well, systematic comparison of urban forms between developed and developing countries based on urban patches spatial metrics highlighted the broad differences in urban form between the developing and developed worlds (Figure 1). Generally, the cities of developing regions exhibit the least complex, most compact, least porous, and densest urban forms. Cities of developed regions display diametrically opposed tendencies (Huang, Lu, and Sellers 2007).

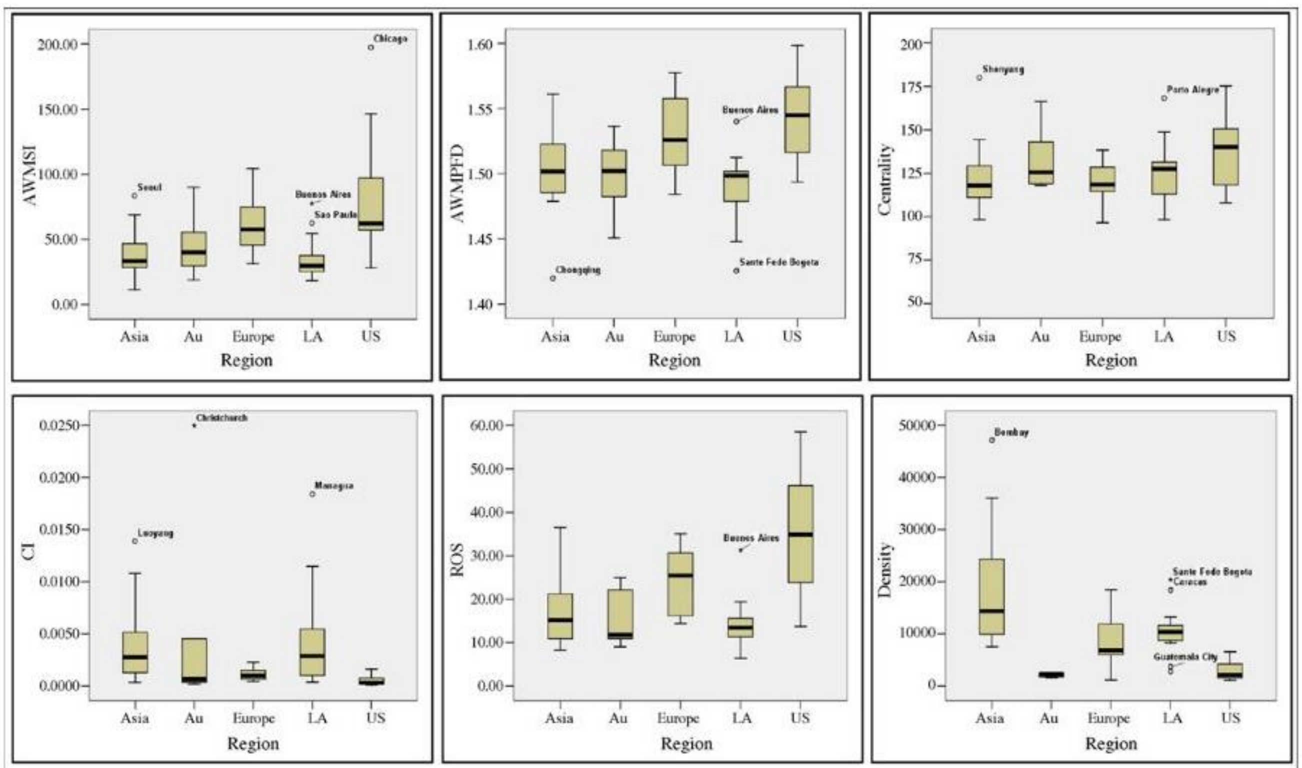


Figure 1 Comparison of spatial metrics (AWMSI; AWMPFD; CI; ROS; PD) across regions. Box length represents the difference between the 25th and 75th percentiles. The horizontal line inside the box represents the median. Dot and star labels symbolize outliers.

Physical factors like geographical location, topography, water bodies and coastlines, regional patterns of economic, political and social development bear a well-established relation to urban form (Berry, 1973; Hawley, 1986; Hall, 1997).

The models of the developed world, whether from Europe or from North America, cannot be exported without major adaptations. Disordered as Asian and Latin American cities are, their form bears little resemblance to the sprawl of the United States, Australian and some European cities (Huang, Lu, and Sellers 2007).

Every context has its own specific characteristics and challenges to be faced. In the current scenario of urban development we witness two extreme phenomena: the population boom in mega cities and the decline of shrinking cities. These two trends cause dramatic tensions of growth and contraction to existing urban fabric, and together with climate change and scarcity of natural resources, set the political agenda on sustainable urban development and urban regeneration. Furthermore, the topic of new towns built from zero is very much on top of the table, not only in the fast growing Asian countries like China or the Arabic peninsula, but also in countries like The Netherlands, with the creation of the International New Town Institute, and the United Kingdom, with the goal of the Eco-Towns programme to build ten new eco-towns by 2020 (TCPA 2007). There are also urban settlements without any human presence, physical structures waiting for life to come or where life has left decades or centuries ago. These are ghost towns and are spread around all the world with different and complex dynamics (Michael Batty 2016).

Large part of this development is not planned and spontaneously concentrates in proximity of big cities in form of informal settlements, mainly residential, that during the years transformed these contexts into megacities of more than 20 million people. This phenomenon is gaining ground mostly in Asia, Latin America and Africa (Berardi 2013). These kinds of settlements hardly fit the points of Burchell and Listokin (1982) at the beginning of the chapter as they occur in absence of typical urban infrastructures, consuming a lot of soil and can hardly be permeated by the transportation network.

1.2.3 European and Italian context

In the European Union, about 80 % of the population lives in cities and towns, which are therefore the places where the environmental problems most touch the quality of life of citizens. European urban areas suffer from the increasing use of energy, natural resources and pressures on living space even if the population increase is relatively small (EEA 2002).

Cities grown very quickly in the past decades much more than the population they host. Sprawling came because of land consumption on a static demographic scenario, reducing agricultural land and increasing average commuting distances. Satellite cities, dormitory neighbourhoods and gentrified compounds depend from the historical compact city as the above mentioned informal settlements. By the way they have been generated by a totally different geographical, social and economic context.

Cities in Europe have also a completely different size in respect of global megalopolis. In fact, except for London and Paris, often excluded from investigation samples, medium size cities and towns host the majority of European urban population. There are also European vast conurbations, called metropolitan areas, which are atypical spatial entities including more than one administrative centre. The metropolitan area of Milan for example includes the cities and part of the provinces of Monza, Lecco, Como and Varese, reaching a population 8 times higher than the sole city of Milan. In respect to the megalopolis in developing countries, these areas have a polycentric ramification mainly due to the slower growth rate speed. Many historical centres, surrounded by uniform suburbs can be found in a landscape that is not completely filled by construction.

2 Cities definitions and approaches

After understanding the object of study, this chapter tries to deeper investigate both city and sustainability starting from official definition. It overpasses the debate on sustainability definition, referring to the specific literature, to focus on the term city. With a matryoshka-like operation (city-town-village-hamlet-settlement), driven by mutually referring definitions, the term is reduced to its smallest examples in order to understand its basic components (Volume, Void, Link, and Function). Definitions by architects, urban planners and researcher from other disciplines are mentioned making an overview of approaches and perspectives on the urban environment. The link between some of these definitions and the corresponding representation is explained as well as the role of components as affecting different point of view. The variety of definitions, often complementary and not contradicting, reflects the complexity of the topic and the need of a systemic approach.

More detailed description about some existing approaches follows, starting with the rating systems for measuring performances, going through urban morphology and building typology for the characterization of urban structure and finally to system theory as a comprehensive framework able to integrate the other two methods and find their proper role and position.

The evolution of rating systems from the building to the community scale is presented together with the currently employed approaches, themes and indicators. An overview of existing community rating system is provided and the most popular three are deeper analysed to understand common and unique features. It emerges that all nearly have the same structure, approach and limit: a lack of context awareness and modelling capacity. They need to be integrated with a measurable study of urban structure to really represent performances and not a mere list sizing performance related elements.

Urban structure is investigated through the combination of urban morphology and building typology, linked by a multi-scalar relationship. The two concepts are first literally defined and then seen in the architectural debate, mainly developed in Italy during the sixties. The notion of type is widely discussed and distinguished by similar possibly misleading terms as prototype and archetype. Morphology studies city structure and the arrangement of its components while typology can group and classify these components according to common characteristics. Examples of possible criteria to be used for the classification of buildings are presented (form, function, age, material, position). The ones requiring only formal and geographical attributes, more coherent with research topic, are better investigated. Typology emerges as a tool able to intertwine different morphological units (buildings, blocks, courts) for two reasons. First of all their reciprocal position and interaction can be used as a grouping criteria and then, they all can be the object of a classification. In the perspective of the development of efficient measurement methods for morphological aspects, proposed by the research, the typological debate can become again actual and benefit from data science methods in order to create semi-automatized classification algorithms as the result of segmentation or classification processes

At last, system theory is presented as the approach able to connect and integrate the previous two. The definition of Complex Adaptive System (CAS) is gradually revealed passing by the one of system, complexity and adaptation. Then, the advantages of studying the city as a CAS are presented. Among those the capacity of urban systems to learn from their past experience. Some possible agents (people, buildings, trees, open spaces…) and their role are introduced as a link to discuss the concept of subsystems and the possible dismantling processes. Both from the functional and scalar perspective, subsystems affect each other and their mutual relationship is useful to understand the city performances and structure after being dismantled. System theory is then presented as a common language for exchanging knowledge between different disciplinary fields. The example of the relationship between human/urban and natural system is presented together with the analogy between a city and a forest. In conclusion, how to investigate a CAS given its complexity is discussed. A combination of historical, comparative and experimental approach is suggested in opposition to every possible attempt of simplification.

2.1 Definitions overview

2.1.1 Literal Definitions

The recent multitude of interpretations that sustainability has received indicates a resistance in the acceptance of an official definition (Berardi 2013). Despite this vagueness the word is frequently and not always properly used. Without entering this debate, already widely discussed, we may agree that if something becomes more sustainable it is positively affecting climate change and is so a goal to be achieved, also in the urban environment. The definition of city is of much interest for the research as it allows to better know the context we are asked to intervene with sustainable strategies.

The term *city* comes from the Latin word *civitas*, from *civis* (citizens). The term is used to identify a large town that usually host a cathedral. *Town* can be defined as a built-up area with a name, defined boundaries, and local government, which is larger than a village and generally smaller than a city. It comes from them Old English *tūn* (enclosed piece of land, homestead, village).
It's also used to identify the central part of a neighbourhood, with its business or shopping area. Following this down-scaling process we look for the definition of village. A *village* is a group of houses and associated buildings, larger than a hamlet and smaller than a town, situated in a rural area. This word also comes from the Latin villa (country house). *Hamlet* can be defined as a small settlement, generally smaller than a village and without a church. The origin of the word is more recent than village as it comes from the Old French *hamelet*, diminutive of hamel (little village), and relates to home (*hám* in Old English).
Settlement closes this list and refers to the act of colonization defining a place, previously inhabited, where people establish a community. A place where one or more families decide to live permanently and can so be called home (Encyclopaedia Britannica).

In *Politica,* Aristotele defines the city as the association of more villages and the village as the association of more families with a common intent. He also says that city is self-sufficient and born to achieve the perfection of existence.

Cities are not static objects and evolve through time. They grow, shrink, merge, can be destroyed or abandoned for many different reasons. The actual conformation of existing cities is only a point on the timeline of their evolutionary path. On this timeline it could be possible to see the disappearance of a city even with the persistence of its physical consistency. This can be explained by the phenomenon of synekism (Soja 2000), the union of several small urban settlements under the rule of a "capital" city and their absorption into a unique composite urban fabric with time. Former towns or villages can so become neighbourhood of a larger expanding city. This make meaningful considering a city as an entity that inherits the properties of all the other kind of smaller settlements that could be part of it.

Merging all the definitions we can identify the fundamental components of a city. City is a spatially defined area (Void), separated but connected to the countryside, made up of group of houses and other public buildings (Volume, Function), where communities of citizens (Agents) live, move (Link) and recognize themselves in its name. We also notice that the scale of a city, or its hierarchical position in a region, can be explained by different aspects related to the above mentioned components. A city is usually more densely built and populated (Volume), more accessible (Link), larger (Void), and host higher level functions than the surrounding settlements.

2.1.2 Disciplinary Definitions

The architecture field is in between art and science. Concepts, differently from harder scientific disciplinary fields, use to have multiple definitions resembling aphorisms more than axioms. Every architect is involuntarily asked for its own definition in order to start working. Great personalities of architecture and planning world left a legacy also thanks to their definitions of architecture, design, house and city. After the Second World War the definitions or associations of idea related with cities multiply. These definitions mainly represent a specific point of view, usually focusing on one of the components, and are so not necessarily in conflict between them but can coexist.

Many authors associate one word to the term city synthetizing a specific approach to the topic. Some examples are City Region (G.De Carlo, 1962), City Territory (L.Quaroni, 1962; A.Corboz, 1991), Ipercity (A.Corboz, 1993), highlighting the interdependence of urban areas with their larger region; Invisible City (A.Isozaki, 1966),Simulated City (T.Ito, 1991) to stress the loss of physical boundaries and distinction between city and countryside and between real and virtual world; Point City (R.Koolhaas, 1978) taking to extremes the compactness and density of people and activities; Collage city (C.Rowe, F. Koetter, 1978), Patchwork- or Carpet-Metropolis (A.Neuteling, 1990) to reassume the variety and historical stratification of different parts of the city and their recognizable urban fabric; Reticular City (B.secchi, 1988; G.De Matteis, 1990) characterised by the inversion of void and volumes from traditional grid fabric; City Cloud (F.Maki, 1979) in contrast with the City Clock vision in a dichotomy of chaos and order. Also authors from other disciplinary fields approached the topic suggesting contaminations and new point of views: Thermodynamic of open systems (Prigogine et Stengers, 1979), Game theory (Calder, 1967) Information theory (Taylor, 1972; Forrester, 1969) Complexcity (Batty, 2013).

For Alberti (1485) and Palladio (1570) city is a big house and house is a small city. This definition is of particular interest for its multi-scale implications as will emerge from the research. Milizia (1813) compare the city to a forest, where there’s need for order and whimsy, eurhythmics and variety. There’s a sense of order coming from a sort of confusion and chaos resulting from regular parts. According to Cattaneo (1858) city is the central idea of history, the only constant while men, war and conquers passed away. Weber (1920) identifies many requirements for a settlement in order to be considered a city. Among those, being a place of exchange, a market place, where producers and consumers meet plays a key role. Le Corbusier writes about city in different moment of his life. In Urbanisme (1925) city is seen as a working tool, an affirmation of man over nature, a human organism that guarantees safety and work, a creation. On the opposite Mumford (1938) considers it a natural fact as a cave, a nest or an anthill. At the same time it’s also a conscious artwork and the place where thought takes shape. In the negative acceptation proposed by Lavedan (1936) we have city where man dominates nature and law cages individuals. For George (1961) city is a demographic unit. It’s a variable organism with a proper dynamic and rhythm of development that attracts inhabitants from the outside in different measure. According to Jacobs (1961), towns are mechanisms for generating contact and problems in organized complexity. Rossi (1966) in “The Architecture of the City” describe it as an organism made of architectural artefacts, highlighting the link between building typology and urban morphology, and a fix theatrical stage of human life. He also divides city into two systems: one functional, coming from the analysis of social, economic and political systems, and one spatial, related to architecture and geography. Mumford agrees on the theatrical analogy (1973) defining the city as the theatre of social drama. Lefebvre (1972) see the city as the place of economic and politic power but also as a place of contradiction as it gather population, needs, claims and aspirations allowing political struggle. More poetically, for Louis Khan it's a muse, a source of inspiration. According to Salat et al. (2011), cities are "living organism" that born, grow, age, and die. Bettencour (2013) draws a perspective of cities as integrated social networks imbedded in space and time.

Other couples of words refer to particular ideas of city the developed in a specific historical period sometimes belonging to an ideological movement. Some examples are: Walled City of the middle ages and not only, Ideal City from the renaissance and its link with cosmic order, Industrial City of the XIXth Century, Garden City by Ebenezer Howard at the beginning of XXth Century, Linear city by Arturo Soria y Mata constructed on a rail transport infrastructure (in Portoghesi 1968).

2.1.3 Definition and representation

There is a close relationship between definition and representation as they are both related to description. City can be represented in many different ways at different scales. Not necessarily every definition has its own representation but some maps are intrinsically linked to one definition. Schwartzplan black and white maps focus on the contrast between Volume and Void component drawing a clear picture of urban morphology. This point of view has been taken by many researchers in order to describe qualitatively or quantitatively urban fabric. Adolphe (2001) research focuses on urban structure and its volumetric consistency, considered as a rigid solid skeleton. Biraghi et al. (2019) apply the same principle finding an analogy between urban studies and hydraulics. They study the city as a porous media in order to apply some measures coming from that disciplinary area (Figure 2).

Figure 2 Top: pictures; Bottom: black and white map; Left: Milan city centre; Right: Stone sample; The same representation allows to compare different objects sharing tools and techniques

Theories focusing on connections benefit from graph theory abstractions. Graphs can be physical as the street network or immaterial like social interaction. Number of researches is growing thanks to the use of user generated Big Data coming from social networks and other applications on mobile devices. Rating systems, when not strongly context-based, may risk to represent the city as a chart, a set of requirements to be satisfied. City can be represented by a number, in the brave and irresponsible attempt to describe it with a sole index, or by a diagram describing something about one specific feature through a set of values.

2.1.4 Conclusions

As previously mentioned these approaches are not in conflict as they are generated by looking at the same object from a different perspective. The immaterial network of connections (Functions), in order to become material, need to adapt to the existing urban structure and is so affected by the conformation of Void and Volume components. The underground transportation system, i.e., limits and is also limited by the presence of Volumes. There is actually no limit to the perspectives to look at an object. If we imagine the city as a point in space, there are infinite other external points to look at it from different distance, angle and position. In addition, also the molecular or atomic structure of this point can be investigated from the inside and the only existing scale limit is given by our technological progress. The most important thing is understanding that one perspective alone is not enough to completely describe the complexity of the city and that every aspect is intrinsically linked to the others with patterns yet to be understood.

After this short overview I decided to deeply explore only some of the presented conceptions and the following approaches to urban environment. I start with the rating systems for measuring performances, go through urban morphology and building typology for the characterization of urban structure and finally to system theory as a comprehensive framework able to find the proper role and position to the other two methods.

2.2 Rating Systems

2.2.1 Building Rating systems

The sustainability assessment of the built environment was addressed with rating tools for buildings more than two decades ago (Häkkinen 2007). Sustainability assessment systems for buildings were first developed in Europe and North America, before diffusing worldwide (Sev, 2011; Berardi, 2012) Although there is a high demand and attention to green buildings, these have demonstrated insufficient to guarantee the sustainability of the built environment (Häkkinen, 2007; Cole & Jose Valdebenito, 2013). Recent literature has discussed the importance to go beyond the sustainability assessment of single buildings and to enlarge the assessment scale to communities and cities (Turcu 2013; Berardi 2013).

Sustainability assessments at the community or city level are proving to be much more than the summation of individual green buildings and infrastructures (Haapio 2012; Mori and Christodoulou 2012). The switch to a larger scale cannot be considered simply as the aggregation of sustainable objects, as scaling up results in complex interactions (Berardi 2013). One of the main critiques of sustainability assessment on the building scale in fact has been its inability to capture what makes a built environment sustainable for its citizens (Rees and Wackernagel 1996).

Although all green building rating systems differ in terminologies, structure, performance assessment methods, relative importance of the environmental performance categories and documentation requirement throughout certification, they seem to focus on the same five aspects of building design and life cycle performance: site, water, energy, materials and indoor environment (Schwartz 2008).

Pope et al. (2004) and Tanguay et al. (2009) have offered a review of available indicators for measuring sustainability. They showed that most of the currently used indicators are characterized by a strong environmental approach. This is evident considering indices such as the Ecological Footprint, the Water Footprint, the Environmental Sustainability, and the Environmental Vulnerability.

Multi-criterion systems are gaining increasing attention as they are easily understood and allow a step implementation for each criterion (Berardi 2012). However, one of the limitations of multi-criterion systems is their additional structure, basing the overall result of the assessment on the sum of different evaluations.

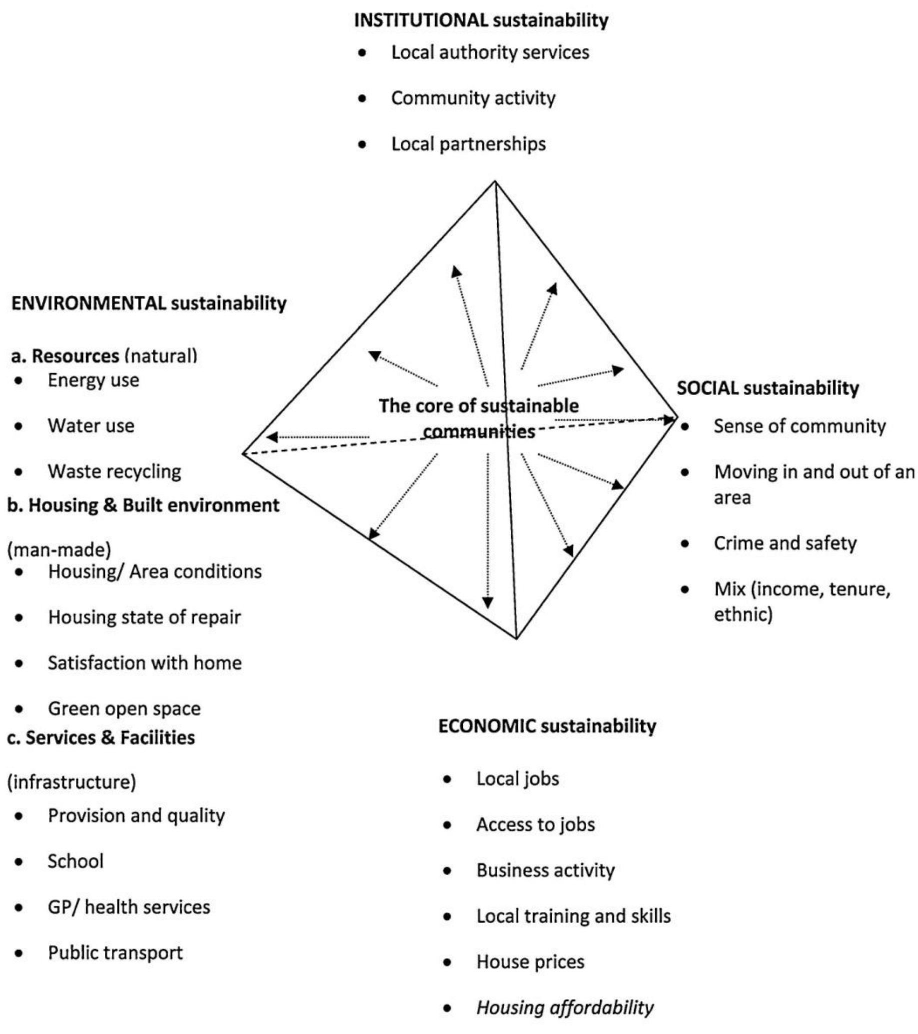


Figure 3 List of indicators main areas for the assessment of sustainable communities (Turcu 2013)

The framework in Figure 3 should be taken as a reference which leaves the opportunity to contextualize different visions of sustainability also by assigning different (relative) importance to each criterion (Berardi 2013).

2.2.2 Community Rating Systems

Berardi (2013) reviewed the most popular and widely used existing rating systems at the scale of urban communities, also referred to as the neighbourhood or district scale, in order to understand if they are able to assess different dimensions of urban sustainability and which criteria are most widely adopted. The systems considered below have been created in the last few years in Europe, USA and Japan.

The three systems are BREEAM Communities (Com), CASBEE for Urban Development (UD) and LEED for Neighbourhood Development (ND). Aside from their worldwide adoption, they were selected because BREEAM, CASBEE and LEED protocols have already reached a significant diffusion for sustainability assessments of buildings, and they promise to diffuse also to communities.

The British Building Research Establishment Environmental Assessment Method (BREEAM) can be used for both new and regeneration development projects. BREEAM Com assesses the environmental, social and economic impacts of a community. The assessment criteria are divided into eight categories: Climate & Energy, Resources, Place Shaping, Transport & Movement, Ecology & Biodiversity, Buildings, Business & Economy and Community (BREEAM 2009). At this time, BREEAM Com has been experimentally applied to Media City in Manchester (UK) and to Masthusen and Varvsstaden in Malmo (Sweden).

CASBEE (Comprehensive Assessment System for Building Environmental Efficiency) is a Japanese rating system based on life-cycle evaluations and considers two main kinds of criteria: performances and environmental loads. CASBEE results are presented as a measure of eco-efficiency on a graph with loads on one axis and quality on the other, so that sustainability for CASBEE corresponds to the lowest environmental loads and the highest quality (CASBEE 2007).

LEED (Leadership in Energy and Environmental Design) for Neighbourhood Development (ND) is a system developed by the US Green Building Council. LEED seeks to optimize the use of natural resources, promote regenerative and restorative strategies, maximize the positive and minimize the negative environmental and human health consequences of the construction industry, and provide high-quality indoor environments for building occupants. LEED sets a challenging yet achievable set of benchmarks that define green building for interior spaces, entire structures, and whole neighbourhoods (USgbc 2014).

Berardi (2013) select seven main categories for the assessment criteria of each system and computed their average weights: sustainable land 33% (sustainable planning, design and buildings, microclimates), location 9% (previous land use, reduction of sprawl), transportation 13% (pedestrian, bicycle or public transportation), resource and energy 16% (use and selection of materials, waste management, energy production and efficiency), ecology 21% (biodiversity), economy and business 3% (employment and new opportunities) and well-being 5% (quality of life).

Neighbourhood pattern and design criteria as Walkable Streets, Compact development, Connected and open community, Walkable streets, Reduced parking footprint, Street Network were also included in the rating systems and often evaluated in a subjective and qualitative way.

Other neighbourhood Sustainability Assessment Tools (NSA) are also currently being applied around the world in addition to the above mentioned three. These are: ECC, USA; HQE2R, European Union; Ecocity, European Union; SCR, Australia; QSAS, Qatar; Green Mark for Districts, Singapore; NSF, New Zealand; HK-BEAM, Hong Kong; EcoEffect, Sweden (G. Zhao and He 2016).

There are also Italian systems and the most relevant are “GBC Quartieri”, similar to LEED and promoted by Green Building Council Italy, and ITACA protocol (Institute for Contracts Innovation and Transparency and Environmental Compatibility)(Mauri, Mazzucchelli, and Sala 2018).

2.2.3 Limits of existing methods

An important aspect in multi-criterion systems is the selection of the criteria. Unfortunately, reasons behind the choice of the criteria are not explicitly discussed by any of the responsible agencies (Haapio 2012).

Bourdic and Salat (2012) criticized existing systems because they only assess the different criteria by comparison with benchmark values, and stated that there is no quantitative evidence that a high-rated community emits less carbon than a lower-rated one. Considering the unscientific selection of the criteria, their weights and the benchmarks, this critic is difficult to overcome. Moreover, the aggregated level of assessment, which synthesizes the evaluation in one single rate, reduces the ability to deliver a robust and transparent output (Mori and Christodoulou 2012).

Another limitation of existing systems is the adoption of a static perspective. In these systems, the assessment is a process realized once at the beginning of the urban community development. However, recent definitions of sustainability have encouraged looking at this as a moving target, showing that assessments done at a single time are not sufficient (Brandon and Lombardi 2011).

Instead, continuous evaluations should be incentivized, in a way that sustainability assessments become an interactive process, which could be used to map the evolution of the urban development (Bentivegna et al. 2002; Lowe 2008). This corresponds to the use of assessment systems as diagnostic tools for in-progress programs.

The analysis of existing systems has shown a link between the assessment systems and the context in which they have been developed. This relationship limits the use of these systems in other countries, unless the criteria are modified to consider the culture and laws of those countries (Haapio 2012). According to this limitation, BREEAM has recently made available different regional weightings in order to account the different priorities among the regions of the UK (Berardi 2013).

Despite the evidence provided by the literature about the importance of the different dimensions and contexts in the urban design process, LEED ND seems not to follow those concepts. Thus far, even though it was created by defendants of ‘new urbanism’, ‘Smart Code’ and the ‘Transect-based’ map, no mention of context-sensitivity appears in the pilot version.

While the new LEED ND rating system has done a good job on bringing attention to many of those matters, it still doesn’t consider vital aspects of good design such as contexts and identity. For instance building a massive green structure, out of scale in a century-old downtown area could be a threat to downtown’s positive qualities, no matter how well it would score in the rating’s checklist. LEED ND at this point seems to lack a focus on good contextual design. The same could be argued about not considering differences in climate and culture which could undermine environmental or liveability issues. Still, we need something more than that: we need projects that fit their cities like a glove (Schwartz 2008).

2.2.4 Conclusions

What appears as the main limit of rating systems in general, and in particular at the district scales, is the difficulty of taking into consideration the physical properties of the context. The attempts to include this dimension produce hardly measurable results, often subjective and not replicable on different contexts. Rating system clearly measure performances through set of indicators that risk to be disconnected from the reality they represent. Simply counting the presence of a certain element doesn't give information on its functioning inside the urban system and, consequently, the way in which it really affects performances. Fortunately there is another body of knowledge focusing exclusively on urban form and its constituents that, if properly investigated, could be integrated with rating systems in order to achieve more context-aware results. The disciplines studying urban structure are urban morphology and building typology and Politecnico di Milano gave a great contribution in the past decades to their implementation and diffusion.

2.3 Urban Form

2.3.1 Urban Morphology and Building Typology

To think global and act local means dealing with the elements and having the image of their composition as a unit simultaneously. As Jane Nicolas Durand wrote, "Just as the walls, the columns, & etc., are the elements which compose buildings, so buildings are the elements which compose cities (Rossi, 1982). For instances, if one wants to work on urban morphology and its performance, the conscience of the building typology is a vital fact that cannot be excluded (Vahabzadeh Manesh 2012).

Between the two facts of building typology and urban morphology a revealing binary relationship exists and the study of this relationship is extremely useful for understanding the structure of urban artefacts (Rossi et al. 1982). The concept of type aims to order the experience according to schemes that reduce to a finite number the infinite possibility of existing phenomena. This, in the end, makes it an operative tool from both cognitive and constructive point of view. This notion, widely used in other disciplines from mathematics to sociology, in architecture has a closer relationship with the form and can be defined as quasi-shape of a phenomenon (Gregotti 1966).
As clearly emerge from Durand words the link between urban form, urban morphology and building typology is multi-scalar. Each discipline has its own representation scale and corresponding object to be investigated. Urban form looks at the whole city often represented as a urban patch; urban morphology studies for large areas of the city the urban fabric that is ultimately composed by blocks and streets; Building typology cast light on the finer grain elements composing the indistinguishable volume masses of the previous scales.

Morphology can be defined as the study of the forms of things. It is mostly used in biology and studies the size, shape, and structure of animals, plants, and microorganisms and of the relationships of their constituent parts. The term refers to the general aspects of biological form and arrangement of the parts of an organism. (Encyclopaedia Britannica) Considering city as a living organism, as we'll see in the complex system framework, allows to analyse its structure and constituents according to the same principles used for natural sciences.

Urban morphology studies urban form, shape and structure. This structure is the result of the interaction of multiple morphological elements representative of a city. These are mainly buildings (Volumes) and streets (Voids). Streets arranged in a network delimit some portion of land, called blocks, which can host both Volumes (building) and open or closed Void spaces (courts). The existing literature mostly focused on buildings as in the end they can be considered the primary element of a city. There can be no court without buildings and also street will have no reason to exist if not for connecting people or activities, both hosted inside buildings.

Typology is about system of grouping or classification, based on the definition of types. The concept of type has been widely discussed in the last centuries. Starting from natural sciences in the XVIIth century, it has been applied to many other disciplinary fields including architecture. A *type* is a category of thing having common characteristics. The members of a type are identified by postulating specified attributes that are mutually exclusive and collectively exhaustive (Encyclopaedia Britannica).

2.3.2 Typological Debate

One of the key authors in the typological debate is Quatremère de Quincy. He distinguish type from model affirming that everything is given in the model while everything is vague in the type (De Quincy 1844). The model is an existing object taken as reference for an accurate copy, while the type is a sort of generative rule for all possible objects, including the model. Type is something permanent and complex that stands before and behind the shape. Types are, in a certain sense, self-made through the centuries-old use that found for necessity the best shape (Valéry 1921). Type is not formulated a priori, it's always deduced from a series of examples with an evident formal and functional analogy. It's a common scheme deduced by the reduction to a base-shape of a set of formal variants. This base-shape can be intended as structural frame or inner topological structure (Argan 1966). Caniggia (1963) gives a name and a precise shape to this ideal base-shape. He affirms that all existing types derive from an initial matrix. The variations or specialisations from this base-type, a 5mx5m mono-cellular house, are called pseudo-types.

Some terms are similar to type and can be confused with it even if they have a different meaning. We briefly introduce them in order to avoid improper uses. *Archetype* is a primordial image, character or pattern that recurs through literature or history. It comes from the Greek word *arkhétypon*, first example. In a certain sense it comes even earlier than type as it refers to very elementary constructs. It also represents a constant aspiration for the work of an architect, a moment harmonious convergence of morphologic, technical and expressive terms (E. N. Rogers 1965). Archetype links architecture to its primordial reasons and represents an expression of truth and expressive clarity (Rossi 1964).

A *prototype* is in the common language a first or preliminary version of something from which other forms are developed. It's the reference model for future development and the most characteristic example of a specific kind. The prototype, differently from type, exists in the real world and is not a sum resulting from the abstraction of a set of similar objects. Type emerges through time while prototype suddenly appears as something completely new. The logical method considers the original work as capable to generate series of analogous shapes. This allows to consider it a prototype (Argan 1966). Also Aymonino & Fabbri (1966) consider it as the first example or model, associating this concept to the work of the French architects of the age of the enlightenment.

2.3.3 Typological classification

Classification is a limitation, result of an abstraction or schematic reduction performed in the comparison of a certain number of objects (Grassi 1967). Typological classification doesn't imply any artistic or historical evaluation: both masterpieces and common objects from any time and place can belong to the same typological class (Argan 1966).

There is not a unique possible typological classification of buildings. A major distinction can be done between form-based and function-based categories. Other criteria used for example for the TABULA project (Loga 2009) are age and material of construction. Considering the research interest on the relationship between Volume and Void, only form-based classifications are taken into account and presented.

Tricart and Rossi (Rossi et al. 1982) proposed a four type classification distinguishing: a block of houses surrounded by open space (isolated block), a block of houses connected to each other and facing the street (row houses, sided block), a deep block of houses, and the houses with closed courts. Holl (1980) elaborated a further number of sub-categories of houses, such as the "L" house, the "H" house, the "T" house, or the "U" house, etc. according to their form and their resemblance to the letters of the alphabet. Belgium Census for example defines the following types: apartments, terraced houses (attached on both sides, called Terraced), detached houses (Detached), semi-detached houses (attached on one side, Semis) (Thomas, Tannier, and Frankhauser 2010).

These distinctions are based on building shape, position respect to other buildings and respect to the lot and the street. Typology is a characteristic that intertwine different morphological units, which together constitute urban fabric and city form. Every classification criteria is valid and the research doesn’t need to select one over another as the most important point is understanding their generative role in the construction of urban form. Biraghi et Al. (2019) presented at the International Seminar on Urban Form (ISUF) the result of an exercise done with students of the course of Urban Morphology and Building Typology. They constructed a sheet where buildings, represented by a simplified axonometric projection of its volume and lot, were assigned to a typology according to a combination of Rossi and Holl criteria (Figure 4).

What has been said for buildings can be applied also to other spatial units as blocks, districts and even the whole city. Rossi (1964) recalls the urban landscape concept from Georges Chabot and the three order of scales (street-block, district and city) as suitable for classification. The block, i.e., is the intermediate element between the building and the city. This element can be defined according to constant characterizing features. Monestiroli (1979) classify the blocks of the pre-industrial city according to the prevalent typology of the buildings they contain in: terraced blocks (row block or court houses), block blocks (all area and sides of the block are occupied), court block (buildings arranged to compose a unique inner court).

The interesting aspect is that block can be studied either according to their own formal properties either on the properties they inherited from the up-stream elements contained in them. A block attribute, i.e., could be the result of a statistical operation performed on one or more building attributes included in it. The work of Schwartz (2008) should be read in this direction. She identifies eight different neighbourhood types in the relation to five different criteria that range from the more urban area (Central District business) to the more rural areas. Biraghi et. al (2019) make an analysis of a large number of urban blocks going from the city centre of Milan to more peripheral areas on the north-east axis of Corso Venezia and Corso Buenos Aires visually classifying them according to their size, shape, depth and to the typology of the buildings inside them. Figure 5 is taken from this work and represents a synthetic sheet gathering some block examples for the above mentioned classification criteria.

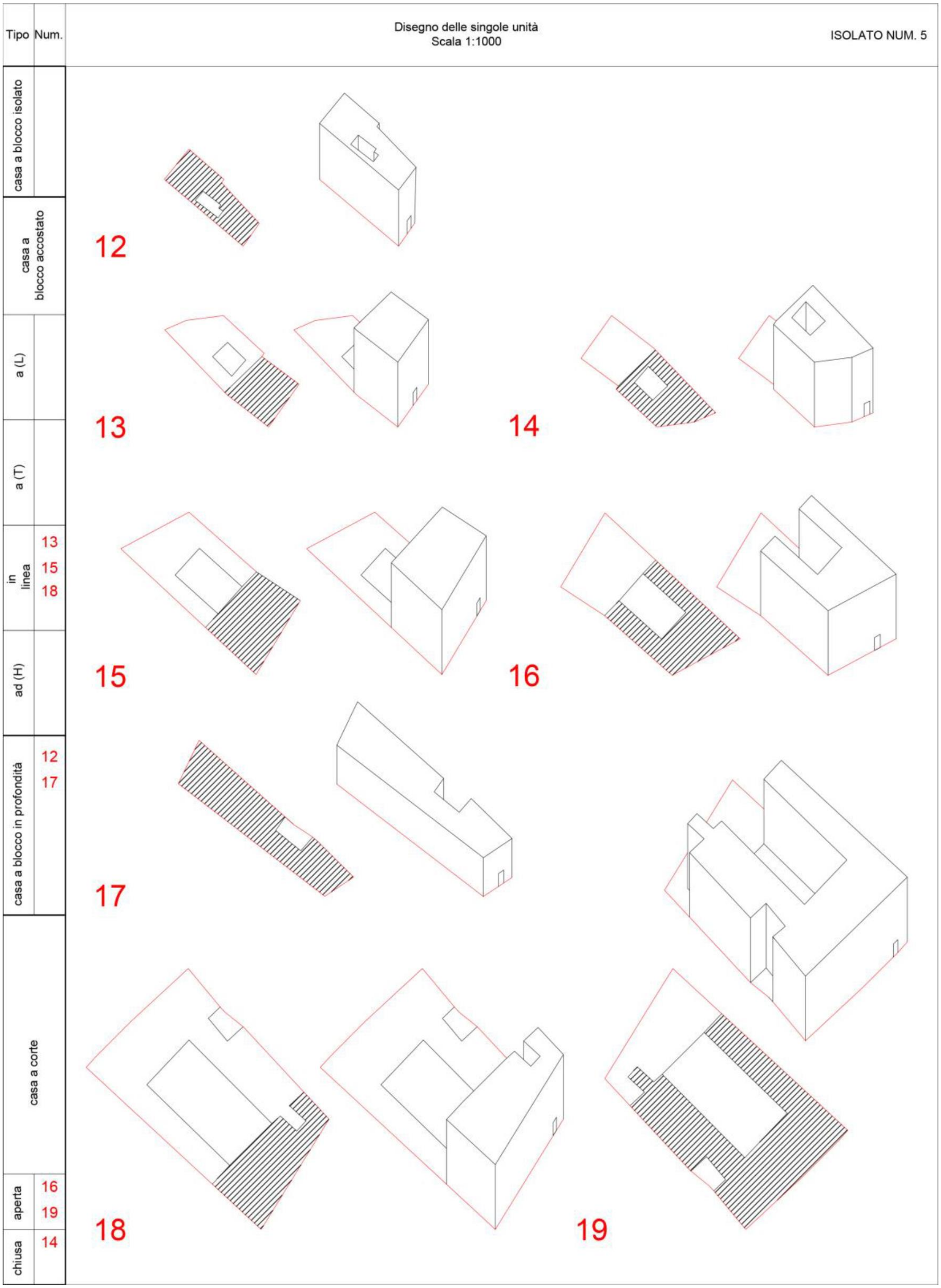


Figure 4 Classification sheet. Buildings of a block are separated and the corresponding typology is identified (Biraghi et. al, 2019)

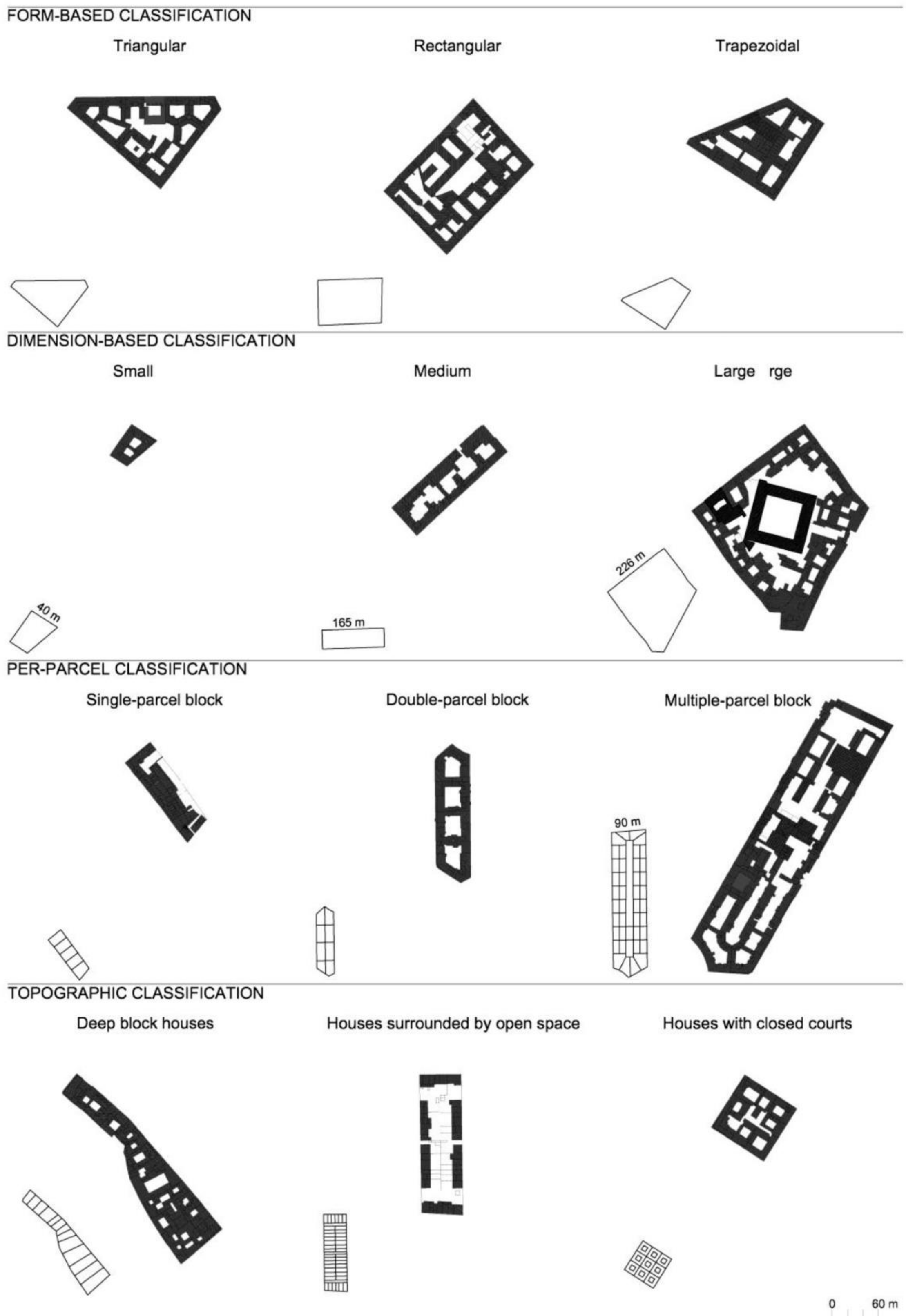


Figure 5 Classification of Milanese blocks according to shape, size, parcel and building type (Biraghi et. al, 2019)

2.3.4 Conclusions

Moneo (1999) underlines the importance of the typological issue but shows some doubts on the possibility of further disciplinary developments. In reality typological studies can live a second golden age thanks to the huge amount of urban data availability and to the possibilities offered by data mining tools and techniques. This research wants to make a long step in this direction by defining new methods for the characterization of built environment and a consequent machine learning-based typological classification.

The need for the definition of building types is underline by many authors. One of the main reasons for that are bottom-up energy modelling purposes (Reinhart and Cerezo Davila 2016a). The type approach has been extensively used in the context of national or regional bottom up building stock models to understand the aggregated impact of energy efficiency policies (Firth and Lomas 2009) and new technologies (Dall'O', Galante, and Torri 2012). The generation of archetypes requires a segmentation process where the investigated building stock is divided into groups according to a certain number of attributes (Loga 2009; Tuominen 2015). These groups can be then characterized with additional standardized values. This last step can be based on a sample building, i.e. an actual building within the group that is documented through an audit, or a virtual building, which is based on statistical building data or expert opinions (Reinhart and Cerezo Davila 2016a).

Segmentation based on geometrical attributes is a similarity detection process. It means that the pattern measurements of a given class are nearer to other pattern measurements in the class than they are to pattern measurements from other classes (Ernesto Bribiesca 2008). There is not one unique possible technique to be applied in order to achieve this result. Famuyibo et al. (2012), i.e., propose a technique as a combination of linear regression and clustering.

The morphological approach, usually based on graphic and textual contents, in order to exploit the possible advantages coming from data science and to be involved in a broader discussion regarding also performances, need to become measurable and transferable also with outputs of other form. This research goes in the direction of implementing and enriching urban characterization through set of attributes and metrics describing both quantitative and qualitative aspects of urban structure, in continuity with the tradition of the architectural faculty of Politecnico di Milano, updating the tools for the typological investigation.

2.4 System Theory

2.4.1 Complex Adaptive System Definition

A *system* is a composition of different elements, a regularly interacting or interdependent group of items forming a unified whole. Its terminology goes back to Late Latin *systemat-*, *systema*, from Greek *systēmat-*, *systēma*, from *synistanai*, to combine, from *syn + histanai,* to cause, to stand (Encyclopaedia Britannica).

In the other hand complexity is a whole made up of complicated or interrelated parts. “The complexity (from the Latin *complexus*, meaning entwined, twisted together) denotes a set of heterogeneous constituents that are inseparably associated. It has the paradox of being at the same time a unit and multiple” (Rueda et al. 2002). A complex system, to put it in nutshell, is a system composed of interconnected heterogonous elements that, as a whole, exhibit one or more performance, and the final performance of the whole system is utterly different than every individual constituent’s performance. Hence, even a minor change in the constituents could cause considerable changes in the system. This phenomenon makes the system behaviour too complicate to be predicted.

At first glance, complexity seems a quantitative phenomenon, an extreme quantity of interactions and interferences between a very large numbers of units. However, complexity not solely includes quantities of units and interactions, but also uncertainties, indeterminateness and random phenomena. In a sense, complexity is always related to chance (Rueda et al. 2002).

It has been illustrated that the level of uncertainty and chance is directly correlated with number of elements as well as their complicated assessment and relation. Accordingly, every system's first standing feature is being a single entity, nevertheless they have been made with different constituents. Due to this fact, if one aims to discern a system he should observe its part not solely individually, but also together as whole.

The definition of *adaptation*, is to make fit (as for a specific or new use or situation) often by modification of an existing. It is derived from Latin *adaptare*, from *ad + aptare* to fit, from *aptus apt*, fit. (Encyclopaedia Britannica)

2.4.2 City as a CAS

Briefly, the CAS is a complex dynamic system with the ability to learn from the past experiences that it has been went through. The potential to study urban issues while considering the city as a CAS provides an ability to deal with many urban questions such as energy consumption issues, social aspects, transportation problems, sustainability difficulties, etc. In this manner, the morphological aspects of cities are able to elucidate also apparently disconnected phenomena (Vahabzadeh Manesh 2012).

The agents are the base elements of the system that adapt in response to interactions. An element within the context of the city can be a building, an open space, a person or even a tree. All the elements interacting together constitute the city.

Despite the agents represent a single unit system with a mutual goal of entire system performances, however, every agent pursues its own interest while respecting certain system`s laws. For example, no individual car contributes solely to the formation of traffic, but rather a traffic jam is comprised of numbers of cars as agents, each pursuing their own interest. In regards to architectural elements, as an agent, designers project different solutions for building designs whilst they must respect regulatory governmental codes, which ultimately shape the city morphology (Vahabzadeh Manesh 2012).

Although the system is comprised of heterogeneous elements with various functions; however, they could be classified in different ways. The members which either share the same function or their function is directly related to each other are categorized in a subsystem. The subsystems are often a complex adaptive system for their own. Human being body is a complex adaptive system, with different collaborating subsystems; Nervous systems and Circulatory system are the complex adaptive system in their own right, once they are part of a greater human body system. Due to the presence of different types of agents and different nonlinear relations between them, complex systems also need many different subsystems in order to link these agents. These subsystems and networks, such as transportation networks, social networks and economical networks, make cities alive. "As well as the large number of distinct agents typically found in these systems, the multiple subsystems add infinitely more layers of complexity as they influence one another" (Brownlee 2007).

Theories of complexity have shown us that to grasp the city as a living phenomenon, we have to start from the parts and their modes of relationship, rather than from some ideal, imaginary totality. What emerges from this is a new paradigm, that of complex forms characterized less by their components than by the relationships between them (Salat, Labbé, and Nowacki 2011).

Each subsystem affects other agents and subsystems either directly or indirectly and this feature is one of the most important characteristics of complex adaptive systems. Effects of transportation network impacts on economic network, and then economic impacts on social networks, and finally individual's quality of life could be an example of subsystem and networks interactions (Vahabzadeh Manesh 2012).

In addition to the functional perspective, there is also a spatial meaning of the term. A sub-portion of a city, as a neighbourhood, or another area defined according to morphological or administrative criteria, can be considered a subsystem on its own. This, in any case, doesn't imply that it can be considered as a disconnected entity from its neighbouring areas or from the system it is included in. It's rather true that a transformation modifying only the sub-system may have consequences on the whole larger system. Due to this fact, the CAS application is a multi-scale interaction.

2.4.3 Learning from Complex systems

One of the most exciting and powerful aspects of moving in complex system framework is the possibility to learn from a wide range of disciplines and application fields that share the same assumptions. Similar interaction or integration patterns may emerge from system of different nature. To make an example we can consider natural system, traditionally seen as the negative of the urban one.

The city is perceived by the people who are used to living within it as a system somewhat isolated from the surrounding background. Still, urban sustainability can, and should, be viewed from at least one other perspective. Recent studies, while keeping the city at the core of their analysis, consider urban areas as systems directly connected to their regional backgrounds. Perhaps the most important insight from this result is that no city or urban region can be sustainable on its own (EEA 2002).

A term that is often mentioned alongside of 'urban agglomeration' is 'rural–urban continuum' (Weber 2001). Composition of such continuum is comparable to that of vegetation continuum: a building is comparable to a tree; a city block to forest stand; group of blocks, that often constitute an administrative unit, to a forest compartment; and, a city to forest. Forest may have less vegetated fringes just as a city may have less populated, or economically less intensive, suburbs (Yoshida and Omae 2005).

Cities are complex entities shaped by a variety of forces and actors. We can only tackle a limited amount of variables and interdependencies yet (Aschwanden et al. 2012).

It is well known that there is a great diversity of morphologies of built-up areas at a regional level, and that the patterns are influenced by a large variety of factors and processes such as natural site conditions, agricultural traditions, historical context, social development, technological context, accessibility as well as economic forces and/or land-use planning rules, which intertwine in a complex system (see e.g. Antrop & Van Eetvelde, n.d.; Barré & Alain, 2004; McGarigal & Marks, 1995; Milne, 1991). Built-up patterns also result from the evolution over time of these components (Thomas, Tannier, and Frankhauser 2010).

We now recognize that human and environmental systems interact in very complex, often nonlinear ways, on multiple time and spatial scales. To analyse the city as a complex system that evolves in response to changes in both socioeconomic and environmental forces would require not only an extension of current approaches but also integrative mode of inquiries combining historical, comparative, and experimental approaches (Alberti 1999).

Clearly, the topic involves so many scientific and social disciplines that it is difficult not only to understand how the whole system works, but also to define its limits. Cities are complex entities influencing and influenced by an extremely broad constituency that goes beyond pure administrative and geographical borders (EEA 2002).

The global process of urbanisation and city growth, with all its consequences of migration, traffic, pollution and natural hazards, must be regarded as an aggregation of forces and components. Land values, migration patterns, planning policies and economy need to be carefully monitored, controlled and studied. Isolating one component from the others could lead to misunderstandings, lack of information and failing to achieve sustainability targets (EEA 2002).

Complex Adaptive Systems (CAS) refers to a field of study and resultant conceptual framework for natural and artificial systems that defy reductionist (top-down) investigation (Brownlee 2007). The major task in simulating complex systems is simulating the complexity itself. This may require maximizing the number of independent variables that affect the desired dependent variable (Mostafavi, Farzinmoghadam, and Hoque 2014).

2.4.4 Conclusions

Rating systems need to be fitted to the context. Urban morphology needs to become more measurable and transmissible using numerical methods. System theory appears to be the best possible approach to connect and integrate the previous two. It can be considered as a common language for exchanging knowledge between different disciplinary fields. This language may seem not immediately comprehensible and easy to manage but, once learned, opens up incredible perspectives and opportunities in the study of the implications, not only environmental, of cities' structural features. Different methodologies exist working within this framework and many authors already wrote about urban systems in these terms (Michael Batty 2009; Tadi 2013; Salat, Labbé, and Nowacki 2011; Khan and Pinter 2016; Boeing 2017). This research has been carried out at Politecnico di Milano where one very innovative and promising methodology has been developed and is currently implemented by the IMMdesignlab ("IMMdesignlab" n.d.), leaded by Professor Massimo Tadi. This methodology is called Integrated Modification Methodology (IMM) and can be considered a tool to understand the link between urban structure and environmental performance. It will be better presented in the next chapter after learning some system behaviours also from outside the urban environment.

3 System Determinants: Compactness, Complexity, Connectivity

Moving from the results of the previous chapter, this one addresses how considering city as a CAS can help understanding the relationship between its structure and performances. First, a literature review confirming that urban form affects environment, climate and other aspects under the performance umbrella is presented. Then, the features for systems optimization (Compactness, Complexity, and Connectivity) are stated. Aware of the need to investigate all of them in order to have a comprehensive picture of the relationship between structure and performance, only Compactness has been selected. The reasons for this choice are its consistency in respect to the others, its affinity with the work of architects and the availability of more complete and updated datasets. Another literature overview shows contents in support of compact development and against sprawl, seen as a negative layout and process. City of short distances provide people what they need where they live, producing benefits not only from the environmental point of view. Once agreed on this relationship, the attention is moved to the actual methodological criticalities that still limit a full understanding of this issue. The tools that could be used to measure or represent the compactness of an area exist, what is missing is a theoretical framework able to drive them to a satisfying result. The problem is so more theoretical than technical. Some of the existing methods are briefly presented distinguishing between simplistic and quantitative methods.

The second subchapter introduces the methodology that has been taken as a reference for the research and how it has been implemented. Given the complexity of the topic it was helpful not to start from scratch but relying on existing methods sharing the same research interests and assumptions. Integrated Modification Methodology (IMM) is introduced clarifying the reasons for its choice. It's then presented starting from its Phasing, constituted by Investigation, Formulation, Modification and Retrofitting, and moving to its constituent Elements and their interaction, focusing particularly on Components. The election of Components (Volume, Void, Network and Function) is supported by the literature. The same is done for the other elements like Key Categories (KCs), System Determinants (Compactness, Intricacy and Connectivity), Design Ordering Principles (DOP) and Performance Indicators. Due to the nature of IMM, that in the end is a complex adaptive system on its own, its structure is not fixed and can be implemented. The adoption of Geographic Information Systems (GIS) allowed a data-driven reconceptualization of the methodology by the author where Components play a crucial role. The implementation is presented introducing concepts as Input Layer, Attribute and Metric. These terms became necessary in order to make operative the existing IMM processes. An example is provided regarding Volume Component and a set of graphics clarify the relationships between the different elements. At last, the reasons in support of a possible adoption of this so called "metric pool" approach even outside IMM and for purposes different from the environmental aspects are explained.

3.1 Compactness, Complexity, Connectivity

3.1.1 The role of urban form

In 1993, during the World Congress of Architects, the American Institute of Architects recognized that "poor design is responsible for many of our environmental problems" (Schwartz 2008).

It's time to recognize that many problems of the city are actually the result of its inadequate structures and form (Huang, Lu, and Sellers 2007). A growing body of literature looks to a "good city form" or "sustainable urban form" to enhance economic vitality and social equity, and reduce the deterioration of the environment (Breheny 1995; De Roo and Miller 2000). The process of urban planning has close relationship also with climate. Simonds (1983) suggests that climate should be a fundamental consideration, given the central purpose of planning is to create an environment suited to human needs (C. Zhao et al. 2011). Urban morphology is an important multidimensional variable to consider in climate modelling (Middel et al. 2018). Correspondingly urban planning determines urban morphology, influencing modes of living and impacting on urban climate. The CSTB (The French Centre for Building Science) has shown that urban morphology alone has an impact on energy performance of the order 2 – i.e. the potential to halve or double a city's carbon footprint (Salat, Vialan, and Nowacki 2010).

A global sustainability assessment method must take into account the urban dimension and not only the single building itself (Salat, Vialan, and Nowacki 2010). City, considered as a CAS, have the opportunity to learn from other well performing systems. Complex System Theory highlights some system structural features that are able to improve its performances. These are Connectivity, Complexity and Compactness.

Connectivity represents the topological integration of system elements. Is intrinsically related to the relational network existing between the elements of the system and the resulting hierarchy. Complexity refers to the number and the diversity of both elements and connections. System with heterogeneous elements and a great number of connections have a high level of Complexity (Systems Academy). Compactness is the more tangible and physical dimension. While the other two are clearly represented by the relational network describing an abstraction of the system functioning, Compactness deals with the Euclidean space. It's materially built on the interaction between Volumes and Voids and deals with the reciprocal position of elements in space, no matter at which scale. The same pattern may emerge at very diverse scales as is based on proportion and relative dimensions. This multi-scale assumption allows to share knowledge with other disciplinary field, considering city, after a zooming process as the subject of their study. City as a porous media i.e. has been used for learning permeability assessment methods from hydraulics field (Biraghi et al. 2019).

3.1.2 Literature agreement

Many authors in urban studies agree on this principle and highlight the importance of one or more of this dimensions on different topics related to urban environment. Hillman in 1996; Thomas and Cousins in 1996, Newman & Kenworthy in 1989, even Jane Jacobs in 1961, are solely some of the main supporters of this notions. One of the tenets in support of compact urban development, rather than sprawl, is that compactness improves environmental performance (Alberti 1999). The idea of the compact city was integrated into the concept of sustainable urban form, which includes Compactness amongst other aims such as sustainable transport and a diversity of potential activities within a neighbourhood. The compact city is characterised by a high density of usage, short travel distances, and associated to a higher quality of life (Schwarz 2010). At multiples scales and for a variety of reasons, there are advantages to development that is mixed and compact (Clifton et al. 2008).

Boyko & Cooper (2011) indirectly describe these three aspects stressing the importance of proximity as a crucial attribute for built form. They suggest population and building density (Compactness), nearness and choice of desired destinations (Connectivity) and a constant buzz of transaction and interaction (Complexity). The impact on environmental performances is obtained by reducing car and fuel dependency providing the inhabitants with what they need to live, work and have leisure in a small perimeter (Salat, Vialan, and Nowacki 2010). Smart growth principles encourage compact, efficient communities with an emphasis on the relationship between land use development and transportation by reducing per capita land consumption and vehicle travel (Schwartz 2008). The European Environmental Agency report (EEA 2002) suggest to state and regional authorities to pursue the concept of compact city (the city of short distances) in order to have better control over further expansion of the cities. This follows New urbanists activities and goals (see, for example, Duany, Plater-Zyberk, & Speck, 2001) that lead to the adoption, in 1996, of the CNU charter in that declared:

"We stand for the restoration of existing urban centres and towns within coherent metropolitan regions, the reconfiguration of sprawling suburbs into communities of real neighbourhoods and diverse districts, the conservation of natural environments, and the preservation of our built legacy. We recognize that physical solutions by themselves will not solve social and economic problems, but neither can economic vitality, community stability, and environmental health be sustained without a coherent and supportive physical framework. We advocate the restructuring of public policy and development practices to support the following principles: neighbourhoods should be diverse in use and population; communities should be designed for the pedestrian and transit as well as the car; cities and towns should be shaped by physically defined and universally accessible public spaces and community institutions; urban places should be framed by architecture and landscape design that celebrate local history, climate, ecology, and building practice."
(Schwartz 2008)

It emerges that the sustainable form could be achieved through a right balance between Compactness, Complexity, and Connectivity (CCC). Any of them would not sufficient by its own to achieve the sustainable form.

The same concept is also expressed by focusing on the negative impact of a city that is neither compact, nor complex or disconnected, as the one generated by sprawl. Some authors dare saying that sprawled settlements are not cities and only the above described CCC is worthy of that name. It has been demonstrated that sprawl has a lot of negative consequences on urban environment like traffic congestion, the loss of open space, high public service costs and property taxes, low levels of physical activity, inflated vehicle-miles travelled and greenhouse gas emissions (Clifton et al. 2008).

3.1.3 Measurement and representation

Only the comprehension of the structure of the city allows us to optimize it and improve its performances. Knowing from existing literature about sustainability implications of compactness, complexity and connectivity it remains open the problem of the definition of these three concepts. In fact, without the tools or a theoretical framework to effectively measure and represent these ideas – essential for implementation – the concepts prove intangible (Talen 2003). Despite the concept's common use in urban research, to date, an internationally-accepted standard for the implementation of indicators that permits a robust comparison of different countries, regions or cities is widely missing (Krehl et al. 2016).

Despite the difficulty of tackling such super-categories on their own, in literature we find many attempts to reduce it to a single numerical index or a small set of indicators. Recently quantitative methods have emerged as a means to more systematic classification and analysis of the issues in these debates (Torrens and Alberti 2000; Wassmer 2000; Galster et al. 2001; Ewing 2002; Tsai 2003). Thus far, applications of these methods have remained confined to individual case studies or specific national contexts, usually within developed countries (Huang, Lu, and Sellers 2007).

The difficulties related to these issues are more theoretical than technical. In fact what is missing is a re-conceptualization of these concepts more than the tools to perform numerical analysis or simulations. We first need to understand what to look for and how to do it. By the way, being aware on the existing investigation methods and spatial analysis software since the beginning helps and may guide towards the construction of a better framework.

3.1.4 Selection of the topic: Compactness

In this framework, a reconceptualization of these concepts will incredibly help the field of urban studies in general and in particular the one considering city as a CAS. The length and the nature of a PhD research allow to focus only on one of them with the required level of detail and scientific relevance. According to my architectural background the most appropriate seems to be Compactness for its physical consistency and for the role played by buildings as agents. This choice doesn't imply any hierarchy among them, in fact the weight or relevance that each determinant play in the definition of the performances of an area varies context by context. It simply represents the simplest starting point according to my skills and the availability and completeness of the existing datasets for urban areas. In fact, for example, detailed dataset regarding punctual distribution of activities in space (Function) are almost impossible to be found as open data. The thesis assumes the correctness of the data used as input (except in case of macroscopic and evident mistakes) and only focuses on the management of the spatial data in order to extract valuable information from them.

3.2 Reference Theory: Integrated Modification Methodology (IMM)

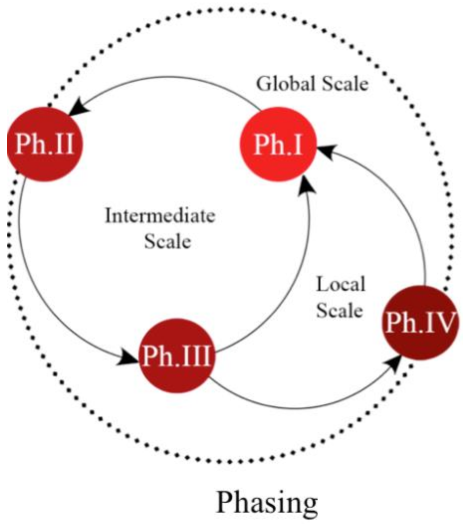
3.2.1 IMM theory

City is a complex system and many components working together intersect influencing each other creating dynamics of interdependence among transformations regarding built form, functions and mobility. To manage this complexity and tackle the problem from a systemic perspective, after an investigation phase, I decided to refer to an existing methodology. IMM (Integrated Modification Methodology) developed at Politecnico di Milano at ABC department (M. Tadi, S. Vahabzadeh, 2011), is a multi-stage, multi-layer, multi-scale, holistic and iterative process, applied to urban components, for improving their environmental and energy performances; it investigates the relationships between urban morphology and energy consumption by focusing mostly on the 'subsystems' characterized by physical characters and arrangement. It also highlight the need to act not only on the physical properties of units (architecture), but also on the operation of the urban system considering functions, services, transportation, resource management and everything able to affect citizens behaviours, in an ecological perspective.

It is intended to assist designers and decision-makers, providing them a fully integrated design process plus a set of Design Ordering Principles to transform an existing urban context into a more sustainable one (Wikipedia). The main goal of the IMM is not focused on finding which form has privilege over the other one; its main concern is to improve the performance of the system, regardless of their form, whether compact or sprawl. In fact it does not intend to compare the different cities together, it rather aims at improving an existing system comparing it with itself, before and after the design intervention. IMM approach to sustainability is aligned to the UN Sustainable Development Goals 2030 (IMMdesignlab).

3.2.2 IMM Phasing

IMM is articulated on four recursive phases in an iterative process. The following chart illustrates it (Figure 6).



1	1a	Horizontal Investigation	Dismantling the system to investigate	Actual CAS Arrangement	Investigation/ Observation & Measurement
	1b	Vertical investigation	The actual value of Key Categories		
	1c	Actual performance of the system based on 12 indicators		Actual CAS performances	
2	2a	Detection of the transformation's Horizontal and Vertical *Catalysts and Reactants.*		Catalysts selection and Reactants ordering	Assumption and Interpretation/ Formulation
	2b	Assumption of the 12 IMM Ordering principles		DOP Arrangement	
3	3a	Horizontal Modification	The *catalyst* drives the local transformation; changing the structure of the layers/Ligands	Catalyzers' Modification and chain reaction	Modification Intervention & Design
	3b	Vertical Modification	Local transformation acts globally, changing the entire system's configuration		
4	4a	Performance of the new CAS based on 12 indicators		New CAS performances	Retrofitting
	4b	Local modification/optimization is a process involving again the first level of superimposition for improving locally their performance. Local optimization works using selected tools/features: - Volume/Voids = Solar Gain; Wind Tunnel; - Volume/Function = Level of mixed use - Function/Voids = Function distribution - Transports/Voids = Number of intersection - Transports/Function= Service area control. - Transport/Volume= Catchment area control		Local modification of the new CAS	Optimization

Figure 6 IMM Phasing process (IMMdesignlab)

The first phase, Investigation & Measurement (1) corresponds to a diagnostic process. The actual state of the system is dismantled into its Components (Volume, Void, Network, Type of Uses) and reassembled into Key Categories (KCs) in order to assess the previously seen system Determinants (Compactness, Complexity and Connectivity) with the goal of achieving an efficient urban form. The following schemes clarifies the role and the hierarchical position of the above mentioned elements taking as example the role of Volume (Figure 7) and Void (Figure 8) Components.

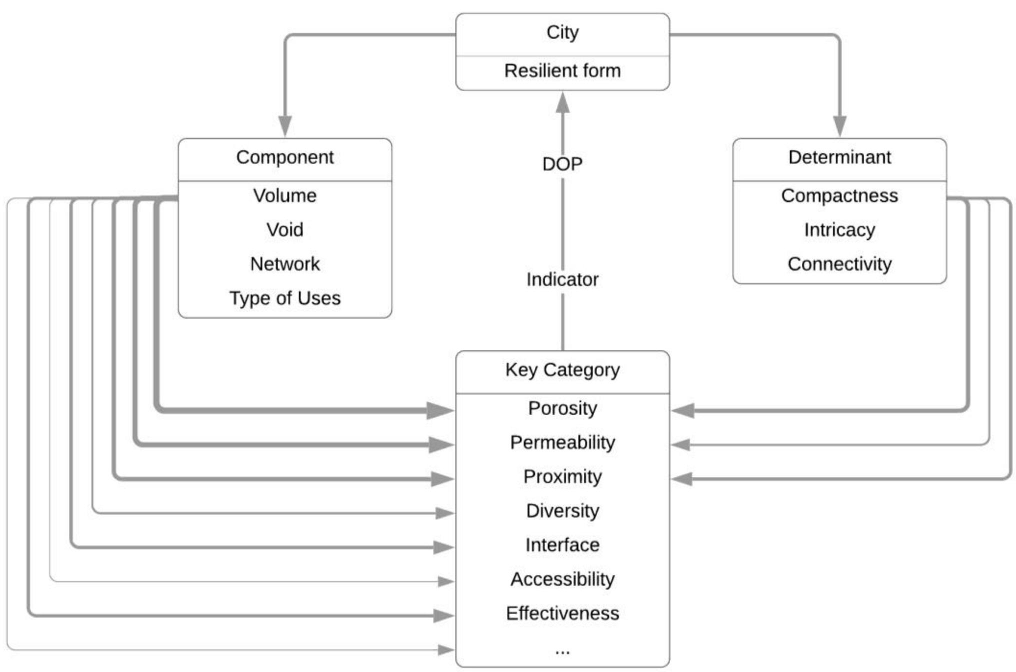


Figure 7 IMM elements and relationships. City is dismantled into Components, then rearranged into KCs with an integration process. KCs integration shapes Determinants affecting City performances. Volume Component role inside IMM

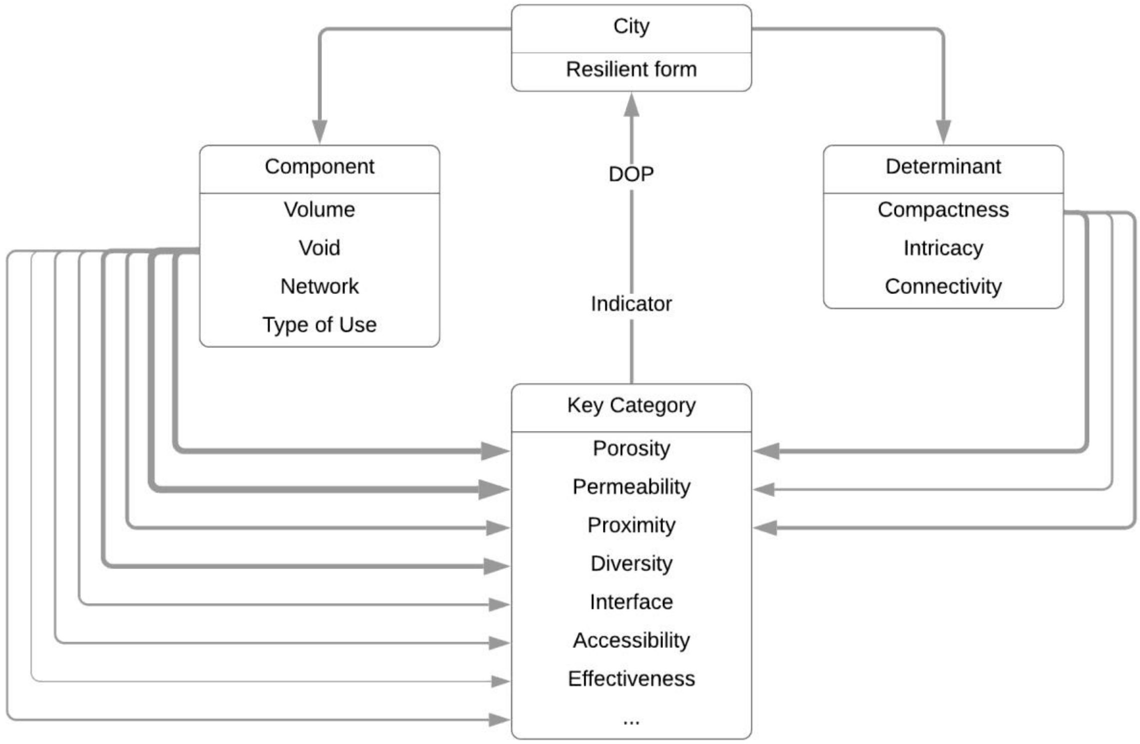


Figure 8 Void Component role inside IMM. The different thickness of the arrows indicates the relevance on the connection. Void Component arrangement affects all the KCs but have a higher impact on Permeability, Porosity and Diversity. On the other side Compactness is determined by Porosity, Proximity and Permeability KCs.

The scheme can be read in two directions because of the iterative nature of the approach. Going clockwise city performances are determined, as agreed in the literature, by its level of Compactness, Complexity and Connectivity, called determinants. These, in order to be investigated, need to be dismantled into more targetable urban system properties, the KCs. The number of KCs inside IMM is currently seven but is not fixed. The KCs are the result of the integration of the Components (Volume, Void, Function and Network), the basic constituents of every city. The components are the result of the dismantling process of cities and are so the starting point of the counter clockwise process of urban diagnostic, articulated in KCs and completed by the measurement of performances through the Indicators. The complete scheme will show the relationship between all the components and the KCs, and between them and system determinants, resulting extremely hard to be represented in a comprehensible way given the complexity of the relationships between the elements. The Formulation phase (2) interprets the results of the diagnostic and makes a draft abstract program of intervention, mainly defining priorities. One component and one KC are elected as catalyser of the transformation while the others behave as reactants. Modification (3) and Retrofitting (4) phases deals respectively with the development of a design proposal based on the DOP principles and with the repetition of the diagnostic process, applied this time on the proposed transformation scenario, in order to evaluate the impact of the modification on system performances. In order to better understand the role and the nature of each stage of the process we'll now discuss the elements one by one starting from the components.

3.2.3 IMM elements

COMPONENTS

A growing body of research provides tools to measure and classify the urban morphology or urban form and shape of developments (Song and Knaap 2004; Wheeler 2003; Andrés Duany and Talen 2002; Godschalk et al. 2006). This appreciation of morphology helps designers and planners understand local patterns of development and their changing processes. Four major elements seem to be the most important to understand urban morphology. They are: land uses (Function), building structures (Volume), plot pattern (Void) and street pattern (Network) (Carmona et al. 2003).

We understand that despite their heterogeneity, cities can be dismantled into four components, whose unpredictable and continuous interaction over times gave birth to contemporary urban areas. These components are Volume (the built part), Void (empty spaces), Function (activities performed by citizens) and Network (networks of different modalities) (Tadi 2013).

Components are the least set of elements to be considered when dealing with urban environment. People are agents whose behaviour is affected by the configuration and interaction of these components; with their lives, they affect and reflect the performances of the city.

KEY CATEGORIES: 1st level of integration

The Key Category concept in IMM refers to the Emergence one in Complex System Theory. It describes a process whereby components interact to form synergies. These synergies then add value to the combined organization which gives rise to the emergence of a new macro-level of organization that is a product of the synergies between the parts and not simply the properties of the parts themselves. Every KC is affected by every Component differently. KCs are applied in the investigation phase for analysing the urban context and its structure before the design intervention, as well as in the final retrofitting phase after the intervention. In studying systems - of any kind - it is common that learning about parts is considerably less complicated than understanding the relations between them" (IMMdesignlab). Figure 9 schematizes the role of Components and KCs and how they are involved in the horizontal and vertical investigation.

Once drawn the diagnostic picture on the results of Components and KCs it's possible to identify malfunctioning parts of the system and which layers are more responsible for that.

IMM Key categories are: Porosity, Permeability, Proximity, Diversity, Interface, Accessibility and Effectiveness. We will not deepen all of them but only the one related to the pure interaction of Volume and Void Components, Porosity and Permeability, in a specific chapter.

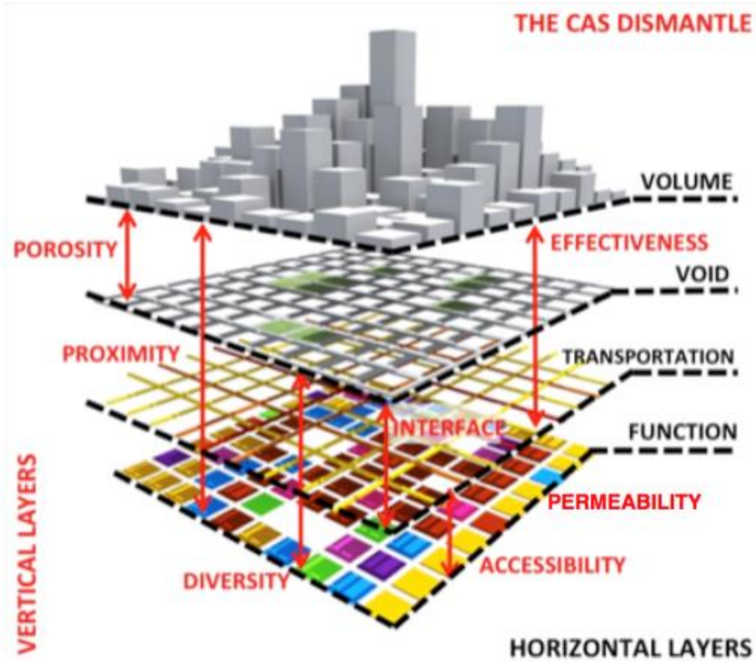


Figure 9 The CAS Dismantle. Scheme with an abstract representation of a city dismantled into its Components (Horizontal layers, in black). The integration of different layers allows the emergences of more complex features called Key Categories (Vertical layers, in red).

DETERMINANTS: 2nd level of integration

In the previous paragraph we have seen some concepts largely recognized as features of a well performing system as Compactness, Complexity and Connectivity. IMM accepts this three substituting the word Complexity with Intricacy to avoid the contradiction of assessing Complex Systems directly through Complexity. They are called Determinants as they decisively affect the nature of city and are the result of the second level of integration, based on KCs that are the result of the 1st one, based on components.

They are inevitably more complex categories that can be hardly understandable and representable in a synthetic or simplified way. Their full understanding will be possible only after testing the methodology on multiple case studies and alternative transformation scenarios in order to let emerge some patterns that link them to more simple objects as the one that, as architects or urban designers, we are asked to deal with like buildings, streets, squares and parks, simple instances of the Volume and Void Components.

DESIGN ORDERING PRINCIPLES (DOP)

DOP are essentially a set of actions that designer can perform in order to improve the current system behaviour. They are used during the Assumption & Formulation phase (2) when the designer interprets the results of the diagnostic. These actions are taken from the literature and are generic enough to let the designer freely move in them, and specific enough to guide it in a positive direction. Here the list of the DOP in alphabetical order:

1. Balance the distribution of functions and developing multifunctional urban spaces.
2. Balance the ground use
3. Balance the public transportation potential
4. Change from multimodality to inter-modality concept

5. Convert the city in a food producer
6. Create connected open space system, activate urban metabolism
7. Foster the local energy production. Building as component of Smart Energy Community
8. Implement permeability to facilitate urban flows
9. Implement water management
10. Make biodiversity an important part of urban life
11. Prevent the negative impact of waste
12. Promote Walkability, Cycling and Reinforce their integration with public transportation.

Even if no one could disagree with none of these principles, it’s clear that their positive impact strongly depends on the context where they are applied. They can’t harm but they can be useless in some extreme cases. What makes them interesting and different from a checklist of a classical rating system is their dynamic nature. The importance, hierarchy or weight of each of these principles varies according to the case study and is determined by the analysis of KCs. So, the list rearranges every time in order to set some priorities among these goals. Figure 10 show first them in alphabetical order and then according to the priority given by two different design context, Porto di Mare in Milano, Italy and Porto Maravilha in Rio de Janeiro, Brazil.

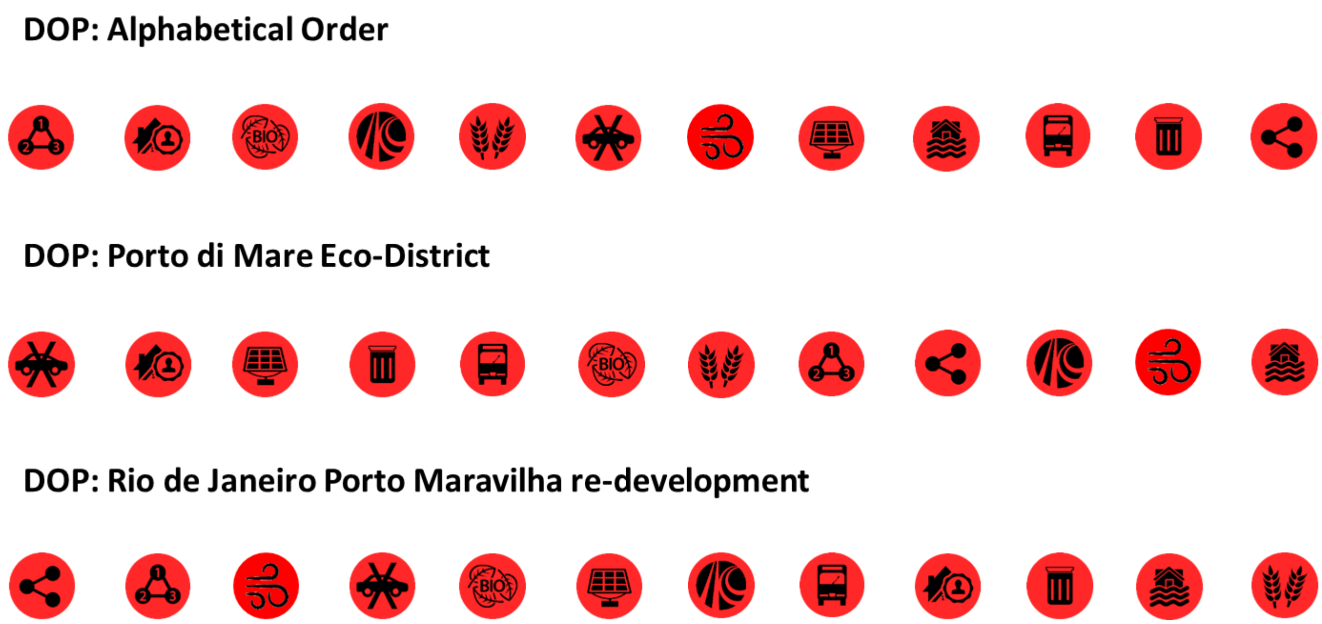


Figure 10 Design Ordering Principles (DOP) arranged first in alphabetical order and then as a result of the Investigation Phase in two different case studies: Porto di Mare, Milano, and Porto Maravilha, Rio de Janeiro

INDICATORS OF PERFORMANCE

Key Categories are used to describe urban structure and its potential way of operating. In other words each of them draws a partial picture of potential system behaviour that is not necessarily representative of the real flows of city users. A straight street between two points represents the most direct and fast way to connect them (Permeability) but it will not necessarily be the most used by walking people. Aspects as the presence of activities on the ground floor (Proximity), of public transportation stops (Accessibility) or shading by volumes in hot climates (Porosity) can affect people choice suggesting to take more tortuous (Permeability) but integrated (Interface) streets. The comprehensive configuration of the CAS is mostly described by the correlation between the different subsystems.

This distance between structure and performances make necessary the use of indicators to understand the real system behaviour and how it can be explained by system structure. It may happen that unpredictable factors affect system agents generating unexpected behaviours.

Every KC can be associated with more than one indicator as well each indicator may be representative for more than one KC, according to the same logic that links KC to metrics. This relationship is mediated by families of indicators representative of the Design Ordering Principles (DOP) and by the three Determinants plus a fourth category of Management. The list of indicator is open and even if currently counts more than one hundred records, it could easily and hopefully reach a much higher number. Not all the indicators can be calculated in every context according to data availability but this doesn't represent a limit. In fact even just few indicators for every family may be enough to evaluate a transformation.

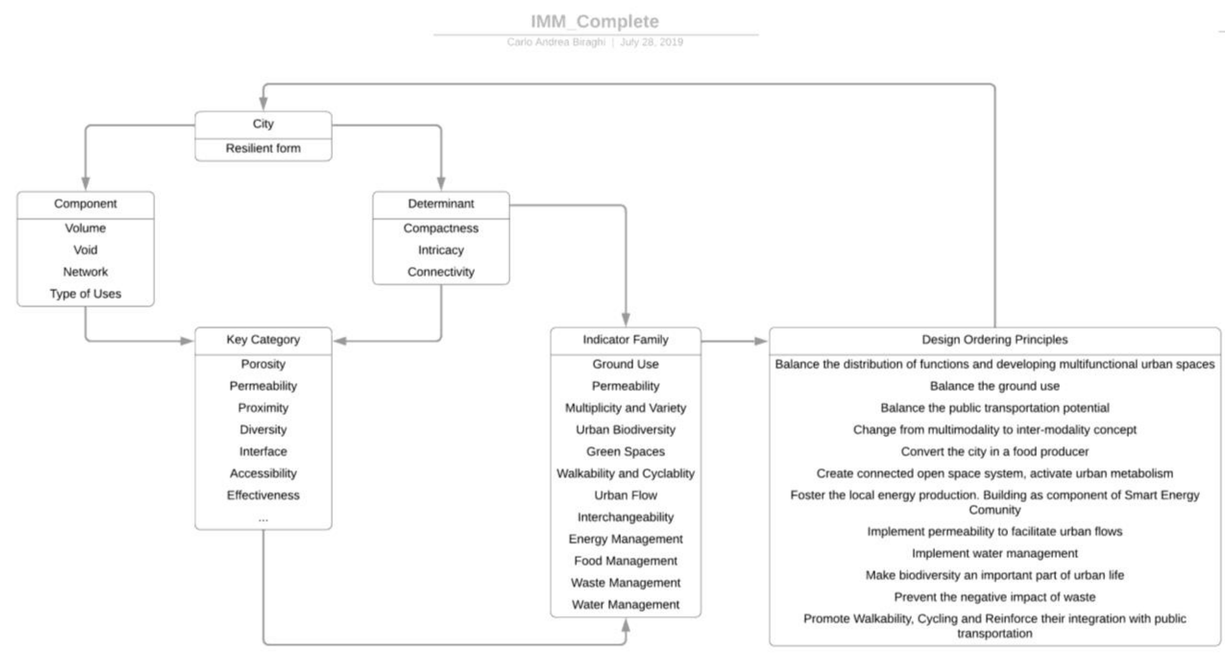


Figure 11 IMM Elements and interaction. DOP are arranged as the result of the Investigation Phase and are used to guide the modification process and bring the system to a new stage.

3.2.4 Research contribution to IMM

This methodology has been useful to allow the construction of a proper theoretical framework and as a room for the research outputs as new metrics and representation techniques. The basis of the theory are explained in a series of papers (S Vahabzadeh Manesh, Tadi, and Zanni 2012; Tadi 2013; Shahrooz Vahabzadeh Manesh and Tadi 2011) but IMM methodology, being a CAS on its own, may evolve in time. This gave the opportunity to locally implement or clarify some steps in the methodology process respecting the overall structure and logic that was already working properly. More precisely, inside this research, the phasing remained exactly the same while the interaction between some elements has been re-conceptualized in order to support the adoption of GIS tools as the engine for the diagnostic phase. This change oriented even more the process towards a data-driven perspective and allowed to manage bigger datasets on larger scales. Every implementation have to follow the principle of avoiding simplifications and increase the capability of modelling complexity without increasing the complexity of the modelling and the required time. It must be operative and provide better results than previous stages of theory both in terms of numerical values and representations.

Moving into a data-driven measurement perspective, *components* become the key starting point of all possible analysis to be conducted on a city. In order to describe, visualize and measure them we need to identify one or more *input layers* that represent their physical consistency. In order to explore IMM boundaries I started moving on the scheme in Figure 11 counter clockwise, moving from components and focusing on their integration that lead to KCs. The simple arrows connecting them to KCs became a protocol process with specific items and rules. The following scheme (Figure 12) can be used as a guide for better understanding the logical structure of the process. I decided to use an Entity Relation (ER) diagram, commonly used in computer and data science, to rely on an established language taking advantage of its lexicon and readability. In the bottom left corner of the image there's a legenda explaining how to read the diagram. Squares are entity, urban recognizable objects, in this case, while rhomboids placed in the middle of the lines connecting two entities are relations. The ones used here are always spatial relationships indicated the topological rules between urban elements. Darker lines with one arrow are generalizations, a way to show separately two or more set of items belonging to the same class.

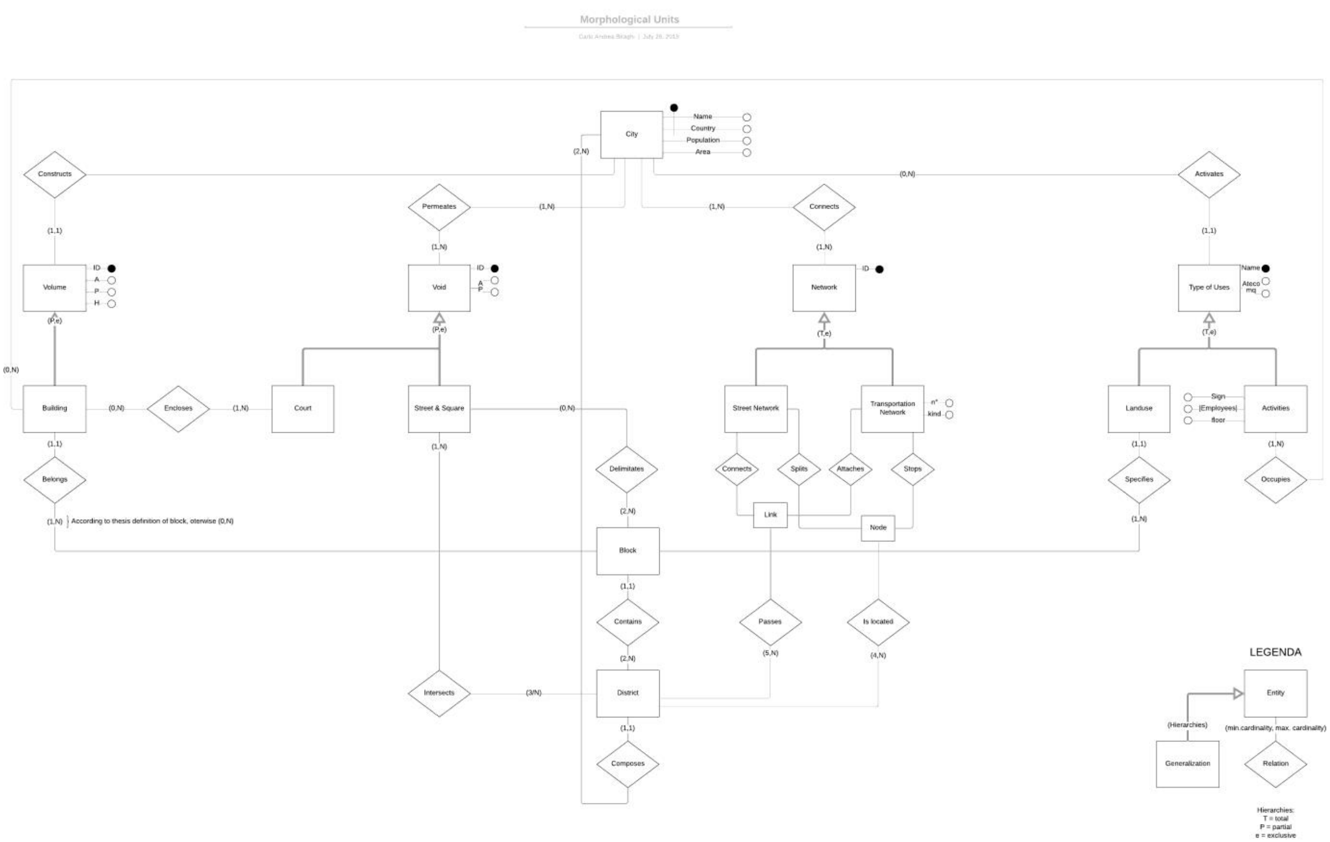


Figure 12 IMM Reconceptualization through and Entity Relation (ER) Diagram. The scheme presents city Components, the corresponding input layers and how the information generated by these layers can be gathered into landing morphological units as block, district and city.

The idea behind this choice is to extract from the input layers all the possible information that they hold, aware that not everything would be useful. By squeezing or exploding the components is possible to multiply the possibility of interaction and the capability to model complexity. Even if starting from IMM, the proposed approach aims to be a comprehensive framework for system theory applicable also outside this methodology for just the diagnostic phase. Considering that the research focus mainly on volume and void components we make here an example of how the first one has been tackled.

INPUT LAYERS

The content of Volume is the physical consistency of built structures, everything that occupies a three-dimensional space above or below the ground level. The same object can be represented in different ways according to the available level of information for a specific context.

A 3D model is the most accurate representation but can be managed only by a certain kind of software, is too detailed to be managed on large areas and there's a lack of available datasets. 2.5D models, based on volumetric units, are slightly less accurate but much more manageable. They can be easily found as Open Data and can be processed by GIS. Both Shape files and CityGML have the required level of detail to exhaustively describe the volumetric consistency of an area. Moving to context with less information and dataset the level of approximation grows allowing only partial analysis. 2D models, urban patches or raster maps should be used only if previously mentioned datasets are missing or incomplete.

The input layer chosen for the research case studies is Volumetric Units, a free shape file available from Lombardy Region Geo-Portal in compliance with INSPIRE guidelines. The instances of the layer are polygons of uniform height with an attribute identifying the building they belong to. This layer also includes statues, monuments, and other volumes non belonging to the building category.

Input layer for the other components could be, for example, street, walkable, green and boundary area for the Void, street links, nodes, public transportation line and stops for Links and land-use and punctual activities for Function.

ATTRIBUTES

The input layers already contain some attributes that could be both geometrical properties and additional information. In the next chapter we'll look closer to this point specifying the more appropriate terms to be used. Additional attributes can be obtained by numerical or spatial operation on the existing one of one or more input layers. Attributes are the ingredients for the construction of metrics.

METRICS

Through the interaction between the elements of one or more components is possible to obtain some spatial metrics. Metrics describe properties of the sample area. It's possible to create almost an infinite number of metrics even if many could result as redundant because built on the same parameters. Building Coverage Ratio (BCR), Street Density, Walkable Area and Job Density are examples of metrics constructed on the interaction of elements from different components. BCR, i.e., is the summation of the building ground area attribute (B_A) of all the buildings in a sample area (Volume) over the summation of the block area attribute (BL_A) of all the blocks in a sample area (Void).

DIMENSIONS

Elements equivalent to Key Categories can be found in the literature with many different names. Sternberg (2000) defines them as integrative principles, or constituents of the experience of built form. Yavuz & Kuloglu (2017) call them space determiners. In the end they are urban properties or dimensions (Carmona 2010), usually already well descriptively defined in the existing literature. These principles if taken into account should lead to good urban design, if neglected to bad planning. In fact, Jacobs (1961) affirms: “They are all problems which involve dealing simultaneously with a sizeable number of factors which are interrelated into an organic whole”. For a successful design all dimensions and contexts should be linked and related in the conception of the design and throughout the design process (Schwartz 2008).

Literature, as previously mentioned, is plenty of other dimensions of good urban design that could be investigated with an approach similar to the one adopted for KCs.

Legibility, for example is the property of real-world cities which influences peoples’ ability to learn to navigate them (Ingram, Benford, and Bowers 1960). Lynch also defines it as: “the ease with which parts may be recognised and can be organised into a coherent pattern”. (Lynch 1960) Penn & Dalton (2018) speak about intelligibility, a very similar concept, as the relationship between local and global properties of space. In an intelligible area your global location is essentially predictable from local information. In a maze, the structure of space is designed to break the part-whole relationship as far as possible (Penn and Dalton 2018). Vitality is also a popular word, introduced by Jacobs (1961) and studied by Montgomery (1998). According to him, vitality contains an active street life, the extent to which a place feels alive, all kinds of socio-cultural activities as well as the number of people using urban places all year long on every day, at every hour of the day. (Yavuz and Kuloglu 2017) Norbert-Schulz (1979) finds Identity when “nature forms a comprehensive totality”. Cullen (1961) and Bacon (1974) write about Continuity as an unbroken flow of impressions and one of the purposes of design. Thomas & Frankhauser (2013) deepen the fractal dimension.

Moving mainly into the Network component (streets and transportation system) we may talk about intermodality. Intermodal transport refers to the use of at least two different modes of transport during one door-to-door journey. The level of integration in terms of ownership, operation or usability is an important aspect of intermodality (Eltis; CIVITAS). The list is potentially endless so we conclude presenting further words found in the literature without their explanation: flexibility, viability, perceptibility (Bentley, 1985), emotion, suitability (Lynch, 1985), transparency (Jacobs, 1993), safety, comfort, variety, cohesion, clarity, balance, unity (Sternberg 2000), attraction, scale, harmony, matching (İnceoğlu & Aytuğ, 2009), walkability (Pafka and Dovey 2017).

The main difference between KC and these other dimensions is the context they can be applied to. KC works in Complex Systems Theory while the others are hardly transferable out of urban design field. Moreover some of them relate to perception more than structure.

A question with no possible answer is which is the hierarchy of these dimensions? Which of them is up-stream or down-stream to the other? Every author has its own contradicting point of view.

For Pafka & Dovey (2017) the permeability of the street network is linked to interface and ultimately it is also connected to street-life vitality and urban intensity. At the same time Permeability and interface are walkability requirements. To achieve Jacobs (1961) vitality, there’s need of permeability and diversity. Even more ambiguity rises when dealing with concepts as density and compactness, often inverted in terms of order. It seems that everyone is looking at the same thing but from different point of views. In fact the most of the authors agree on which dimensions have a link but everyone elects a different one as the principal.

METRIC POOL

Demanding to determine who is right or wrong and which set of words is the most appropriate is a dead end street. Is clear that everyone is at least partially right also because many concepts clearly overlap. If we accept the challenge of measuring all these words, and we adopt the research approach of multiple attributes to define dimensions in a complex way, it becomes also clear that some metrics will be necessarily used to describe more than one urban property.

This metric based approach, adopted by IMM methodology but applicable also independently from it, is inclusive and allows to calculate almost an infinite number of urban dimensions according to different needs. This doesn't mean that all the possible properties should be investigated or calculated for the study of the environmental performances of a CAS, but that all of them could be useful and representative even for the study of some other phenomenon. Just as an example, Penn & Dalton (2018) relate space patterns to social behaviour.

REPLICABILITY

This research focuses on a comprehensive description of urban Compactness through a set of maps, diagrams and values to give both a qualitative and quantitative definition of this phenomenon, strongly related with environmental sustainability. It introduces a new way of analysing KCs passing from a single numerical value coupled with a synthetic map to a set of quantitative and qualitative metrics associated with the corresponding representations. This step is crucial as it allows to investigate the different facets of every property offering a better overall comprehension of the urban structure. The research can be seen as a test of this new approach and its positive results suggest that this implementation should be replicated on the other IMM elements. The other two Determinants (Intricacy and Connectivity) can be taken into account by exploding the remaining two Components (Network, Function) and exploring their interdependence with Volume and Void. The enlarged metric pool will inevitably allow to characterize also the remaining KCs. A similar work, already started and ongoing, would be of great scientific interest as it complete the set of extractable attributes and metrics from city basic informative input layers. Figure 13 graphically shows the entire Components' Input Layers and morphological units. This tree-diagram is parent of that in figure 46 where additional branches have been displayed for Volume, Void and partially Network layers.

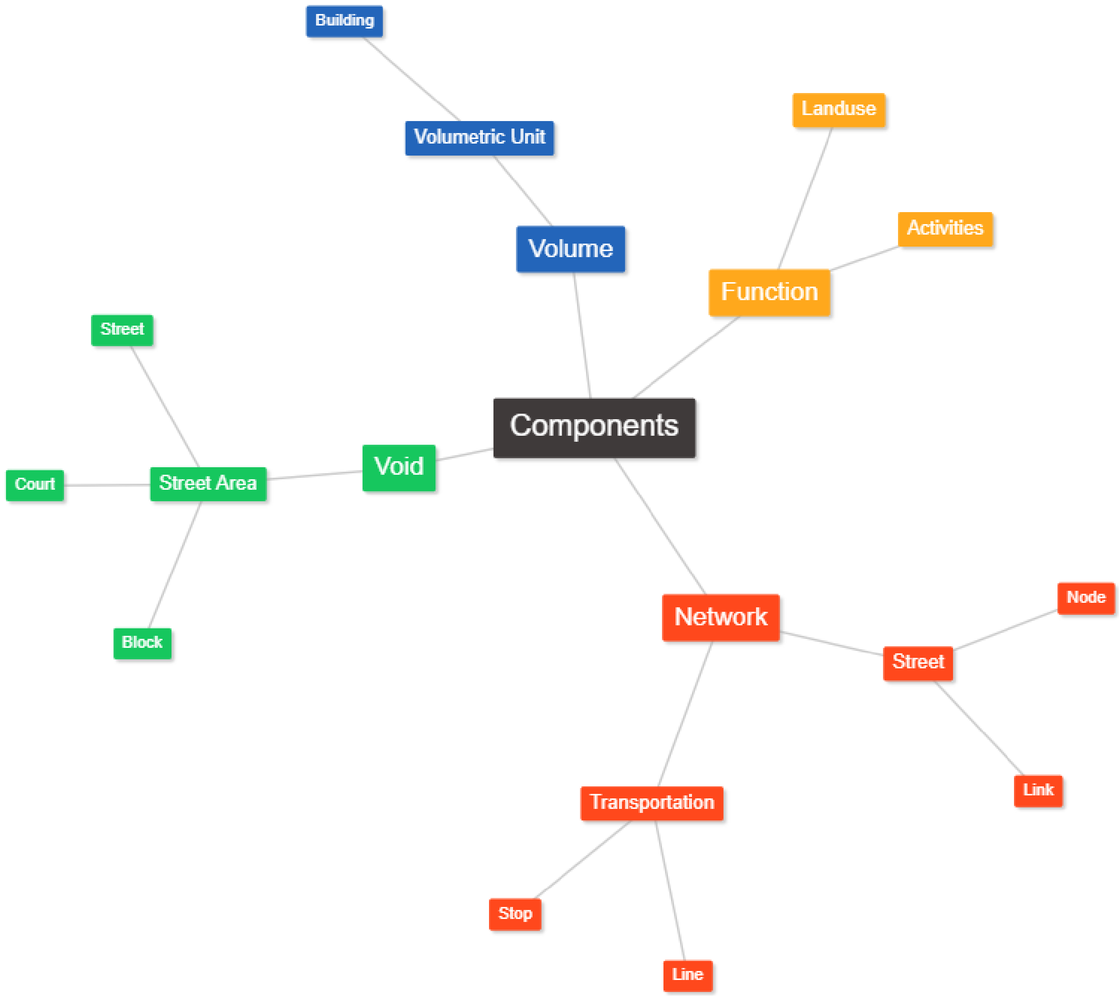


Figure 13 Components to Input Layer. Starting branches of the larger three showed in Figure 46 showing the more input layers corresponding to the system Components

4 Multi-Scale Modelling Approach

This chapter presents the research modelling approach as a natural consequence of the hints, limits and needs found in the existing literature. The approach tries to draw a comprehensive framework to answer many different issues, a sort of global remedy for local needs. These needs and issues will be first presented and then followed by a linear comprehensive explanation of the research method. Every paragraph begins with literature consensus and ends with research position on that issue.

It starts presenting how the existing studies on the relationship between structure and performance produced ambiguous results and tries to understand the reasons for that. It emerges that the biggest lack is in the structural characterization of urban morphology, the area where the research will mostly focus. Research questions are recalled and the authors trying to answer them are studied. From the review of the most affine researches (L. Adolphe 2001; Huang, Lu, and Sellers 2007; Yang and Chen 2016; Yoshida and Omae 2005; Thomas, Tannier, and Frankhauser 2010; Mohajeri et al. 2016) comes the decision of adopting the “Morphometric Method” to improve morphological characterization using block, district and city as landing areas and Volume and Void as generators. Other aspects of are listed and explained in order progressively reveal all the nuances of the research approach: Multiplicity and variety in opposition to reductionist approaches, accepting complexity and trying to model it with multiple values; Quantifying quality to exploit the possibilities of numeric representation using them to translate words from classic urban design authors into measures; Maps, values and diagrams as complementary communication channels for the different actors and purposes of a design process. The importance of playing around with data and visualization as a learning tool is stressed citing also urban-related videogames; Spatial Metrics as descriptors of urban patterns against density or other commonly used measures not representative of volumes’ configuration. The need of new metrics is underlined by many authors as increasing the number of independent variable will increase modelling capability and, finally, our understanding of complexity; Tools like GIS and BIM open new possibilities together with a wider diffusion of standardised databases; Object-oriented morphological units will be generated and treated as input layers to overcome the lack in existing common datasets and increase the number of possible interactions between Components. Plots can’t be precisely derived from other geometries so they’ll be only approximated while Blocks and Courts will be created and used.

The problem is then seen from the disciplinary and scale perspective showing how in the state of the art many self-imposed disciplinary and scale boundaries exists. These imaginary boundaries can be easily overpassed by learning from other systems (multi-disciplinary) and adding resolution as a fourth continuous dimension (multi-scale). The importance of boundaries in the modelling process is presented together with all the issue related to their definition. Focusing on the scale, urban patch is redefined as the last step of a continuous bottom-up clustering process. Even if it won’t be investigated in detail, this change of perspective opens new scenarios for the definition of urban patterns across scales. Also fractals are very briefly introduced more as an inspiration than as a mathematical operative tool to investigate cross-scale relationship and resolution.

The last subchapter is dedicated to context and how it enters the debate between local and global, metrics, indicators, methods and solutions. The role of comparisons inside the research is clarified also thanks to a better definition of optimization. Research promotes comparison between areas of the same city or between different stages of the same system using the same metrics for every context to obtain customized optimization paths. After spending many words in diagnostic investigation, its role of improving designer awareness is reminded.

4.1 Theoretical framework

4.1.1 Urban Form and Environmental Performances

Despite the general agreement on the relationship between city and sustainability we are still far from having clear answers to all our questions. What is an environmentally appropriate urban form? The study of urban morphology in relation to environmental processes is still too fragmentary and lacks a theoretical framework to answer such a complex question (Alberti 1999).

The available evidence on these relationships is mixed and contradictory. Only few studies claim that urban form is a good predictor of environmental quality and performance. However, several scholars argue that these studies are based on dubious assumptions, poorly framed questions, or weak methodologies (Handy 1992; Anderson, Kanaroglou, and Miller 1996; Crane 1996). In addition to methodological problems, the literature on the interactions between urban patterns and environmental performance lacks a conceptual framework to investigate these relationships and to improve upon the results of previous research. Before we can make any progress in determining how urban patterns affect environmental performance, we must develop a comprehensive model of the interactions between urban and ecological systems and identify what significant factors govern these interactions at various scales.

Always Alberti (1999) offers a synoptic review of current studies that directly or indirectly address the interactions between urban patterns and environmental performance. This chart (Figure 14) is useful to examine what we do and do not know about how selected measures of resource uses and environmental quality relate to alternative patterns of urban development; however, no conclusions can be derived from these studies regarding the aggregated impacts.

Environmental Performance / Urban Patterns	Sources	Sinks	Support Systems	Human well-being
Centralization	↔ Solar radiation ↔ Energy use ↓ Energy supply ↓ Number of trips by auto ↔ Trip length	↑ Urban heat island ↔ Atmospheric pollution ↔ Water pollution	↔ Climate & air pollution ↑ Flooding ↑ Pollutants runoff ↓ Habitat fragmentation	*No systematic studies*
Density	↓ Solar radiation ↔ Energy use ↓ Energy supply ↓ Number of trips & VMT by auto ↔ Total travel	↑ Urban heat island ↔ Atmospheric pollution ↑ Water pollution	↑ Climate & air pollution ↑ Flooding ↑ Pollutants runoff ↓ Habitat fragmentation	↑ Population exposure to air pollutants
Grain	↔ Travel patterns ↓ Energy supply	↔ Urban heat island ↔ Atmospheric pollution	*No systematic studies*	*No systematic studies*
Connectivity	↓ Energy use by private transportation	↓ Atmospheric pollution	↑ Habitat fragmentation	*No systematic studies*

Figure 14 Synoptic review of existing studies. Arrows indicate the direction of the relationship: top - increase, down - decrease, horizontal, uncertain (Alberti, 1999)

In the absence of a theoretical framework on the interactions between urban and ecological systems, we cannot interpret the individual results to make conclusions as to how these patterns affect environmental performance in an aggregated sense. Moreover current studies do not seek causal relationships between patterns and processes, nor do they address the sensitivity of correlations to measurement scale. Most studies that examine urban patterns and environmental performance aim to correlate one pattern variable with one environmental variable. Although correlation studies are valuable exploratory tools for generating hypotheses, we need to develop long-term experimental studies to fully understand how urban systems affect ecosystem dynamics (Alberti 1999).

Current studies do not provide a systematic analysis of the relevant links between urban patterns and environmental performance. Only a few dimensions of environmental performance have been studied in relation to patterns of urban development. These are mostly indicators of energy use, transportation-related emissions, and air quality. Current studies correlate environmental performance with gross measures of urbanization. Only population density has been studied systematically in relation to indirect measures of environmental change. Furthermore, when the link between environmental quality and urban patterns is not clear, it is more difficult to design and implement appropriate planning strategies (Alberti 1999). In conclusion, research on the effects of urban development patterns on the use of energy, the flow of materials, and ecosystem functions remains highly underdeveloped (Clifton et al. 2008).

In addition, urban form affects not only environmental performances but also other sustainability aspects. Thomas et al. (2010) work is related to research in geography, urban economy and urban planning, and aims to link urban forms and other socio-economic variables such as social equity, quality of life, and access to facilities, jobs and green spaces. This field of research has been explored especially in the context of the debate about the compact city. To give only two examples, statistical relationships between form indicators and social/environmental variables can be found in (Burton 2000), and the relationship between form and the perception of their environment by individuals is explored in (Garcia and Riera 2003).

Urban form has an important impact on how people perceive and experience space and on human social activities (Jiang and Claramunt 2002). Other authors as Krehl et al. (2016) and Huang et al. (2007) develop an approach for the understanding of the complex relationships between economic and social, as well as built structures and changes in urban regions.

Aware of the interdependency between social, economic and environmental issues and the need of facing all of them together in order to have a complete view on an urban system, this study is limited to the environmental side. The research works on this lacking framework and tries to enrich the existing pool of urban measures to be correlated with environmental performances. This decision is supported both by the author background and competencies and by the lack of satisfying results on this part. In fact, while on the environmental side the scientific community is very active, only few authors dare to face the morphological one with an objective and measurable approach.

4.1.2 Research questions and approaches: literature review

The research moves from questions that other authors tried to answer in the last decades:

- How to characterize urban morphology?
- How to demonstrate the relationship between urban form and environmental performance?

Quantitative analyses based on reproducible results from data processing are already performed. Morphological characterization through analysis of certain variables is useful for the comprehension of urban areas in the present world (Yoshida and Omae 2005). Weber (2001) notes that capacity to compare cities, or different areas of the same city, is important for assessment of any city's prospects. Quantitative characterization based on morphological properties can be a step in such a geographical comparison as well as the first marker for a chronological comparison (Yoshida and Omae 2005).

Adolphe (2001) developed a complete, non-redundant and operational system of indicators compliant with tools used daily by urban planners on real projects. He introduces a set of six geometrical and topological synthetic indicators that answer both questions. This extremely interesting work has some limits. The above mentioned indicators are more complicated than declared and many of them are punctual so applicable to the district scale only in a discrete way.

Also Huang et al. (2007) adopt a similar approach. They first calculated seven spatial metrics on satellite images of 77 metropolitan areas around the world. Then, a cluster analysis classified the cities into groups in terms of these spatial metrics of urban patches. The paper also explored the origins of differences in urban form through comparison with socio-economic developmental indicators and historical trajectories in urban development.

Yang & Chen (2016) answer these questions regarding urban microclimate in high-rise and high-density urban environment. The environmental part is achieved by field measurement on a certain number of stations. The morphological parameters have been calculated locally, creating a catchment area around stations. Both studies combine the use of measures with representation techniques like rose diagrams (L. Adolphe 2001) or gradient maps (Yang and Chen 2016).

The work of Yoshida & Omae (2005) answers only to the first question but in a very precise and interesting way. They work on an urban landscape model, and a 2 km · 2 km area in Tokyo is used as a study site. The approach has the following two characteristics. Firstly, city blocks are used as spatial units for morphological properties to be derived and interpreted. Secondly, the morphological properties derived are interpreted on quantitative basis. Six metrics are calculated for each block, and interpreted with attentions to their interrelationships as well as geographical distributions (Yoshida and Omae 2005).

The generators of these properties are volumes and more specifically buildings. Assuming that common life styles, planning rules, architectural choices, etc. may lead to similar built-up patterns, Thomas et al. (2010) analyse the spatial arrangement of individual buildings (built-up patterns) to see how they vary within the region being studied.

All these studies deal with urban morphology as a result of the arrangement of its constituents looking for a context-related optimal form to be achieved. According to the literature the more popular sustainable form is the compact one. Anyway more specifically, an assessment is needed to define the optimal compactness of urban neighbourhoods (Mohajeri et al. 2016).

The research moves from this studies and tries to construct a common logical framework. The so called "morphometric method" (Yang and Chen 2016) is here adopted to establish empirical relationships between urban form and other environmental, social or economic phenomena. The number of metrics is increased to test their redundancy and capacity to describe a particular morphological feature. The importance of blocks is recognized but the contents generated by buildings are collected also at the district and city scale, with a preference for non-punctual metrics.

4.1.3 Multiplicity and variety

Complex Adaptive Systems (CAS) refers to a field of study and resultant conceptual framework for natural and artificial systems that defy reductionist (top-down) investigation (Brownlee 2007). Dealing with complexity any approach based on simplification will cause to unrealistic results, therefore, simulation of complexity is recommended rather than simplification of it (Vahabzadeh Manesh 2012). Isolating one component from the others could lead to misunderstandings, lack of information and failing to achieve sustainability targets (EEA 2002).

Many authors adopt this approach describing one phenomenon with multiple measures. Krizek (2003) describes ''neighbourhood accessibility'' integrating five measures (population and housing densities, land use mix, street intersection density, and average block size). Talen (2005), in an analysis of an African-American neighbourhood in Cleveland, Ohio, combines several measures – enclosure, lost space, suitability, public space, proximity, mix, centres and edges – to construct a composite map of ''good'' urban form (Clifton et al. 2008). Adolphe (2001), Yoshida & Omae (2005) and Yang & Chen (2016) use a variable number of multiple morphological indicators to describe environmental aspects.

Krehl et al. (2016), with their analysis on density, show that there is not one perfect measurement, rather, the complexity and diversity of the urban spatial structure reveals itself when considering multiple, conceptually different figures. Always speaking of density as an example, some scholars have suggested that is a composite of concepts such as intensity, compactness, pressure on non-built space/ spaciousness and height (Boyko and Cooper 2011). We may discuss if density truly includes the other words or if is on their same hierarchical level, but we agree on the need of avoid a reductionist approach in favour of a multiple one.

Mohajeri et al. (2016) use different complementary indicators to describe different aspects of urban form related to compactness. Pafka & Dovey (2017) with their work on permeability and interface catchment make a comparison between the proposed metrics and other measures from the existing literature to explore how they together can capture differences between real morphologies, and not to find the best ideal exclusive measure that will make the other obsolete.

Considering that selecting the appropriate indicator is not a simple task (EEA, 1999) and the above mentioned examples show that is also not preferable, the research accept multiplicity and variety as optimal descriptors of complexity.

4.1.4 Quantifying quality

Many classic works in architecture and urban planning literature highlight some principles of good urban design. In Camillo Sitte's work City Planning According to Artistic Principles (1965, first published in Vienna in 1889) and much later in Edmund Bacon's The Design of Cities (1974), good urban design was to be based on artistic principles of good form. Though in each of their works "art" is sometimes meant in the romantic sense as the exercise of the artist's inscrutable genius, at other points, and more importantly for present purposes, art also reflects principles that can be explicitly communicated. These are principles based on the geometry of visual perception, the scale of the beholder's body, and the continuity of the beholder's experience (Sternberg 2000). Writing in 1909, English town planner Raymond Unwin (1994), whose work drew heavily on Sitte, declared that we "need to establish relation and proportion between parts of our design". Formalist ideas like Sitte's can be seen in the works of the recent generation of urban designers, such as Allan Jacobs' (1993) fine writing on street definition. Edmund Bacon (1974) adds a number of additional guides to good form, demanding that good design should interlock and interrelate buildings across space.

It appears that formalist principles are linked to the relationship between void and volumes, streets or squares and buildings. These principles of proportion, dimension, distance, distinctiveness, contrast, juxtaposition, complementarity, movement, and light and shadow (Sternberg 2000) can be expressed through quantitative measures. Measures are so not only useful to quantify urban environment for regulation purposes, but also to objectively represent its qualities. To make an example out of the research field, the colour of the eyes is a qualitative aspect that could be described numerically first by dismantling the iris into the colours that compose it in different percentages, and then dismantling these colours into set of integer numbers referring to a colour code as RGB or CMYK. The same can be done, sometimes not in such an easy way, for almost every principle of good urban design or other qualities of the built environment.

4.1.5 Maps, Values and Diagrams

There is always the danger in quantitative research that we prove the bleeding obvious. The map itself is a form of spatial knowledge that can be designed to highlight a specific dimension. For example levels of permeability may be graphically obtained by stripping away all information except the public space network. So what is the point of quantification? How to ensure that we do not simply construct a measure that confirms what the map has already told us? While maps of homogenous abstract morphologies are relatively easy to read, real cities are more complex. The comparison of case studies has led to surprising results that did not match the initial understanding of the morphologies derived from studying the maps (Pafka and Dovey 2017).

Moreover measures often provide averages and, as such, do not represent more fine-grained fluctuations in what is being measured (Gordon and Ikeda 2011). For example, the density of dwellings in London in 2008 was 122 new dwellings per hectare (DEFRA 2010). However, some areas will have had much lower dwelling densities (less than 30) and others, much higher densities (more than 400) (Boyko and Cooper 2011).

This dualism has positive effects not only in the analysis phase but also when we move to design. The need of both quantitative and a qualitative output is stressed also by Gil & Duarte (2008). The first to feed generative design methodologies and to produce technical reports, the second to provide visual feedback for traditional design methodologies and to support presentations of the design.

Expressing design updates both in terms of visual and numerical output allows designers (or any decision maker) to become aware of the implications and qualities of a particular solution option (Beirão, Nourian, and Mashhoodi 2011). We suggest that the joint use of both maps and measures – maps that demonstrate the measures – is crucial to gearing practice to research (Pafka and Dovey 2017) and design.

Another possible representation consists in graphs or diagrams, constructed on multiple numerical inputs. They are schematic representations of the real world able to synthetize the appearance, structure, or workings of something. They are the equivalent of an overlapping of multiple maps with the advantage of being easier to be read. The diagrams, despite being simplified abstractions of real phenomena, must be meaningful to the urban designer so that he immediately knows how to incorporate this information into the design process (Gil et al., 2008).

All these output together facilitate the understanding of the analysed object, especially if we are studying cities and urban systems. For all these reasons a joint use of maps and metrics based radar diagrams will be used to investigate and describe urban Compactness and the KCs composing it.

4.1.6 Spatial Metrics

Most of quantitative urban studies focus on density. However, density does not reflect the variety of the possible spatial structures of cities (Alberti 1999). Progress toward smarter growth or a new urbanism can only be made with a more complete understanding of urban form (Clifton et al. 2008). It seems important to have quantitative descriptors, which allow distinguishing different types of urban patterns and which are less ambiguous than traditional density measures (Frankhauser 2004).

Even if the actual landscape of spatial metrics is huge and disorienting, many authors ask for new spatial metrics. Boyko & Cooper (2011) affirm that there is a need to develop measures that are able to represent the three-dimensionality of urban form. Alberti (1999) says that Urban Pattern metrics that could be relevant to environmental processes across various scales still need to be developed. For Khan & Pinter (2016), further research into more reliable scaling-based indicators is suggested. For a reflection on the form of urban patterns it would be convenient to have data that represent their particular features and allow a comparison of their morphology (Frankhauser 2004).

There is virtually no limit to the number of features that can be measured and used for quantitative analysis (Clifton et al. 2008). Considering that the major task in simulating complex systems is simulating the complexity itself, this may require maximizing the number of independent variables that affect the desired dependent variable (Mostafavi, Farzinmoghadam, and Hoque 2014). We could conclude that the more meaningful, representative and non-redundant metrics we develop, the better our understanding of complex phenomena will be. The more data collection and availability increases, the more it became clear that indicators might be an effective tool to better understand and monitor complex systems (EEA 2002). There is room for new metrics that quantitatively describe qualitative aspects of the build environment, especially for a fine grain scale as the neighbourhood one, also because the existing one often handle the same quantities differing mainly by unit of measure or minor details.

4.1.7 Tools and data

Geographic information system (GIS) technology has made analysis of spatial patterns a simple exercise on a laptop computer and as engaging as a video game. Several software packages are now available for analysing spatial development patterns and for predicting the consequences. In addition, the quality of spatially referenced data has reached levels unimaginable a few years ago (Clifton et al. 2008).

An essential tool in this process is the creation of spatial databases that can establish the framework for spatial analysis, management and monitoring of the territorial processes. These databases can play an important role as the initial steps towards an urban atlas (EEA 2002). The existence of standards in the construction of urban databases (INSPIRE, OSM) permits to create measures that can be calculated between the whole range of urban morphologies (Pafka and Dovey 2017). The diffusion of vector layers make meaningful to work with them, instead of raster, for their accuracy, crucial for fine grained investigation, and for the possibility to deal with urban elements as buildings instead of generic masses.

These data allow analysts to focus on spatial patterns at very high levels of resolution, such as the tax-lot parcel. Finally, because the data are ‘‘object’’ oriented, the measures can be computed for nearly any self-defined geographic unit (Clifton et al. 2008).

The research integrates GIS (QGIS, ArcMap) and 3d modelling software (Rhinoceros+Grasshopper). GIS is used for morphological analysis and atlas generation while BIM and parametric modelling tools should be mainly used for environmental performances simulation.

4.1.8 Object-oriented morphological units

While buildings and street network are almost always present, not all the morphological elements of a city are currently represented inside existing datasets. Plots are employed in US and UK but can hardly be found in other European countries and especially in Italy because of the geometrical conflict between cadastral and topographic maps (Marini and Pirotti 2010). Blocks, intended as the negative of street area that contains buildings, is also not included in many datasets and can be so only indirectly visualized but not managed as an object. The same could be said for courts. One of the reasons could be linked to the fact that these elements doesn’t have a clear property and are not used for tax-related issues, or simply because they belong to the Void component and so intuitively harder to be shaped or framed respect of building masses.

According to the research approach based on the combination of numerical and visual output, having the possibility to enlarge the set of morphological elements represented in an object oriented manner, enormously increase the modelling capability.

It has been proved that is practical to treat a city block as a spatial unit in certain types of analysis for urban morphology, especially when a high spatial resolution data set is available. They are solid components of morphology of rural–urban continuum (Yoshida and Omae 2005).

City blocks are a key morphological element because they are the only geometry able to both collect information from the objects inside it (buildings, courts, plots) and to create information for larger spatial units as district or city. They are the negative of street area and this make easy to obtain them even when not included in standard databases. Plot is also quite important but hardly available, impossible to be obtained by performing spatial operations on other input layers, and only involves private spaces. Blocks can be seen as the sum of all the plots and this simplify a lot the management of spatial inputs.

For this reason a set of algorithm has been develop in order to create object oriented layers of missing morphological units through geometrical operations performed on the input Volume and Void layers.

4.2 Multi-Scale and Multi-Disciplinary approach

4.2.1 Multi-Disciplinarity

The reason behind the interest of the research on CAS is its potential to be analysed by different available methodologies, because it has been under the spot light of different disciplines for recent decades.

Clearly, the topic involves so many scientific and social disciplines that it is difficult not only to understand how the whole system works, but also to define its limits. Cities are complex entities influencing and influenced by an extremely broad constituency that goes beyond pure administrative and geographical borders. Thus, an integrated multidisciplinary approach appears to be the most appropriate tool for a comprehensive understanding of urban issues. Nevertheless, at international level, such an approach is often missing (EEA 2002). In fact, most research on the subject of urban form has been constrained by disciplinary boundaries, with few attempts to undertake a multidisciplinary review.

Interest in urban form is strong among scholars trained in multiple disciplines. Further, the issues of concern to the various disciplines often dictate the scale of analysis, the specific phenomena of interest, and often the source of data. These systematic differences between disciplines define distinct perspectives on urban form and approaches to measurement and quantitative analysis. Too often principles of urban form are proposed without due consideration of multi-disciplinary perspectives and the scales at which such perspective might be most pertinent (Clifton et al. 2008).

The landscape ecology perspective, for example, generally includes work by natural scientists concerned about environmental protection and resource conservation. They tend to focus primarily on undeveloped areas and so, not in patterns of urban development, but in landscape patterns in the areas not developed for urban use. Further, because landscape ecologists are primarily interested in ''natural'' landscapes, landscape measures of urban form focus primarily on types of land cover (urban, cropland, rangeland, forest, etc.), not types of land uses (residential, commercial, industrial, etc.) (Quattrochi and Pelletier 1991).

While many studies deal with land use at the city or metropolitan scale, the research on the urban development patterns remains highly underdeveloped (Clifton et al. 2008). There is also need for a framework that allows to connect the results of the morphological analysis at the different scales.

4.2.2 Multi-Scalarity

The relationship between urban patterns and environmental performance is scale dependent. Of course, the study of urban patterns and environmental performance must apply to the city and metropolitan scales. However, urban patterns are relevant to environmental processes operating at multiple scales. Scale considerations include both the resolution of a given urban pattern measurement and the geographic extent or boundary of the area under consideration. The study of urban patterns and environmental processes requires crossing spatial and hierarchical scales. Therefore, a nested approach is needed (Alberti 1999).

The form of a city is constituted by the spatial and social patterns that compose it and that allow us to describe its networks, its built spaces, and its empty spaces in geometric, topological and hierarchical terms in two and three dimensions. The city's form cannot be disconnected from the degree of resolution at which it is observed. We need to go beyond the overly simple opposition between local and global form and add to the three spatial dimensions the scale of resolution (Salat, Labbé, and Nowacki 2011).

A large-scale urban space can be partitioned into a finite number of small-scale spaces. Using such a partition, the degree to which small-scales are interconnected or integrated can be analysed (Jiang and Claramunt 2002). This principle is valid both for abstract grids and for other kind of boundaries as the administrative or morphological one. Xu et al. (2017), i.e., verify the quality of their work by testing it on grids of growing side length from 100m to 600m.

City maintains its complexity at every scale. Is not possible, or meaningful, to define the exact and precise size of the different investigation scales, due to fact that CAS is a significantly complicated system comprised by different subsystem which every one of them could be a CAS individually. To discern the relationship between the different scales clears the obscured image of the system structure (Vahabzadeh Manesh 2012).

Owens (1986) noted that different aspects of spatial structures become important as we move across various scales. At the regional scale, the broad patterns of settlement are significant; at the local scale, what matters is the design, siting, orientation, and layout (Alberti 1999).

In addition, we should consider which measures we use to determine the scale of an urban area. The most common are Area and Population but according to the huge variety of possible density values, they are not always comparable. Tables 1 and 2 show some examples of settlements to show how the concept of scale is context-dependent and shaped differently by the selected measure.

Table 1 Comparison between world cities at city, urban and metropolitan scale. Huge differences in density values makes hard to use area or population as scale determiners.

City	Milan			Stockholm			Boston			Manila		
Country	Italy, EU			Sweden, EU			Massachussets, USA			Philippine, Asia		
Scale	City	Urban	Metro	City	Urban	Metro	City	Urban	Metro	City	Urban	Metro
Population	1'368'590	3'206'000	4'937'086	935'619	1'515'017	2'226'795	667'137	4'180'000	4'628'910	1'780'148	12'877'253	22'710'000
Area	182	1'575	2'945	188	381	6'519	232	4'600	11'700	43	614	1'475
Density	7'533	2'036	1'676	4'977	3'976	342	2'876	909	396	41'515	20'975	15'398

Table 2 Comparison between world cities of similar area. The mid group is particularly interesting as it includes cases at three different scales characterised by extremely high differences in population value.

City	Helsinki	Tunis	Philadelphia	Houston	London	Istanbul	Paris	Sao Paulo	Jakarta
Country	Finland, EU	Tunisia, N. Africa	Pennsylvania, USA	Texas, USA	England, UK	Turkey, Anatolia	France, EU	Brasil, S. America	Indonesia, Asia
Scale	City	City	City	City	Greater London	Urban	Metro	Metro	Metro
Population	629'512	1'056'247	1'567'442	2'099'451	8'673'713	13'576'000	10'755'000	20'186'000	26'063'000
Area	214	213	142	1'625	1'572	1'399	3'800	3'173	2'784
Density	2'939	4'968	11'070	1'292	5'518	9'704	2'830	6'362	9'362

4.2.3 Boundary definition

Cities are complex entities influencing and influenced by an extremely broad constituency that goes beyond pure administrative and geographical borders (EEA 2002). The city is perceived by the people who are used to living within it as a system somewhat isolated from the surrounding background. Still, urban sustainability can, and should, be viewed from at least one other perspective. Recent studies, while keeping the city at the core of their analysis, consider urban areas as systems directly connected to their regional backgrounds. Perhaps the most important insight from this result is that no city or urban region can be sustainable on its own (EEA 2002).

Subsystems as district or communities, in addition, are not a bounded entity. An urban community can be identified in different ways in terms of land use, infrastructure or people density (UN-Habitat 2006). These criteria raise ambiguity about urban boundaries (Berardi 2013). The work of Lynch (1960) remembers how the extension and the perimeter of a neighbourhood is somehow something personal strongly affected by citizens' habits and perception. That's why is common to find multiple conflicting neighbourhood spatial divisions within the same city on maps generated by different bodies and for different purposes.

According to Ingram et al. (1960), districts can also be discovered within the data finding groups of items which have strong similarities to each other which they do not share with other items in the space. In order to identify districts within an arbitrary data space we can use techniques from the field of cluster analysis, for which a number of algorithms have already been developed.

Another aspect to be considered is that measures can change dramatically within short distances depending on morphology (Pafka and Dovey 2017). Slightly scaling or moving a boundary may tremendously affect the analysis. Geostatistical tool as the variogram can be used to explore the spatial variation of measures in order to find abrupt changes or continuity in the urban fabric. A similar approach was adopted by Frankhauser (2004).

A particular fractal method of analysis, the radial analysis, can be used for identifying ruptures in the pattern (Frankhauser 1993; Michael. Batty and Longley 1994). Figure 15 shows this process. After having chosen the position of a site (counting centre) a square surrounding this centre is progressively enlarged and the built-up mass counted inside the square. A special representation of the obtained relation between the mass and the size of the square allows to identify the ruptures. This procedure allows us to select districts, which show a specific morphologic behaviour that is later expressed in the fractal dimension (Frankhauser 2004).

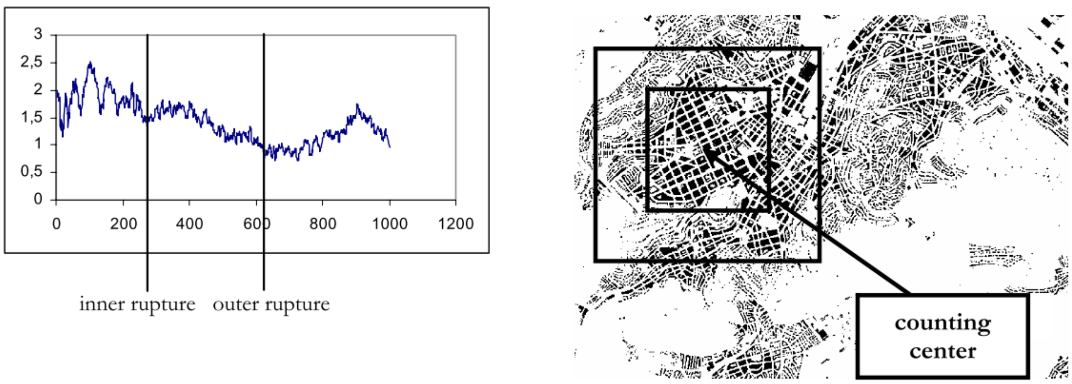


Figure 15 Identifying different ruptures by means of a radial analysis. On the left the so-called curve of scaling behaviour that helps to identify these ruptures on the measuring curve.

When moving from spatial metrics to performance indicators the scenario becomes even more complex. In fact, while the urban structure lays on a specific area, its performances can be strongly affected by flowing generated by externalities and simply passing into the sample one. The city centres, i.e., presents high level of pollutants because of their position that increase their probability of being crossed by car trips, despite the good levels of public transport accessibility.

4.2.4 Bottom-up modelling

Patch

Most of the literature in urban studies focuses at city and metropolitan scale and deals with urban patches as input geometry. These studies already reached a high level of detail and scientific approval among scholars (Huang, Lu, and Sellers 2007). McGarigal (2004) defines patches as discrete areas of homogeneous environmental conditions. Patches are classified based on the type of land cover or the extent of human development. Studying urban boundaries requires reflection on how to define them (Frankhauser 2004) and the criteria are not so evident or strongly scientifically based. Urban patches are clusters obtained by ideally performing an offset of a predefined distance on the building layer and grouping together all the buildings with a lower relative distance. The distance of

200 m between neighbouring buildings, used in France to delimit agglomerations seems therefore rather arbitrary (Frankhauser 2004). Macroscopic patterns emerge from the dynamic and nonlinear interactions of the systems low-level (microscopic) adaptive agents (Brownlee 2007), as, in this case, buildings. A graphical way to pass from buildings to clusters is performing a continuous offset followed by a merge on connected geometries. Figure 16 shows this procedure for the city of Milan at two different zoom levels. Grey shapes are clusters that look like real blocks or superblocks including some existing streets.

Figure 16 Map representing urban patch (50m) offset and buildings in Milan. Whole city (left), zoom on smaller portion (right)

Every offset distance will produce a different number of clusters and a representation of them. If we plot on the x axis of a graph the offset distance and on the y axis the number of single-part geometries (clusters) we obtain a function that describe the relative distances of buildings in an area and the homogeneity of their distribution (Figure 17).

Figure 18 shows a simplified graphical version of the above graph on a different context. In order to make the picture clear for the reader the continuous increment of the buffer has been replaced by a discrete one with an interval of 20m. The first number indicates the number of clusters while the second one the corresponding buffer distance. Thicker rings as the one going from 40m to 100m means that despite an increase in buffer distance, the number of cluster remains the same. The corresponding graph will present a horizontal tract at value 2 on the y axis.

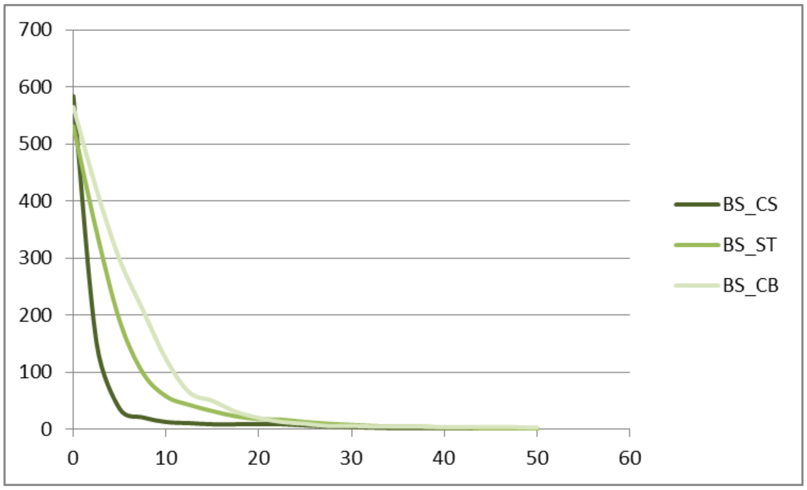


Figure 17 Building Distribution Function. On the x axis buffer distance, On y axis number of clusters defined as separated agglomeration of volumes. The graph shows the distribution for 3 areas in the city of Brescia: Historical city centre (BS_CS), XX Century development near to train station (BS_ST) and a modernist neighbourhood (BS_CB).

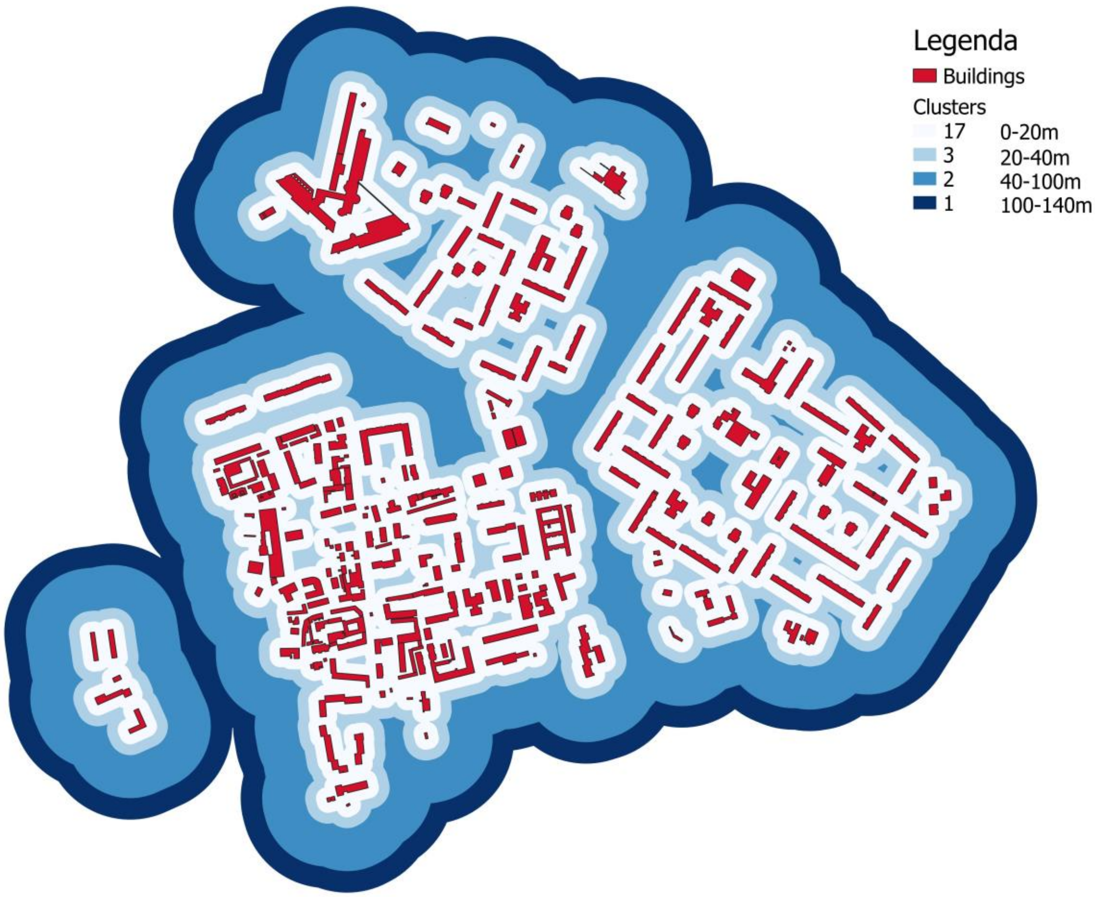


Figure 18 From Building to Patch. Building multi-buffers map (20m increment) of Trenno and Gallaratese area in Milan.

From this new perspective patches becomes the end point of a growth process that allows to study urban patterns and not only urban form. Many of the new metrics that has been introduced are based on this relationship across scales and will be better explained in the metrics section.

Fractal

Another extremely interesting multi-scale approach are fractals, a mathematical concept applied to urban pattern mainly by Frankhauser and Thomas (2004; 2008; 2010; 2013) The most striking feature of fractal objects is the fact that they are by definition multi-scale. This is the direct result of the procedure used to construct a theoretical fractal. This procedure is based on repeating the same operation, defined by the generator, on smaller and smaller scales (Frankhauser 2004).

The fractal, as well as the urban patch approaches will not be applied in the thesis because of the consistency and specificity of the already existing studies. Existing studies already define some criteria to describe a specific scale or the link between different urban scales. A possible implementation could be the application of these techniques on finer grain urban patterns or even at the scale of the single building. In fact, methods like the box counting one can be applied to shapes of any kind and size. This method looks like a match between the vector and many raster representation of an object at different resolution with the goal to obtain as a result the dimension of this object, intended not as its area or volume but in a more mathematical meaning. A tool already exists to perform such analysis (Fractalyse) but it would be of great advantage to have more control on these operations and to integrate them into a GIS-like environment to increase the possibilities of automatization and integration with other techniques here presented.

4.2.5 Future developments

Out of the scope of this research, also a building can be considered as a CAS on its own. With the same logic used to investigate the city we can dismantle it into components and explore the architecture of their ligands. It follows that properties as porosity can be computed also relatively to a single building based on its mass distribution and cavities. Yuan & Ng (2012) explore this field to assess pedestrian-level urban ventilation. Another analogy could be the window to wall ratio of a façade as the inverse of the building footprint on a sample area. The perimeter of a building will incredibly change considering ornament and more realistic 3d representation respect to the 2.5d simplified volume used for urban studies, showing the change in dimension according to the resolution. This example strengthens the importance of a multi-scalar approach and also suggests that comparing geometries divided by a jump in scale may increase our understanding of the object we are studying.

4.3 Context

4.3.1 Global vs Local

A key question that has yet to be resolved is whether or not it is possible to develop a core set of urban sustainability indicators that could be used by all municipalities in a state, a country, or even internationally (Maclaren 1996). Murbandy/Moland demonstrates that this is possible to a certain extent. As stated by Bossel (1996): Sustainability can only be discussed in relation to a particular region, since it is directly related to its carrying capacity. Sustainability indicator sets are, hence, region-specific (EEA 2002). Cities are all made by the same components so is surely possible to compare them. But is it useful?

On one side standardization is useful to assess and compare data, problems, contexts, cities and policy options regarding sustainable development and to synthesize highly complex issues in a simplified and compact manner to spark debate and guide further in-depth analysis and policy-making (Yigitcanlar and Lönnqvist 2013; Moreno Pires, Fidélis, and Ramos 2014).

On the other, the adoption of universal solutions or benchmark for indicators can be dangerous. For example, even in more developed Asian mega cities like Seoul and Tokyo, indiscriminate application of measures from Europe and North America have proved inappropriate (M. Jenks and Burgess 2000; Yokohari et al. 2000). Prescriptions derived from contemporary planning movements in Europe or North America (e.g. Compact city, Smart Growth, New Urbanism) may be even less applicable to the cities of developing countries. Research on the most polluted mega cities of the developing world has already pointed to the very compact nature and high density of cities in China, India and Mexico (Wang 1999; Huang, Lu, and Sellers 2007)

Indicators should be standardised to allow a cross-country comparison and should, at the same time, reflect the context for which they are designed. This implies that a compromise between standardisation and diversity should be obtained when designing a specific set of indicators (EEA 2002). The debate between local and global indicators could be overcome by adopting metrics that can be applied across the vast differences of urban contexts (Pafka and Dovey 2017) with different benchmark values for each of them.

Many authors agree on the importance of context and its role in the definition of solutions. The quest of single remedy to be implemented in different context, as a sustainable form, is doomed from the start (Ungers 1984). There is no single sustainable city form; the choice of a planning and design approach for the improvement of an existing city or city region depends entirely upon the characteristics of that city or city region and may therefore have to be different in each case (Frey 1999). It would be non-sense to impose, i.e., Sitte's turbine plazas as a general requirement. These concepts must be seen as sources of personal insight or inspirations, not as mandates. It would be a fundamental misunderstanding to take them as all-purpose policy recommendations or blanket prescriptions (Sternberg 2000).

Context also puts study findings into perspective: for example, one study found that people in the UK were not willing to pay a premium to live in dense neighbourhoods (Burton, 2000). In contrast, residents of Hong Kong paid more to live in high-density areas because of the availability of high-quality amenities, but also because of high land values and the low availability of land (Smith 1984; Boyko and Cooper 2011)

Context involves a whole host of relevant psychological, social, cultural, economic, geographic, physical, ecological and technological dimensions of a situation (Churchman 1999). Each situation will determine which dimensions are relevant and how those dimensions are relevant (Haughey, 2005; Stokols, 1987). Thus, a significant result in one place may or may not be significant in another due to variations in cultural and social contexts (Forsyth 2003).

Other studies have found similar results. An evaluation of the environmental quality of 50 residential areas in London revealed that the majority of areas perceived as above average were either above or below the recommended density range of 125–250 hrh. Only 17% of the study areas that were perceived as above average fell within the density range (Llewelyn-Davies, South Bank University, and Environment Trust Associates 1994). These findings are corroborated by research in Finland, which showed a positive relationship between dwelling density and environmental quality, but at density ranges below 100 dwellings per hectare and above 190 dwellings per hectare (Broberg 2010). Many metrics can hardly be maximized or minimized, the optimization lies in a range of acceptable values. This range is context specific because of the influence of climate and of the multitude of other above mentioned factors.

Designers need to understand that analytical results are simply numbers that only acquire a value when placed within the whole evaluation framework together with a solution and a program. The same analytical results can have positive or negative interpretations depending on their context (J. Gil, Duarte, and Syntax 2008).

The research is not suggesting a unique solution for different contexts, but rather a unique question. Avoiding the need of comparisons between cities belonging to different contexts, the competition moves to another level. Each city competes with itself and its past trying to shape a more sustainable future for its citizens. Different areas of the same city can be compared and start a "mutual learning" process sharing both goals and practices on the same context. The research believes that the same methods, tools and metrics can be used to understand and describe all possible urban contexts, while each optimization process will follow different paths mainly according to climatic, environmental, cultural, political, economic and social conditions. This principle drives the construction of spatial metrics able to highlight the differences existing in the global variety of urban areas.

4.3.2 From diagnostic to design

We shouldn't forget that the final purpose of analysis is increasing the awareness of the designer and permit the creation of a better transformation scenario. Design interventions modify the structure of the system and so its performances, not necessarily improving them.

When the link between environmental quality and urban patterns is not clear, it is more difficult to design and implement appropriate planning strategies. In many cases we cannot resolve the scientific uncertainty that characterizes important environmental problems, but we can design the empirical studies to learn about how urban and environmental systems interact (Alberti 1999).

Designers need to understand that analytical results are simply numbers that only acquire a value when placed within the whole evaluation framework together with a solution and a program. Evaluation requires an interpretation of the analytical results as it tests them against regulations, development targets, and quality and sustainability benchmarks (J. Gil, Duarte, and Syntax 2008).

Complex phenomena with feedback loops and interdependencies are best understood by playing them, seeing the phenomena unfold and respond to user intervention. This aspect of play and learning is important in urban design education but also in practice. Popular games like the SimCity series have a focus on entertainment, but they also encode urban models that become understood through play thereby enabling the user to win. Recently, these games have moved from essentially economic management to urban quality-oriented targets, as in the cases of SimCity Societies and City Life (J. Gil, Duarte, and Syntax 2008).

The demand for simulations, incorporating different scales and interdependencies, is increasing in order to evaluate and predict the impact of planning efforts (Aschwanden et al. 2012) and the feedback speed of this process is crucial and needs to be maximised.

5 Urban Characterization

This chapter is organized starting from a survey of existing literature to arrive to the implementations proposed by the author. For this reason the paragraphs of both survey and implementation subchapter are the same. They treat, in this order, metrics, maps and tools to understand how to measure, represent and process urban datasets. Metrics survey presents a list of existing measures from different fields (urban studies, geometry and graph theory) divided by the related IMM Component (Volume, Void and Network). Maps section collects representation techniques, often related to the calculation of a group of specific metrics, which could be adapted to different topics or purposes. Its goal is mainly to stimulate designers' and analysts' creativity and increase their awareness of the urban issues by visual outputs. Tools section begins by elucidating the difference between tool and software and how this affects the current diagnostic scenario. It follows distinguishing analysis from simulation and mentioning the most common instruments currently used for this purpose. An ongoing research program with a software house is presented in order to fill the existing gap between GIS and BIM software for urban diagnostic purposes.

The survey of the existing literature raised the need of performing a preliminary ordering activity before the beginning of the implementation. The glossary section observes the chaotic condition of current labelling and acronyms in urban studies and in particular among spatial metrics. It first explores all the terms currently used to identify the more appropriate for the construction of a research vocabulary. Then, using tools as taxonomy and a survey tries to define a general criterion for metrics labelling and the definition of their acronym.

The last part of the chapter presents all the implementations introduced by the research in terms of metrics, maps and tools, following the structure of the first subchapter. Before that, an introductory paragraph visually clarifies the adopted input and ancillary layers to prepare the reader for an easier understanding of the following parts. The metric section in also divided in groups (multi-scale, volume/surface, box or minimum bounding geometry, buffer, centroid, block and courts) and every new metric is explained, adding its possible location inside IMM KCs and the minimum application scale. Once presented all the metrics, a retrofitting process on more than 60 metrics is explained referring to detailed statistical and correlation studies in Appendix A. The result is a selection of 30 validated metrics including both existing and new one, that will be used to characterize Porosity and Permeability KCs in chapter 6 and other KCs in further future developments of the research. The maps part, as done for the survey, is a mix of new representation techniques and new applications of existing methods. Sometimes the innovation lays in the construction of a specific new layer (BL_BP) more than in its visualization procedure. The tool paragraph explain in words all the algorithms that have been developed for the thesis and shows in a synthetic data flow diagram (DFD) their position inside the modelling process. Minimum input and expected output are also explicated. The images of the visual programming algorithms are collected in Appendix B and complete the information of this part.

5.1 Survey

5.1.1 Metrics

Once agreed on the need for new spatial metrics as first step is useful to map the existing one to understand their pros and cons, what is already well mapped and what is missing. To give an order to this operation I referred to the components of IMM and their relevance in the definition of Compactness (Volume, Void and Network). The Function component has not been taken into account as almost irrelevant for the definition of Compactness. The metrics are now presented without a precise order, as the alphabetical one is hard because of multiple labelling and the chronological would require to define when exactly one metric has been introduced, that is a hard and useless task. They are grouped by field of study going from the simplest and widely used to less applied or more specific one. In case of metrics with multiple names, the one considered the most appropriate will be the first in the list.

VOLUME

URBAN STUDIES

- Building Coverage Ratio (BCR) / Site coverage / Coverage Area (C) / Ground Coverage (GC) / Ground Space Index (GSI) / Building Density (BD)

Is the total built area in an area divided by total sample area. Could be *gross* if the sample area includes all void space (streets, parks, railways) or net, if the divisor is limited to plot area.

- Floor Area Ratio (FAR) / Plot ratio / Floor Space Index (FSI) / Floor Area Density (FAD) / Building Intensity / Built Density

Is the total building floor area in an area divided by the sample area.

- Building density (BD) / Number of Building per hectare / Building to Land (BTL)

Is the total number of buildings in an area divided by total sample area. The more this number is high, the more the urban tissue is diverse and resilient (Salat, Vialan, and Nowacki 2010).

- Buildings Height (BH) / Mean Height of Buildings

Is the total building volume in an area divided by the total building footprint in the same area (C. Zhao et al. 2011).

- Building Height Limit (Bh)

Is the height limit of buildings or building maximum height.

- Building Volume Density (BVD) / Volume Density (VD) / Volume Area Ratio (VAR) / Absolute Rugosity (Hm) / Canopy Height (Hc) /

Is the total building volume in an area divided by total sample area.

- Frontal Area Density (FAD) / Frontal Area Index (FAI)

Is the total building vertical surface in an area divided by the sample area. In the case of FAD it may refer only to the facades facing the streets but is not explicitly specified. FAI uses to be calculated locally in a specific wind direction and can be arranged on a rose diagram (Yuan and Ng 2012).

- Surface Area per Projected Area

Is the total building vertical surface divided by the total building footprint

- Building Orientation

Calculated on single buildings sides, can be represented on a rose diagram. The orientations of the sides of buildings are non-normalised when all sides count equally in the rose diagrams but normalised when more weight is given to the long sides, which are then considered as composed of many short parts. Can be weighted also on surfaces multiplying side length by their height if available (Mohajeri et al. 2016).

- Passive Volume

Is the passive volume of a building divided by its total volume. The passive Volume is obtained by performing an inner offset of 6m from external facades and represent the portion of building naturally illuminated and ventilated by openings. (Salat, Vialan, and Nowacki 2010)

- Nearest-Neighbour Ratio

Is the average distance between buildings from centroids normalised by the total area of a neighbourhood. If the ratio is less than 1, the building configuration indicates clustering; if the ratio is greater than 1, the configuration is more uniformly distributed (Mohajeri et al. 2016).

- Population density (PD)

Is the total number of people living in an area divided by total sample area. Even if is not directly a Volume measure, I decided to include it for its wide adoption and ease. Volumes are in any case the place where people live so the link is clear and indisputable.

GEOMETRY

There is a long history of interest in the scientific community in developing an effective compactness measure. These measures can be grouped into four categories: area–perimeter measurement, reference shape, geometric pixel properties, and dispersion of elements of area.

Area-perimeter

- P/A

Is the perimeter of a 2D shape divided by its area (Ritter, 1822). It suffers from the fact that the measure varies when shape size changes. To account for this limitation, the measure can be made dimensionless by dividing the shape's area by the square of its perimeter. Here some metrics that overcome this limit:

- Circularity Ratio = 4A/P2 (Miller 1953)
- Compactness Ratio = 2√πA/P (Richardson 1961)
- CIPQ = 4πA / p2 (Osserman 1976)

The main idea is to divide compare a shape with the circle, used as reference as the most possible compact shape. By adding π in the numerator of Miller's circularity ratio, CIPQ's range is changed to (0, 1) (instead of 0 to 1/π in Miller's measure). A shape with a high value of CIPQ is considered to be more compact than a shape with a lower CIPQ (W. Li, Goodchild, and Church 2013).

These metrics are valid for 2D shapes but he same principle can be applied to the third dimension.

- S/V

Is the surface of a 3D shape divided by its volume. In order to make it size independent has been developed another measure:

- Form factor (C) = $S/V^{(2/3)}$

The power 2/3 enables to compare compactness independently of the size effect.

Reference shape

- Digital Compactness Measure = CDCM = A/Asc (J. P. Cole 1964; Kim and Anderson 1984)

Is the area of a shape divided by the area of the smallest circle that circumscribes that shape. It varies from 0 to 1 but is not additive nor scale invariant. According to Li et al. (2013) it cannot be applied to shapes with holes. On the contrary, I believe that, at least in the urban application, there are no risks in doing that. This measure is an alternative of:

- CGibbs = 4A/L2 (Gibbs 1961)

Where A is the area of the shape and L the longest line between two points on a shape's perimeter. Computationally speaking, this line is not always easy to be obtained. For this reason the CDCM has been preferred.

- CBottema = $1 - |A \cap A0| / A0$ (Bottema 200AD)

Is the area of the intersection between the shape and its equivalent circle divided by the area of the circle, subtracted to one. It works by overlaying the shape S with a circle C of the same area and computing the overlap. A is the area of S, and A0 is the area of C.

- Elongation Index = El = $|A \cup A0| / |A \cap A0|$ (Wentz 2000)

Is the area of the intersection of the shape and its equivalent circle divided by the union of the same two shapes.

These two measures can be applied to shapes with holes but are still sensitive to size changes. Moreover, the circle can be overlaid on the shape in many different positions, so a search must be invoked to determine the position of maximum overlap, making this type of method less competitive from a computational perspective.

Other shape-reference approaches include the comparison of the area or diameter of the maximum inscribed circle to that of the minimum circumscribed circle. The approaches in this category have common drawbacks. (W. Li, Goodchild, and Church 2013)

Raster

- Normalized Discrete Compactness = CNDC = (LD – LDmin) / (LDmax – LDmin) (E. Bribiesca 1997)

The idea is to count the number of cell sides (LD) shared between pixels that represent a shape S, and then calculate the measure CNDC. LDmin and LDmax are the lower and upper limits of the number of cell sides that can be physically shared with the same number of pixels within S. Defining p as the number of edges on the border and n as the total number of pixels in S, LD, LDmin, and LDmax can be obtained from the following equations:

$LD = (4n - p)/2$

$LDmin = n - 1$

$LDmax = 2(n - \sqrt{n})$

This method has been extended also to 3d shapes using voxel instead of pixel and faces instead of sides. (Ernesto Bribiesca 2008)

The NDC approach has the advantage of being scale invariant, and can be applied when computing the compactness of shapes with holes (W. Li, Goodchild, and Church 2013). The weak aspect of this measure is that rasterization is a discretization process. This means that the shape on which compactness is calculated is not the real one but an approximation. In addition the result depends on the pixel size used, as it happens i.e., for the box counting method for determining the fractal dimension of an object.

Dispersion

MI Shape Index = CMI = A2 / 2 πIg (Massam and Goodchild 1971)

Is the area of the shape divided by two time pi the Moment of Inertia about the centroid of that shape. The shape index base upon MI, CMI, is calculated as the ratio of the MI of a circle of the same area about its centre, to the MI of the shape about its centroid.

This approach involves the calculation of the second moment of an area about a point, also known as the moment of inertia (MI). According to Massam and Goodchild (1971), each shape can be considered as composed of infinitesimally small units of area da, and the MI of a shape is defined as the second moment of an area about a point s on the shape as follows:

$Ig = \int zg2\ da$

where z_g is the distance from da to the centroid.

The ‘centroid’ in here intended in its strict mathematical sense as the balance point and the point about which the MI is minimum for any shape. This measure is additive and insensitive to shape size (Bachi, 1999). One interesting aspect of this measure, usually applied in regionalization problem at the urban patch scale, is that could work also with buildings without the need of any discretization. In fact every building (or volume, or block eventually) can be considered as one of the infinitesimally small units previously mentioned, calculating the MI from the centre of masses of the built environment as a whole.

VOID

- Average block area (Weicher 1973; Schmidt 1977)

Is the total block area in an area divided by the total number of blocks in an area.

- Average block perimeter (Fowler 1987)

Is the total block perimeter in an area divided by the total number of blocks in an area.

- Number of blocks / Block Density (Southworth and Ben-Joseph 2003)

Is the total number of bocks in an area divided by the sample area.

- Longest diagonal of the blocks (Stangl 2015)

Is the average value of the longest diagonal of the blocks in an area.

- Area Weighted average perimeter (AWAP) (Pafka and Dovey 2017)

Is the product between the perimeter and the area of each block in an area divided by the total block area in the sample area. This method ensures that the impact of a large impermeable block is not lost in the average. Any dead-end streets need to be removed from the analysis so that the block perimeter corresponds to the shortest distance around the block, without entering the dead end. In algebraic terms this can be represented by the following formula:

$AwaP = (Pi \times Ai) / AT$

Pi and Ai are the perimeter and area of each block i, respectively, and AT is the total area of all blocks.

- Street Coverage Ratio (SCR) / Roads ratio (Ts roads)

Is the total street area in an area divided by total sample area.

- Urban Canyon / Aspect Ratio (H/W)

Is the mean height of buildings in a street divided by the mean street width. It's useful to compute it locally (street by street) to have an understanding of the different kind of urban canyons in an area, but it can also be computed globally to have an average measure of the whole area.

It is an indicator of penetration of wind and of shading of the street. It depends on the climate and on the objective: a big H/W corresponds to a narrow street and will be efficient in hot climate to give shade to the streets; on the contrary, a small H/W corresponds to a wide street and will allow the wind to penetrate the streets which is good for pollutants dispersion (Salat, Vialan, and Nowacki 2010).

- Sky View Factor (SVF) (Oke 1981)

Is the ratio at a point in space between the visible sky and a hemisphere centred over the analysed location

SVF has become a popular metric to parameterize urban morphology, but current approaches are difficult to scale up to global coverage (Middel et al. 2018). It can be used to estimate the range of solar-powered cars in street canyons; calculate the energy use for air-conditioning in buildings during the summer months; predict snow melting in the winter; and estimate pedestrian exposure to UV for skin cancer prevention (Middel et al. 2018).

Figure 19 Fisheye photographs generated from Google Street View (top), detected horizon limitations (bottom), and respective Sky View Factor (bolded text) for four locations around the globe (Middel et al., 2018)

- Pedestrian Catchment Ratio (PCR) (Pafka and Dovey 2017)

Is the total street area included in a catchment figure of a certain distance divided by the total area of that figure. For a grid network the pedestrian catchment will have the shape of a square inscribed in the circle.

- Interface Catchment (IC) (Pafka and Dovey 2017)

Is the total block perimeters within a catchment figure.

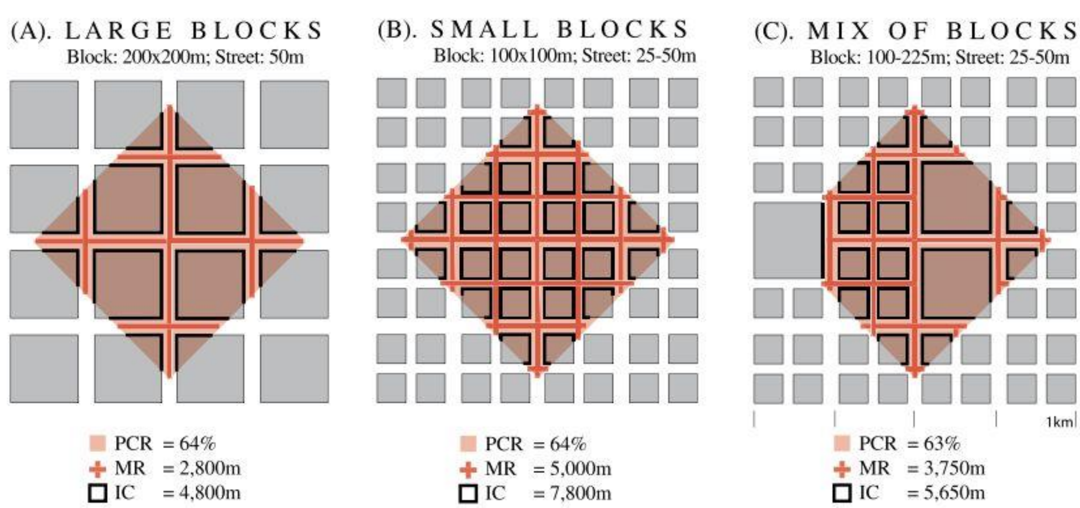


Figure 20 Measuring pedestrian catchments: three methods/three morphologies (Pafka & Dovey, 2017)

NETWORK

URBAN STUDIES

- Streets Density / Road Network Density (N)

is the total length of street links in an area divided by total sample area (Salat, Vialan, and Nowacki 2010; Salomons and Berghauser Pont 2012).

- N°of links / Link density (Salat 2010)

Is the total number of links divided by the area of the sample area

- Average Link length / Average distance between intersections / Equivalent grid side

Is the total distance between couple of nodes of the street network connected by a link, divided by the total number of links. The second name of the metric can be ambiguous as two intersections, or street network nodes, may not necessarily be connected by a link. It could be calculated, achieving a different result, as a distance matrix on every node. Average link length sounds more appropriate and unmistakeable.

- Cyclomatic number (μ) (Salat, Vialan, and Nowacki 2010)

Is the total number of links (L) minus the total number of nodes (N) in an area plus a constant value *C*, usually equal to 1. It gives an idea of the number of different ways to go from one point to another everywhere in the area studied. A big Cyclomatic number would mean a large variety of different ways and so a big connectivity.

$\mu = L - N + C$

- Connectivity (l/n) (Ewing, 1997)

Is the total number of links divided by the total number of intersections in an area.

- Metric Reach (MR) (Peponis, Bafna, and Zhang 2008)

Is the sum of street lengths reachable within a given distance from any given point within a network.

- Network distance

Is the comparison between network isometric accessibility and the ideal circular accessibility. Can be computed both on catchment areas or on the length of the links included in these areas.

- Linear distance to network distance

Is the linear distance between divided by the network distance between two points. The network distance is the distance computed moving only on the links of the street network and is always longer than the ideal linear distance.

- intersection density / node density (Frank et al. 2006; Maghelal 2017; Knight and Marshall 2015)

Is the total number of intersections divided by the area of the sample area.

- number of intersections per road kilometre (Pushkar, Hollingworth, and Miller 2000)

Is the total number of intersections divided by the total length of street links in an area expressed in Km.

- ratio of intersections to cul-de-sacs

Is the total number of intersections (2+ link nodes)) divided by the total number of cul-de-sacs (1 link nodes)

- internal connectivity (Clifton et al. 2008)

Is the number of intersections divided by the sum of cul de sacs + intersections. Intersection is considered a node of the street network connected with at least two links.

- proportion of four way intersections (Cervero and Kockelman 1997)

Is the total number of intersections connected to four links divided by the total number of intersections in an area

- number of access point to a study area (Southworth and Ben-Joseph 2003)

Is the total number of access point to an area. An access point is an intersection between a link of the street network and the limit or boundary of the sample area. As it is, can be hardly used to compare different contexts. An idea could be to divide it by the perimeter of the boundary of the sample area, in order to understand the frequency of accesses.

- external connectivity (Clifton et al. 2008)

Is the median distance between the access points of an area.

GRAPH THEORY

Each complex network (or class of networks) presents specific topological features which highly influence the dynamics of processes executed on the network. The analysis, discrimination, and synthesis of complex networks therefore rely on the use of measurements capable of expressing the most relevant topological features. Firstly, the basic structural properties of a graph can be studied by solely considering its topology. The network topology specifies how items, called nodes, are interconnected or related to other nodes by links. A graph G is a data structure consisting of a set of N nodes connected by a set of L links. Secondly, each link in G can be further specified by a set of link weights (such as delay, packet loss, available bandwidth, monetary cost, etc.), and each node can be characterized by a set of node properties (such as processing time, queue length, uptime, etc.). A network is fully defined when, in addition to the topological structure, multiple protocols, dynamics and constraints are set on top of the graph. This multilayer nature of a network leads to a natural metric classification split in topological metrics, and service metrics (Martín Hernández and Mieghem 2011)

In urban studies the most common network is the street one but it can be modelled in many different ways. Just to make an example, a roundabout can be considered as a single node with the street links bending to reach the centre of the square or as a circular link with a number of intersections equal to the number of streets meeting it. One alternative to the classical street-intersection method are the axial lines or visibility lines (Hillier and Hanson 1984).

The axial line-based representation of an urban structure is the earliest approach of the space syntax. Axial lines are used to represent directions of uninterrupted movement and visibility. From the point of view of human spatial perception, we consider that an axial line is a vista space that is small enough to be perceived from a single vantage point of view (Jiang et al. 2000).

To illustrate the main principles of this approach, we represent here a fictional urban system. The derivation of its axial map starts from line 1 then 6 then 5 then 4, . . . and finally the resulting axial map consists of 13 axial lines as shown in Figure 21.

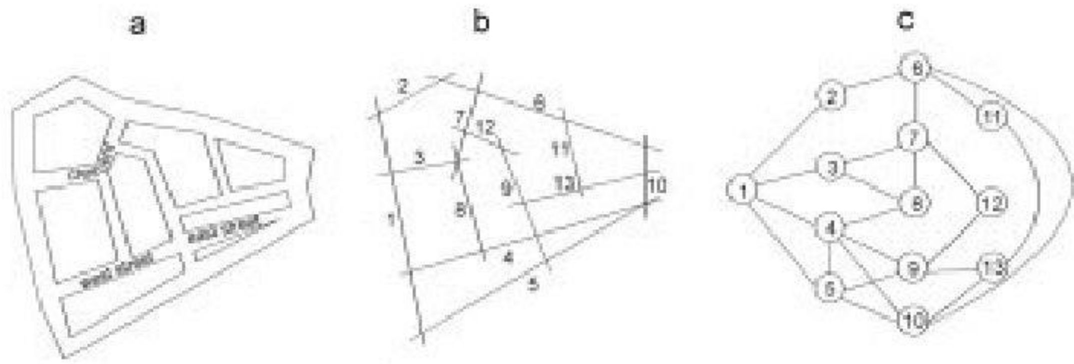


Figure 21 (a) fictive urban system; (b) axial map; (c) connectivity graph (Jiang & Claramunt, 2002)

For the understanding of the urban structure is enough to rely on the topological metrics, based on an unweighted graph. Considering that this research field is marginal in the research, only the most common metrics will be presented while many other metrics will be just briefly mentioned together with the relative reference literature.

Thanks to the development of the ArcMap toolbox UNAtool by the City Form Lab of Cambridge University, the following graph metrics have become very popular, especially in their application to buildings as a punctual input:

- Connectivity

The Connectivity of a link measures the number of links that directly intersect that given link. It also denotes the number of immediate neighbourhoods of a link.

- Control value

The control value of a link is given by the sum of the inverse connectivity values of the immediate neighbourhoods of this link. Literately the control value shows the degree to which each link “controls” its immediate neighbourhoods.

- Depth

The depth of a link is defined by the number of links distant from a given number of steps to that link. While connectivity considers immediate neighbours, depth considers k neighbourhoods. (Jiang and Claramunt 2002)

- Reach (Nikolovska et al. 2012)

The Reach measure captures how many surrounding buildings each building reaches within a given Search Radius on the network. The measure can be weighted on any quantitative attribute of the buildings.

- Gravity Index (Hansen 1959)

First introduced by the Gravity measure assumes that accessibility at a point i is proportional to the attractiveness (weight) of destinations j surrounding I, and inversely proportional to the distances between i and j. The gravity type index thus captures both the attraction of the destinations (Wj) as well as the spatial impedance of travel required to reach those destinations (Dij) in a combined measure of accessibility.

- Betweenness (Freeman 1977)

The Betweenness of a node is defined as the fraction of shortest paths between pairs of other nodes in the network that pass by node i. Is a measure of how an element is fundamental for the communication between two other elements of the group. The Betweenness measure can be used to estimate the potential of passers-by at different buildings on the network.

- Closeness (Sabidussi 1966)

The Closeness of an Input Point is defined as the inverse of distance required to reach from that point to all other point in the system that fall within the Search Radius along the shortest paths. Is a measure of how an element is close, in topological terms, to all or just some of the elements of a group.

- Straightness

The Straightness metric illustrates the extent to which the shortest paths from a point of interest to all other point in the system resemble straight Euclidian paths.

Another notion related to local and global integration is the basic properties of symmetry and asymmetry. Mathematically, the relationship of two nodes a and b are said to be symmetric if the relationship of a to b is the same as the relation of b to a. The integration value is actually a measure for relational asymmetry and it is measured with either Relative Asymmetry (RA) or Real Relative Asymmetry (RRA) (Jiang and Claramunt 2002). Martín Hernández & Mieghem (2011) make an anthology of topological metrics dividing them into Distance, Connection and Spectra as showed in the following chart.

Table 3 Classification of the topological metrics, together with the proposed symbols (Martín Hernández & Mieghem, 2011)

Category	Class	Metric	Symbol
Topological	Distance	Hopcount	$H_{A\to B}$
		Closeness	C_i
		Eccentricity	ε_i
		Diameter	D
		Radius	R
		Girth	γ
		Expansion	e_h
		Betweenness	B_i
		Ce. Pt. of Domimance	CPD
		Distortion	t
	Connection	Degree	d_i
		Entropy	H
		Joint Degree	$\Pr[d_i, d_j]$
		Assortativity	r
		Coreness	k_i
		Clique	$n - clique$
		Clustering C.	C
		Rich Club coefficient	Φ_k
		Giant component	G_C
		Reliability	$\kappa(G), \lambda(G), ...$
		Chromatic number	$\mathcal{X}$
	Spectra	Algebraic connectivity	μ_{N-1}
		Spectral radius	ρ
		Spectral partitioning	s_i
		Principal eigenvector	x_1

CONCLUSIONS

This set of metrics shows another possible distinction criterion that crosses the component division. In fact some of the metrics are simply based on mathematical operations performed on the attributes of the layer instances, while other need a specific simulation or the creation of additional geometries generated in relationship to the parent one. This survey has been useful to decide where to focus the research efforts for the definition of new metrics. Link component has already been widely studied and some operative tools have been developed (UNAtool) and a further contribution could more probably come from other disciplinary research fields. Volume component has a lot of research dealing with its quantitative dimension but few efforts have been made to measure qualitative aspects closely related to building typology. Building remains the only key morphological unit but there's room for an additional exploration of its shape through numbers. Void component, probably as a heritage of the modern movement, has been underestimated. While blocks have been studied as an abstraction of volumes, as the negative of street network and as determiners of the urban fabric, the other morphological units attracted less interest. Streets have been considered more as links than as spaces, squares remained at the time of Sitte's studies and courts simply neglected and felt as a romantic sign of an unrepeatable past.

5.1.2 Maps

This section reviews representation techniques including maps, diagrams or graphs. Some are classical tools and already widely used, others have been rarely applied in the urban studies field but look very promising. The goal is to show them as independent communication possibilities, not necessarily linked to a specific context, metric or disciplinary field, in order to stimulate urban designers and analyst creativity.

Isovists

An Isovists, or viewshed, is the area in a spatial environment directly visible from a location within the space. Isovists are three-dimensional, but they may also be studied in two dimensions: either in horizontal section ("plan") or in other vertical sections. They can be produced for every point in physical space.

The contour of an Isovists may or may not vary with location. If we are in a convex room, i.e., then the contour of every Isovists in is the same. If the room is not convex or contains partitions, then there would be many Isovists whose area would be only partial, less than that of the whole room. To help understanding this concept we may think of the Isovists as the volume of space illuminated by a point source of light.

A set of Isovists can be used to generate a graph of mutual visibility between locations (Turner et al. 2001). An Isovists field is the result of the computation of Isovists for a set of vantage point in the space. In essence, each Isovists field is computed by placing an agent at the given vantage point i and `walking' that agent in a given direction until the agent encounters an obstacle (Michael Batty and Jiang 2000).

This technique is currently used in architecture and urban design mainly to study perception. They allow answering questions as: `How far can we see, and how much can we see?' `How much' space is enclosed? And what obstacles interfere with `how far' and `how much' one can see? (M. Batty 2001).

The Isovists shape can be further investigated introducing simple geometric measures based on distance, area, perimeter, compactness, and convexity. Benedikt (1979) identified six geometric measures derived from Isovists fields and Conroy (2001) has extended and modified this set of measures in defining the properties of Isovists in virtual space. The following picture shows the Isovists drawing procedure (Figure 22) and an application to the analysis of interior spaces according to different metrics (Figure 23).

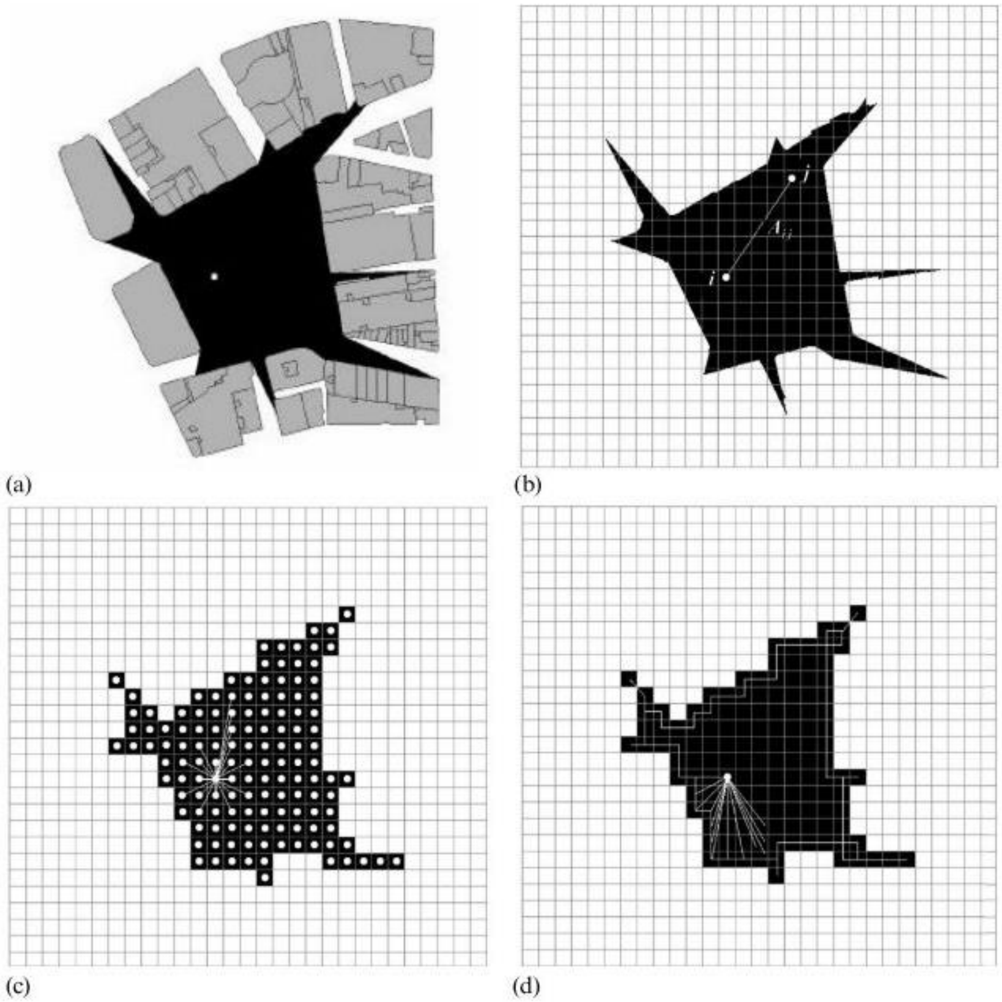


Figure 22 Defining Isovists through visibility graphs: (a) the Isovists polygon generated from the viewpoint defined by the open circle at `o'; (b) a typical edge in the visibility graph defined about the root vertex of the Isovists at i; (c) the Isovists polygon a as a set of vertices, grid centroids, and a sample of edges; and (d) the perimeter marked out from rotating the visibility graph edges around the viewpoint `o', with a sample of edges shown (Batty, 2001)

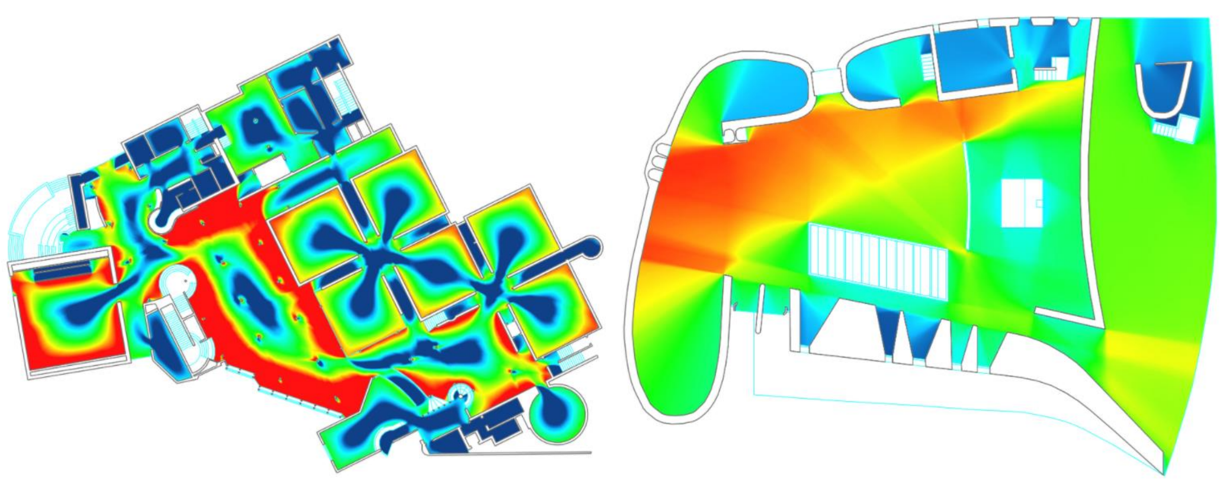


Figure 23 Coloured representation of Isovists fields for Mönchengladbach Museum Abteiberg and Ronchamp Chapel. (Isovist.org)

Hemispherical View

The hemispherical view is a dimension-reduced view capturing 3-dimensional form through horizon limitation fractions. It represents the space of a hemisphere on a circular plane area by a system of projections. Is currently used to calculate SVF metric by dividing the picture pixels into sky (white) and obstacles (black) like buildings, trees or other elements impeding sky view (Figure 24). This representation could be used to investigate other aspects of the space by analysing its shape in addition to its proportion of black and white pixels. In the third example the first filtering process reveals that the façade of one building is completely glazed, as it reflects the colour of the sky. Also the coloured picture can be interpreted to acquire information about the materials of facades and the presence of trees.

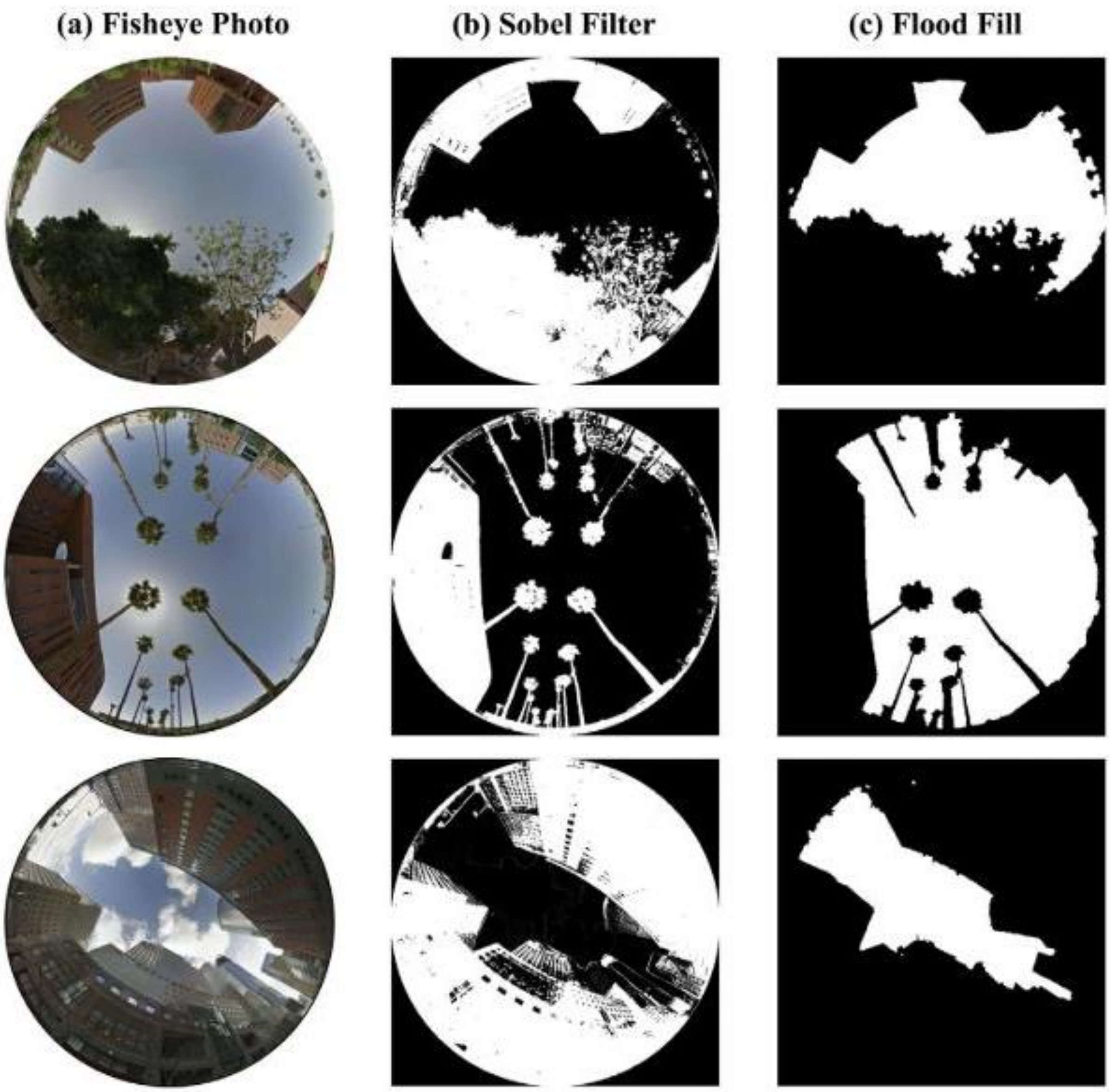


Figure 24 Three examples of sky detection in GSV fisheye photos using (a) a Sobel filter, (b) a flood-fill algorithm and (c) classification into sky and non-sky pixels (Middel et al., 2018)

Gradient map

A *gradient* is an increase or decrease in the magnitude of a property (e.g. temperature, pressure, or concentration) observed in passing from one point or moment to another (Encyclopaedia Britannica). Gradient map are based on punctual sources of values. Continuous geometries are mathematical objects that present some criticality for being employed in real world applications like measurements. A continuous object can so be discretized into a finite number of portions through various methods. A mesh is a representation of a given shape or form, consisting of an arrangement of a finite set of geometric components. These components are usually points, connected by lines that delimitate planar faces. The points are the core element while their topology, the way in which constituent parts are interrelated or arranged, can change. It's possible for example to construct different mesh from the same set of points. Having some attribute values concentrated in certain points allows to the software to compute all the values of the continuous space between the given point as a function of the input data (Jiang and Claramunt 2002). Here Mohajeri et al. (2016) represent the gradient of several compactness indicators for the city of Geneve (Figure 25).

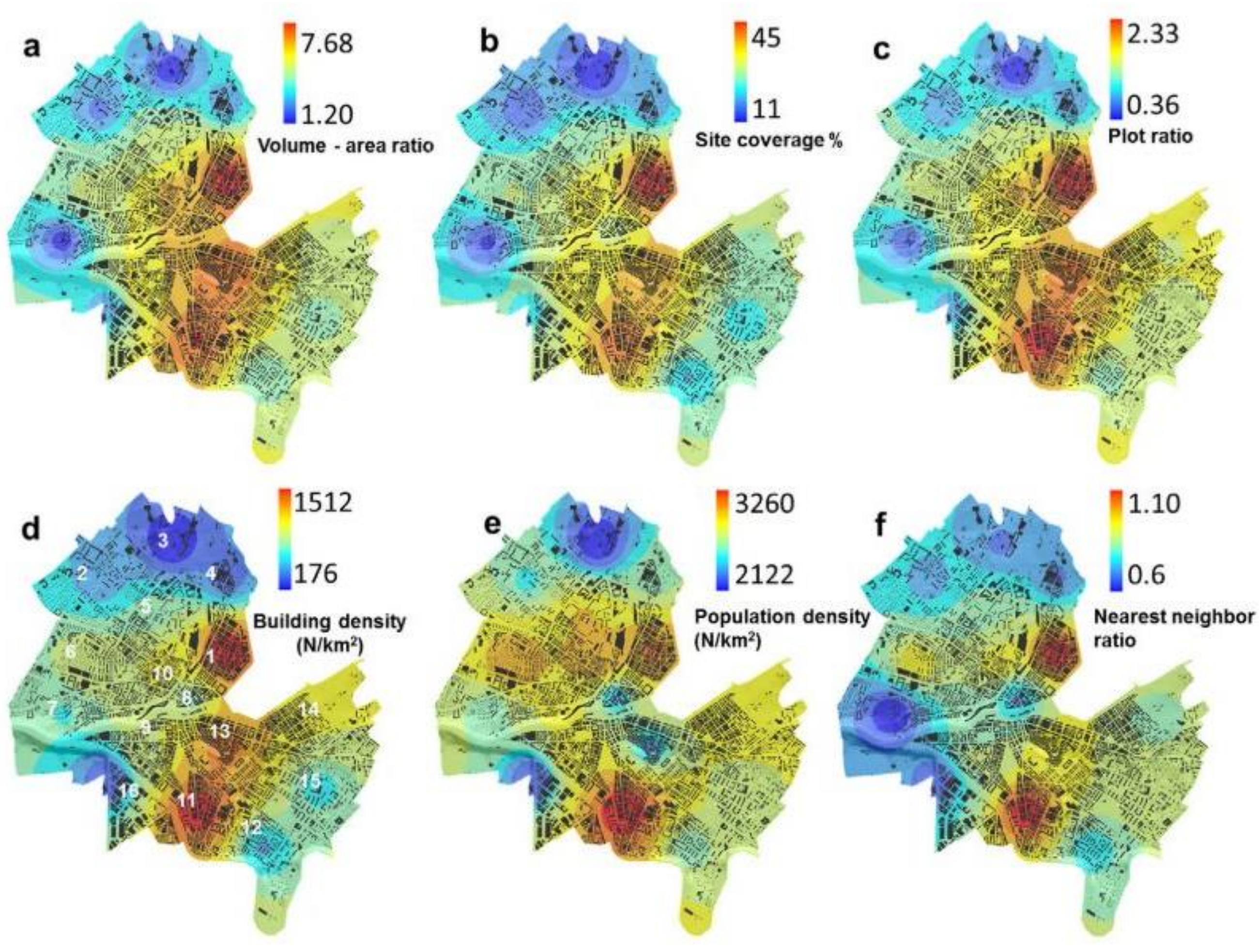


Figure 25 Variation of urban compactness indicators between different neighbourhoods in the city of Geneva (Mohajeri et al., 2016)

Yang & Chen (2016) have a similar approach. They generate a thermal atlas by overlaying the key morphological variable layers based on the coefficients determined by the empirical models. A set of PET maps is thus generated, and verified against field-measured data (Figure 26).

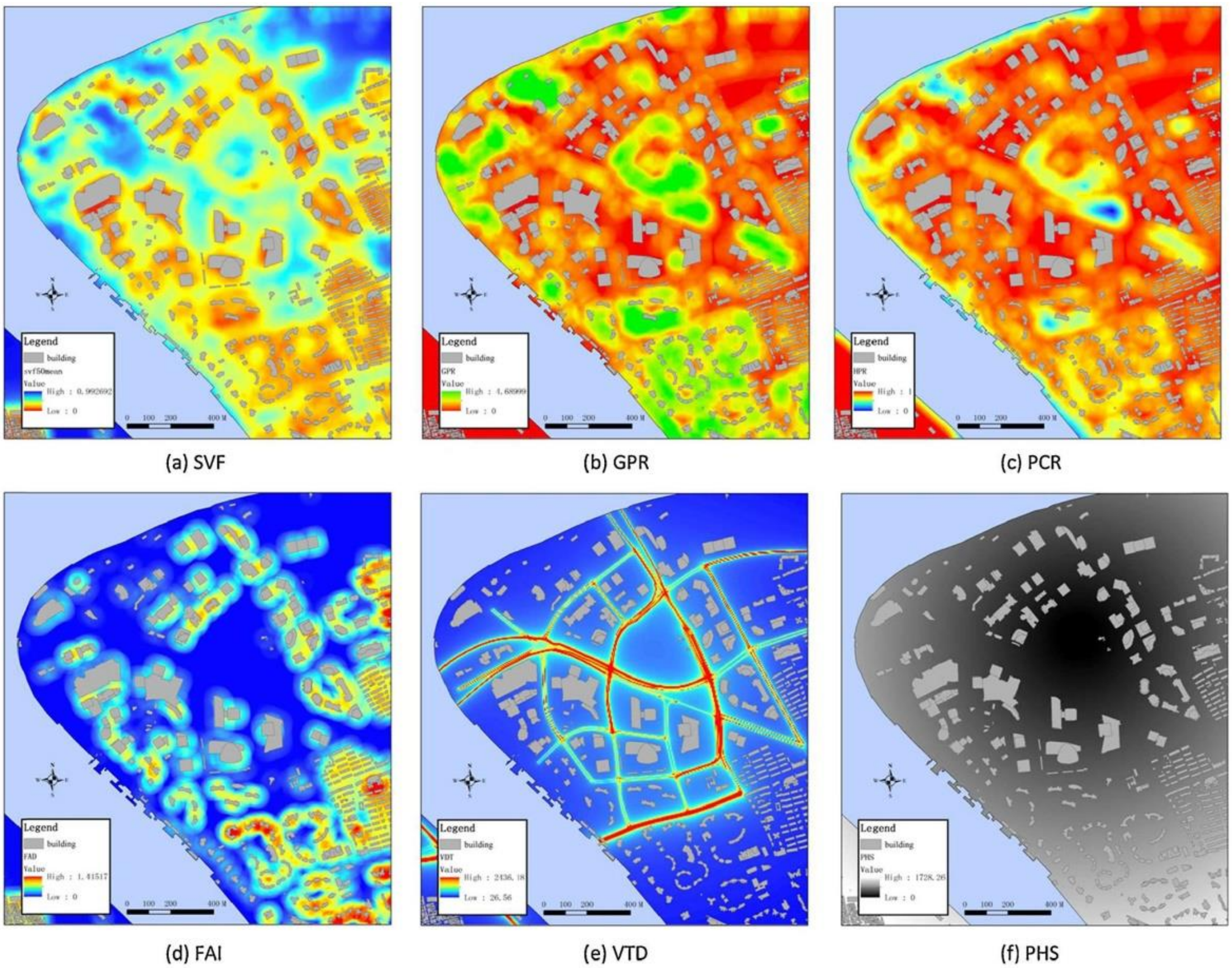


Figure 26 Gradient maps based on six morphological sub-layers (50m radius average) (Yang & Chen, 2016)

False Colour Composite (FCC)

It consists in the production of a false colour composite (FCC) by selection of three appropriate variables for red, green and blue channels and simplification of the 3-dimensional feature space through automated multiple-thresholding. Shades of colours on such a FCC, as a simplified form of gradations in the feature space, derive relevant and contextual material for both visual interpretation and quantitative analyses. Yoshida & Omae (2005) use this technique for the morphological characterization of blocks and comparison of its result with the governmental scheme (land use) (Figure 27).

Figure 27 False colour composite made from three morphological variables (left) and governmental specification of land use (right). RGB channels: R = S/V; G = mean building volume; B = volume density
Land use: Red = residential blocks; Cyan = commercial blocks; Magenta = mix used blocks
(Yoshida & Omae, 2005)

The key principle is the translation of numerical inputs into colours through the mathematics of colour scales. It's a very promising technique to overcome the limits of overlapping or "fusion" between different colour hatches, strongly affected by transparency levels and by the order of visualization.

Differently from the gradient map, this technique can be applied for object oriented data, as blocks, producing a sort of discrete gradient by the presence of different values through the morphological units in study area but requires a classification.

Urban Landscape Model (ULM)

Urban landscape model (ULM) is an abstraction of real urban landscape in which features and land covers of an urban area are exhibited in three dimensions (Dowman 2000). There can be several types of ULM having different levels of spatial details and kinds of thematic contents (Yoshida and Omae 2005). They can be based on a grid, a mesh, or on existing morphological units as block, plots or even buildings. From this perspective, also a 2.5D model of the city is an ULM built on buildings geometries with height attribute. The generation of ULM is considered an especially crucial task (Sohn and Dowman 2001). Figure 28, i.e., presents an ULM representation of built density.

In support to this representation, Pesaresi and Bianchin (2001) explain that today's city is not recognizable in its existence through meaningful architectural edifices. Private land ownership and speculative activity has led to the primacy of size over form. By quoting from (Aymonino 1977), they also point out disappearance of 'an urban form' and emergence of 'a massive agglomeration'.

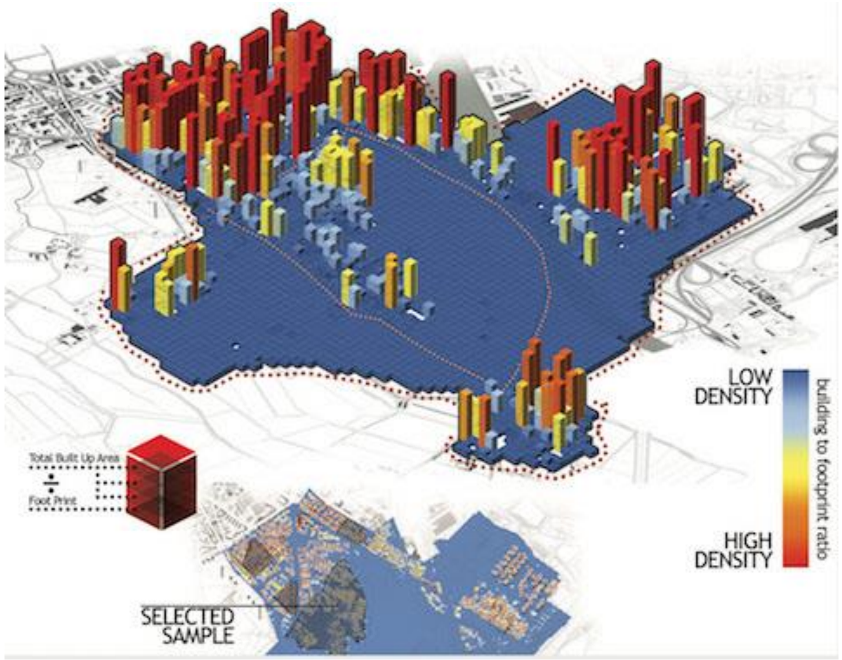


Figure 28 Former Porosity representation based on Volume Density for Porto di Mare area (IMMdesignlab). This is an example of ULM where every square of the sample area is extruded and coloured according to one or more parameters

Profiles

A profile is an outline of something, as seen from one side. It can be an architectural drawing as sections or elevations or a spatial representation of gridded values as in the example below. Krehl et al. (2016) draw density profiles on an axis centred on the town hall of different cities to visualize how volumes and FAR vary by increasing the distance from the city centre (Figure 29).

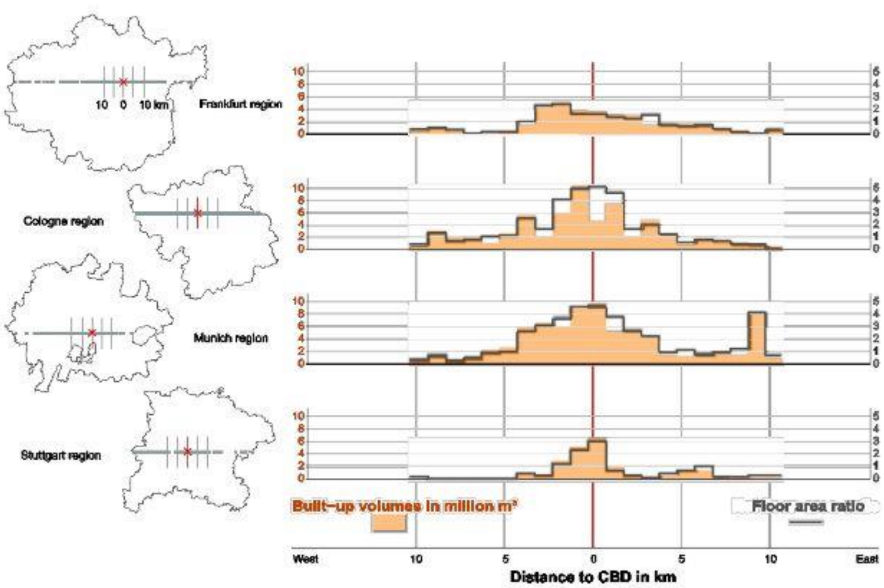


Figure 29 Selected density profiles of the case study regions; built-up volume and floor area ratio values for the grid cells located along the respective core city's latitude, the latter indicated by the town hall's geographic location (Krehl et al., 2016)

This graphical output could be used to relate more independent variables and their spatial distribution trends or to match a real architectural section with one or more abstract properties.

Box plots

Box plots are a simple way of representing statistical data on a plot in which a rectangle is drawn to represent the second and third quartiles, usually with a vertical line inside to indicate the median value. The lower and upper quartiles are shown as horizontal lines either side of the rectangle.

Each box represents one measure at the time. They can be used to show the trend of a measure in different contexts (as in the example) or to compare different measures referred to the same instance. They complete the information given by the average with information on the distribution of sample values (Figure 30).

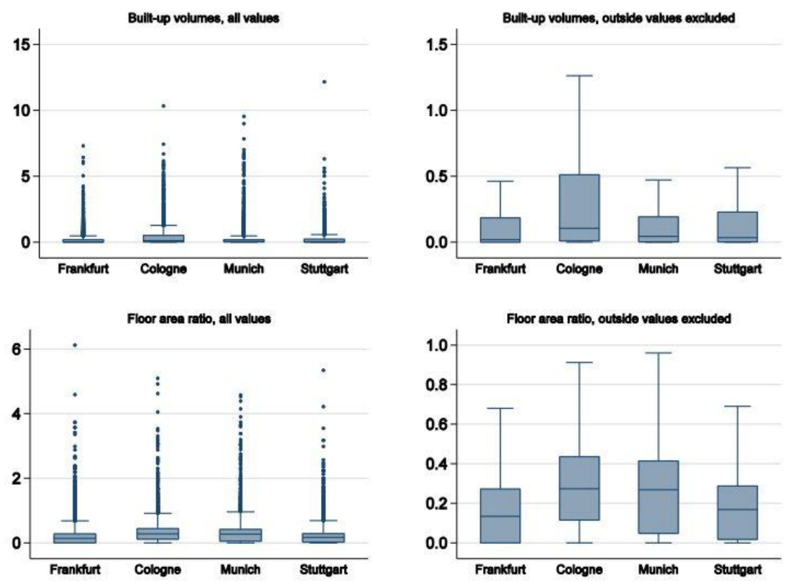


Figure 30 Box plots of built-up volumes (million m3) and floor area ratios for 4 German cities: Frankfurt, Cologne, Munich and Stuttgart (Krehl et al., 2016)

Scattered plot + sample

Scattered plot is a graph in which the values of two variables are plotted along two axes, the pattern of the resulting points reveals the presence of any correlation. This kind of graph allows to plot together also more than two variables by including the z axis or characterising the black dots. Dots features to play with are colour, shape and size. This sets the maximum number of variables to be included in the graph up to six. Ideally colour can be dismantled in its constituent channels (RGB, CYMK) as seen for the FCC method giving the possibility to have even more variables.

There are examples that associate some of the dots with the object they represent. These graphs can be called Scattergram. In fact every point could be any kind of instance as a person, a building, a district or a block as in Yoshida & Omae (2005) research (Figure 31).

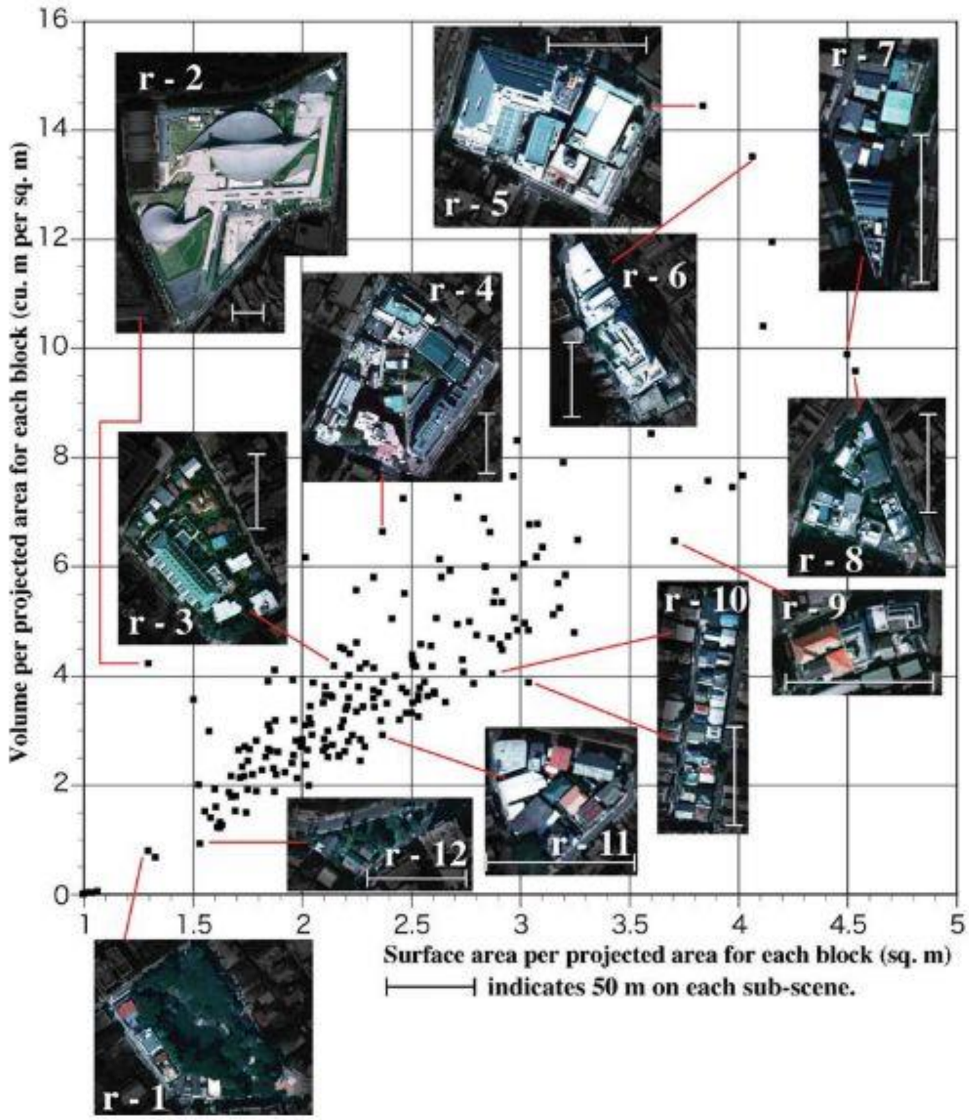


Figure 31 Residential blocks: Scattergram featuring volume and surface area per projected area (Yoshida & Omae, 2005)

Matrix (scattered plot)

A matrix is a rectangular array of quantities or expressions in rows and columns that is treated as a single entity and manipulated according to particular rules. An example of commonly used matrix in urban studies is the one who relates origins and destinations (OD Matrix) of trips, a tool for accessibility studies. Matrices can be used to represent almost everything or as a generative tool. Krehl et al. (2016) adopt matrices of scattered plot diagrams to explore variables correlation across different urban contexts (Figure 32). In a square matrix with the same dimensions on both raw and columns, the top-left bottom-right diagonal correlate an object with itself giving obvious results. Using its cells as heading of the fields helps saving space and avoiding redundant information.

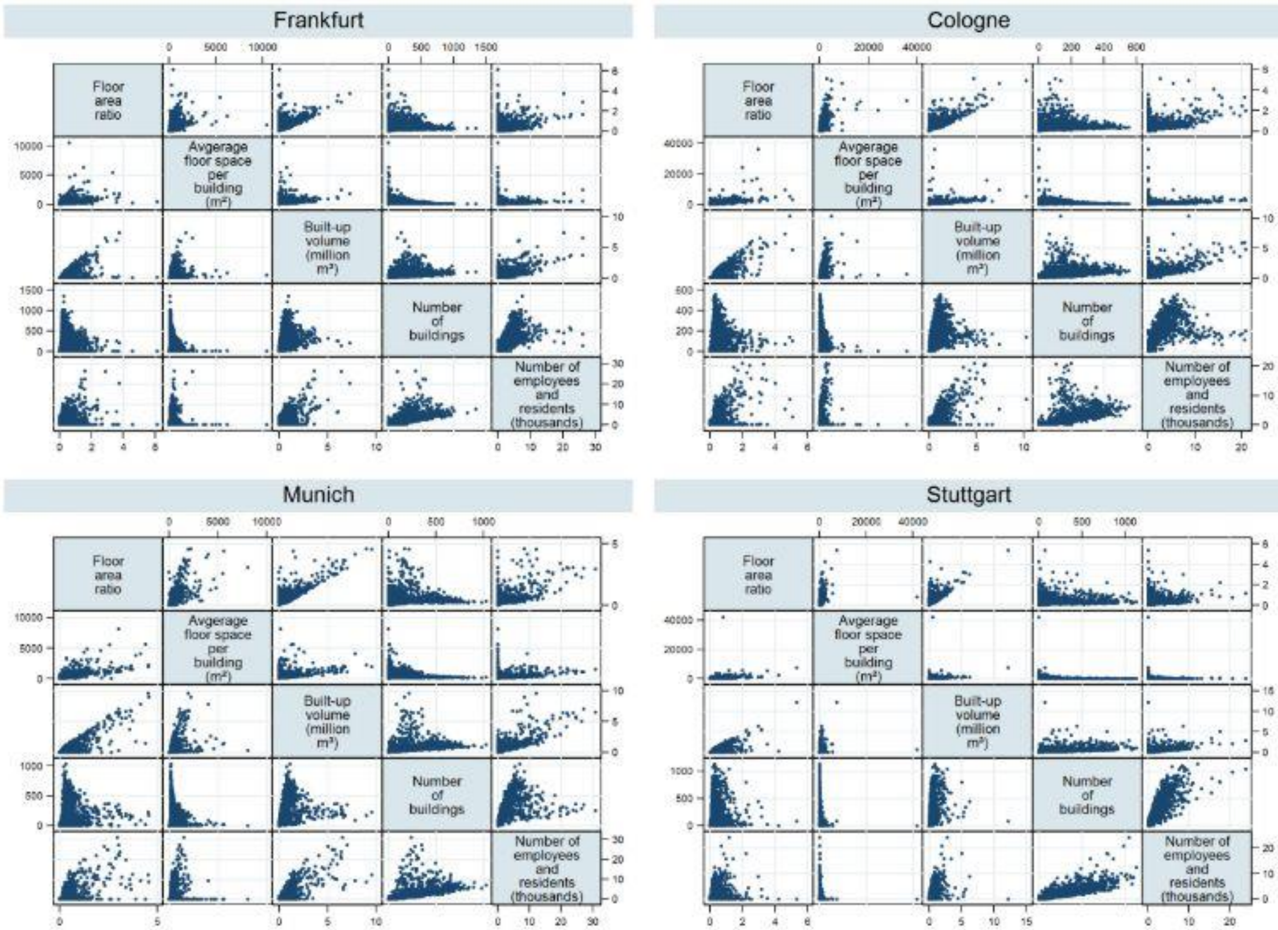


Figure 32 Scatterplot matrices showing the relationship between built and activity densities (both measured in levels) (Krehl et al., 2016)

Clusters

A cluster can be defined as a group of similar things or people positioned or occurring closely together. Cluster analysis, in statistics, is a set of tools and algorithms that is used to classify different objects into groups in such a way that the similarity between two objects is maximal if they belong to the same group and minimal otherwise (Encyclopaedia Britannica).

The closeness of the objects belonging to a cluster may be either topological or physical. The second meaning is more interesting for the application to urban studies. In fact, especially in regionalization problems, clusters are used as a representation of spatially close objects, considered as a whole unique new object not totally corresponding to the sum of their individual consistency. Cluster in this sense is an approximation similar to our visual perception of an object when we zoom out and loose definition.

The most common cluster in urban studies are urban patches that have been widely used to describe urban form at city and regional scale (Frey 1999; Huang, Lu, and Sellers 2007). A number of spatial metrics has already been developed and tested in very diverse context as shown in the schematic picture below (Figure 33).

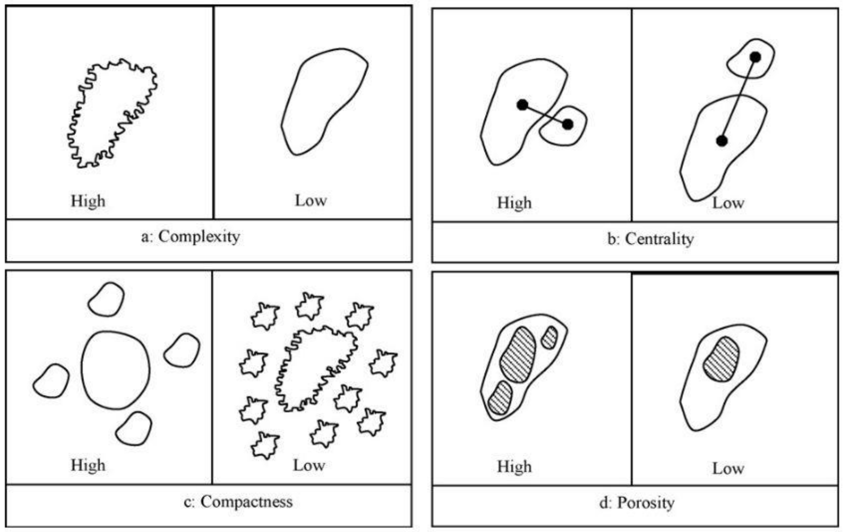


Figure 33 Schematic representation of urban patch spatial metrics (Huang et al., 2007)

Axial lines

The axial line-based representation of an urban structure is the earliest approach of the space syntax (Hillier and Hanson 1984). Axial lines are used to represent directions of uninterrupted movement and visibility, so they represent the longest visibility lines in two-dimensional urban spaces (Figure 21). A set of axial lines, that mutually intersect and cover a whole free space, is called an axial map. According to Hillier's initial definition, an axial map constitutes the least number of longest axial lines (Hillier and Hanson 1984).

Axial lines can be derived by the software Depthmap developed at UCL giving as input a closed polyline representing the street area contour. An alternative interesting application is to use the same technique but giving a different input as for example building outlines. The result is a sort of potential street network that ignores the existing one and "adapts" to building position and orientation (Figure 34).

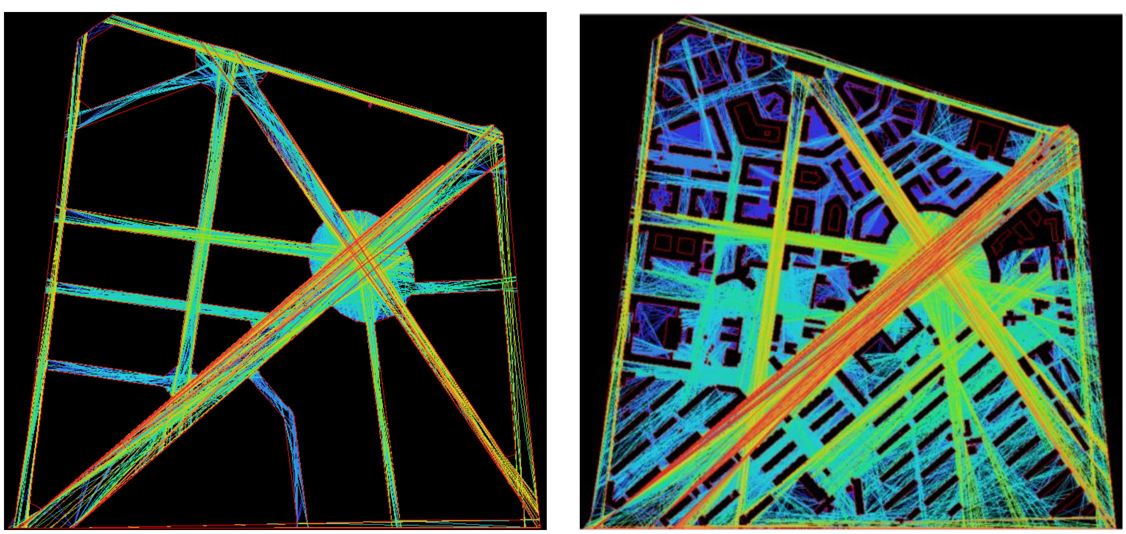


Figure 34 Axial maps for Mazzini neighbourhood in Milan (upper part of Porto di Mare area) traced on street area (left) and void area (right). First map can be used to represent permeability of vehicles flows while the second is a visibility representation.

Axial maps can be used to compute all the metrics coming from the graph theory as explained in the previous chapter.

CONCLUSIONS

There is often a reciprocal relationship between representation and numerical value. In some cases as the gradient map, the image is directly generated by the same data that construct one or more metrics. In other, as the Isovists or the hemispherical view, attributes and metrics can be calculated on these additional geometries. These geometries are elements of what can be called ancillary layers as they can be used to provide additional information related to the parent objects, no matter if is part of Void or Volume component.

Actually, many efforts has been put in the study of the void space, also thanks to the perceptive approach, mostly with point based representation and their discrete repetition on a grid approximating the continuous space. One reason could also be the attempt to give a shape, and a boundary, to something that is continuous and vague by definition. Another reason is dynamic nature of void space, necessarily related to movement, that suggest to find methods to describe the properties of a space from the perspective of a moving, often walking, user. For the same reason there's a lack of this attempts on the Volume component. Buildings are well-defined and static units with their own shape, size and character.

5.1.3 Tools

TOOL vs SOFTWARE

Before presenting the tools found in the literature is better to clarify some points. First of all we need to distinguish between tool and software. A *tool* is a device or implement used to carry out a particular function, a thing used to help performing one specific job. Application *software* is instead the programs and other operating information used by a computer. It directs the computer to execute commands given by the user and may be said to include any program that processes data for a user (Encyclopaedia Britannica). Software can contain a set of tool and tool can be seen as very small and specific software.

This premise is necessary to understand the current overwhelming amount of computer application related to the urban environment sector. In fact there is a tendency in developing a specific tool for the computation of one or few metrics or the creation of one or few maps instead of working inside the framework of already established and widespread software, developing plug-ins.

In a religious analogy, while a tool is a saint, a software is a religion. It's clear also to non-practicing faithful or to an atheist that saints cult, even for the more popular one, could never have the same diffusion of a religion or the same complexity of rite and celebrations. A tool is easier to be developed and to be learned, but cannot give any exhaustive result working stand-alone. The initial advantage becomes a weakness when the user is asked to get familiar with dozens of different tools, whose activities could be performed by an equivalent number of commands included in a software. The software is also definitely more flexible. This difference can be explained looking at the different target of tools and software. Tools are often thought for non-expert users and try to simplify as much as possible the workflow to achieve the expected, partial, result. Software is more complicated and need the user to enter their operative logic in order to orient in their landscape of possibilities.

Exploring all the existing tools in detail from an IT perspective will require time and competences that are out of the resources of this thesis. In addition, as explained in the previous chapter, I believe that is more important to define a proper working framework than selecting the best possible formula or algorithm to perform a specific action. There are many ways to achieve the same results when modelling so every tool, or command, is equivalent to the others as long as it enables the user to get the expected results.

ANALYSIS VS SIMULATION

According to the IMM methodology, the diagnostic process is composed by the analysis of the urban structure, through the horizontal and vertical investigation, and the evaluation of system performances with the Indicators. The first require the management of large amount of spatial data usually available as shape files. GIS (Geographic Information System) software are the most appropriate tool to handle this datasets and among all the existing one the most known and widely used are ESRI ArcMap, as authoring software, and QGIS as open source. Both software include several addendum to perform specific actions in the form of Toolbox or Plug-in. These elements can be compared to the above mentioned tools with the advantage of working inside a larger software framework, increasing the possibilities of mutual interconnection.

The second part needs 3d models as input and a huge computational capacity in order to perform simulations based on complex geometries and their attributes. Considering the interactive nature of an informed design process, the modification phase should be hosted into a comfortable environment able to gather feedbacks and allows fast and precise geometric transformations. The most suitable environment for these operations is BIM (Building Information Modelling) as simple 3d modelling are limited to the geometrical part, missing the attributes. The research doesn't enter into this field as its focus is on the first one but it's aware of the need to approach also the simulation aspect in the same way. For this reason we prefer not to mention any authoring software for the BIM part. BIM use to be applied at the building scale but for the research purpose, a scaling operation is necessary. In order to keep a manageable amount of data, the increase in the number of buildings to be studied must be combined with a loss of detail in the instances. Buildings need to become simple 2.5D composite empty boxes, building systems have been replaced by neighbourhood infrastructures for energy, waste and water management.

A new kind of software, that tries to combine the two approaches, is actually under development. They fall under the acronym CIM, standing for City Information Modelling (J. A. Gil, Almeida, and Duarte 2011). The advantage of these working platforms is the possibility to handle available GIS datasets with the editing, representation and simulative potential of a BIM. Together with the IMMdesignlab we started a partnership with Nemetschek software house for the implementation, inside Vectorworks environment, of a fully integrated IMM based design module ranging from diagnostic to retrofitting, including the modelling of alternative scenarios. This work started in May 2019 and the first achievements, based on the sole evaluation of Porosity Key Category, will be presented during the Data Centre World event that will take place in London in October 2019. It will consist in a live demonstrative session based on a paper called "Digital Urban Diagnostic – IMM investigation process using Vectorworks". This collaboration, starting on the conclusion of this PhD research, is based on the theoretical implementations here presented and translates into Vectorworks Marionette (visual programming extension, as Dynamo for Revit or Grasshopper for Rhinoceros) some of the algorithms developed by the author for QGIS, ArcMap and Rhino visual programming modules.

URBAN STRUCTURE ANALYSIS

As previously said GIS software allow to deal with spatial data also in a very complex way. In addition to the standard command and components, there’s the possibility to implement python scripting with an integrated module, and to use visual programming modules to automatize a set of recursive operation. The presence of Toolboxes and plug-in incredibly increase the working possibilities also for users without a programming background. Plug-ins can be considered as tools internal to the software and so, as tools, they focus on one or more specific operation, geometry, metric, urban design dimension or even performance. Making a list of all the existing plug-ins will be impossible and useless considering that new one are implemented almost monthly or weekly, so only some the one closer to the research topic will be mentioned as example:

- Operation: Multi-Ring Buffer and Select Within (Heikki Vesanto)
- Geometry: Networks (Patrick Palmier), UNAtool (City Form Lab)
- Metric: AwaP (Ivan Majic), Box Counting Dimension (Eduard Kazakov)
- Dimension: Visibility Analysis (Zoran Čučković), Interface Catchment (Ivan Majic)
- Performance: OpeNoise (ArpaPiemonte), UMEP (Frederik Lindberg et al.)

The same kind of logic can be applied to distinguish independent tools. Among the vast number of existing tool only the one related with some of the representations collected in the previous paragraph are here presented. DepthmapX (UCL) permits to perform graph analysis and to compute related metrics as Betweenness, closeness and straightness. Star Logo (MIT) allows to compute Isovists, Patch Analyst (Rempel 2004) requires urban patches as geometrical input and returns spatial metrics mainly described in Huang, Lu, and Sellers (2007), Fractalyse (Thema) may be used to compute fractal dimension of black and white image, curve and network and contains also several image processing tools.

In conclusion, every environment, programming language, tool or software allowing the management of vector or raster data can contribute to the characterization of the built environment. An example will be given in Chapter 6 where plug-ins for MATLAB and ImageJ (image processing tool) will be used to compute permeability metrics.

URBAN PERFORMANCE SIMULATION

Cities are complex systems that require large-scale simulation tools to quantify, analyse, and predict environmental impacts. There’s a need to simulate the inter-dependencies between the variables and subsystems of an urban region to create an integrated framework for computing urban environmental performance (Mostafavi, Farzinmoghadam, and Hoque 2014). The demand for simulations, incorporating different scales and interdependencies, is increasing in order to evaluate and predict the impact of planning efforts (Aschwanden et al. 2012).

The concept of simulating urban sectors to support design decisions is not new. In 1989, SimCity, a city management simulation environment was released for gamers to build houses, streets, factories, airports, and parks with metrics for crime, pollution, and economic stability. The most recent version, SimCity 4, offers sustainable design measures such as solar and wind power generation, sustainable transportation choices, and energy efficient building standards (Minnery and Searle 2014). SimCity and others, such as ESRI's CityEngine, are mainly design tools that emphasize visualization and data reporting, and offer little opportunity for quantitative analyses.

In the research community, tools to quantify urban performance measures are emerging. Urban Building Energy Modelling (UBEM) is a promising framework for the assessment of neighbourhoods' performances. It come from a merge between individual building energy models (BEM) on one side and regional and country-level building stock models on the other. These analytical tools for designer and policy makers developed and established in the last decades. Reinhart & Cerezo Davila (2016) deeply review emerging simulation methods and implementation workflows for such bottom-up urban building energy models (UBEM). They discuss simulation input organization, thermal model generation and execution, as well as result validation, presenting also an outlook for future developments. An UBEM requires the combination of several data sets including climate data, building geometry, construction standard and usage schedules.

Mostafavi et al. (2014) present a comprehensive perspective of the characteristics of existing urban scale modelling tools. UrbanSim, developed at the University of Washington, is intended to be used by planning organization at metropolitan scale and NGO. It combines land use and transportation development with economic impacts, and has been applied to actual urban contexts (Patterson and Bierlaire 2008). UrbanSim estimates the impact of infrastructure and policy decisions with outcomes, such as motorized and non-motorized accessibility, housing affordability, greenhouse gas emissions, and the protection of open space and environmentally sensitive habitats. SUNtool is a European urban neighbourhood modelling tool that integrates building performance with its surrounding microclimate effects (Robinson et al. 2007). The focus of SUNtool is buildings, particularly predicting the optimal built form of an urban neighbourhood with regard to optimizing pedestrian comfort and building energy efficiency. At the Massachusetts Institute of Technology, the Sustainable Urban Design Lab is developing an urban modelling tool that analyses daylighting potential, walkability, and operational energy use (Reinhart et al. 2013). The Urban Modelling Interface (UMI) works as a plug-in for the CAD modelling software Rhinoceros 3D, which allows developing parametric 3D urban models and exporting and executing them in EnergyPlus while also offering daylighting, lifecycle and mobility analysis out of the same model (Reinhart et al. 2013). It's intended to be used at the early stages of urban design and planning interventions to assess the environmental performance of urban neighbourhoods. Using a similar plug-in approach, an integrated UBEM tool for ArcGIS was developed at the ETH Zurich, capable of producing results with a custom simulation engine at multiple spatial and temporal scales (Fonseca and Schlueter 2015).

Among them, one of the most promising tools seems to be IUMAT developed by Mostafavi et al. IUMAT (Integrated Urban Metabolism Analysis Tool) is a system-based sustainability analysis tool. It quantifies and aggregates the social, economic and environmental capitals of urban activity in an integrated framework focusing on the metabolic flows of urban development. It is a way of integrating and rationalizing the disciplinary boundaries between urban analysis, planning and policy (Mostafavi, Farzinmoghadam, and Hoque 2014).

The IUMAT framework focuses on the urban region primarily as a collection of buildings, rather than an economic system. Therefore the urban dynamics are modelled in terms of any kind of change caused to these core elements of the city, whether it is variation in the number of existing buildings or changes in building program or demographic and economic factors inside the buildings. Any of these changes can affect the spatial distribution of transportation patterns and other urban flows or even the shape of urban development during the desired time intervals of study. The IUMAT framework simulates changes in demographics, economics, land cover, transportation, energy and water and material resources as reflected in the core urban elements (Mostafavi, Farzinmoghadam, and Hoque 2014).

Another interesting environment partially explored during the research is Grasshopper, the visual programming module of McNeel Rhino, and its plug-in for environmental analysis.

As everything can be coded, everything can be developed as a grasshopper plug-in. Nearly 500 plug-ins exist ranging from very simple operations to extremely complicated concepts, and more than 30 only regarding urban simulation. They cover topics like climatic data (Ladybug, Mr.Comfy), thermal comfort and daylight simulation (Honeybee, TRNLizard), acoustics (Pachyderm, Snail), wind and fluid dynamics (SWIFT, Pigeon)

Ladybug allows you to import and analyse standard weather data, draw diagrams like Sun-path, wind-rose, radiation-rose, run radiation analysis, shadow studies, and view analysis. Honeybee connects Grasshopper3D to validated simulation engines such as EnergyPlus, Radiance, Daysim and OpenStudio for building energy, comfort, daylighting and lighting simulation (developed by Mostapha Sadeghipour Roudsari). SWIFT allows to do advanced CFD modelling with OpenFOAM through Grasshopper. Its results can then be processed to generate Outdoor Wind Comfort maps, and obtain Facade Pressure Coefficients for multiple wind angles (developed by markp). Most of the operation mentioned in the urban structure paragraph can be done but with the limit of not being able to manage attributes and information in a simple and stable way. For this reason and for the capability to manage data with a large spatial extent, its use in substitution of GIS is not a promising perspective except for very limited contexts.

CONCLUSIONS

This overview on existing tools allows to affirm some things. First of all, technology is not a limit. We can perform almost any kind of analysis or simulation that we could imagine often in multiple alternative ways. The abundance of solutions makes harder to find a common language that could foster the cross pollination between research groups, even from different disciplinary fields. It seems that all the existing software can easily perform only a certain amount of operation but not others. This could be due to the fact the urban diagnostic, and especially IMM methodology, crosses the traditional disciplinary boundaries forcing also the software to act out of their comfort zone, what they have been planned for. CIM seems to be a very promising direction for software implementation as it will finally be something designed for a multi-scalar and multi-disciplinary purpose. A holistic software for a holistic approach able to work on all the ranges of urban design, from block to city.

5.1.4 Research Assumptions

The paragraph 5.3 will present the strategies introduced to implement the characterization possibilities of urban morphology. That can be considered one of the core parts of the thesis. The variety of the results emerged from the different surveys make impossible, and also redundant, to re-test all of them, also because of the need of using, and learning, specific tools for specific metrics. Moreover not all these tools are free, updated and some requires datasets not available for the selected case studies.

The urban analysis have been carried out in QGIS developing some graphical modeller algorithms using only vector layers representing Volume and Void component from a formal point of view. As a consequence, every metric requiring a computation currently outside of this boundary have not been calculated. Fractal dimension, axial lines, raster and network have not been considered for the metric implementation and retrofitting phase. Some minor parts have been developed in Grasshopper and ArcMap, always working within the same geometrical and morphological boundary.

For what concerns the maps and representations, there was no need to test them, as I presented only positive and very generic examples in the survey. When possible, new representations have been studied to support one metric.

5.2 Research Vocabulary

Before showing in detail the process and the results of the characterization phase, is appropriate to define a research vocabulary in order to avoid misunderstandings. The previous sections included some citation with ambiguous use of words. This hopefully didn't compromise the understanding of the concepts but from now on, every part will refer to the following glossary and taxonomy.

5.2.1 Glossary

A work on a glossary must start from definitions. A definition is a statement of the exact meaning of a word, especially in a dictionary. Defining helps understanding and vice versa, these are two faces of the same coin.

It happens that the general meaning of a word can be slightly modified, or bent in order to better fit one particular disciplinary field. Also, dictionaries usually present a general meaning, strongly linked to the etymology of the word, and additional definitions belonging to specific sectors.

Considering that this research moves inside system theory (ref.), the words used should be transferable and applicable to the study of other objects within the same framework. In the same way as having a common currency fosters economic exchange between countries (ref?), a common language should encourage multi-disciplinary studies.

English is accepted as the language of the scientific community and will be so used for defining these principles.

Words often have synonyms, and thus may look apparently interchangeable with each other. However every word has its specific meaning, and even very similar ones may differ by a nuance. In a codified sector as research is, it becomes crucial to avoid misunderstandings like having many words with the same meaning or more meanings for the same word.

LITERATURE

The definition of a unified urban planning ontology suitable for both analysis and design will facilitate the sharing of knowledge between models, tools and scientists. This should eliminate the existing monologues based on each side's rhetoric and jargon, which create barriers to mutual understanding among practitioners and software alike. (J. Gil, Duarte, and Syntax 2008)

The existing literature shows ambiguity when dealing with spatial metrics or similar concepts. It is common to find the same concept called in a different way in two different papers, or in two sentences within the same paper. Even if sometimes this does not affect the clarity of the work, in other cases, unfortunately it does.

Here some examples. Silva et al. (2014) affirm "Porosity Index or Ratio of Open Space (ROS) is the permeability indicator which measures the proportion of open space, compared to the total urban area." This use of the terms conflicts with the following attempt to clarify:

The definition and scope of indicators still causes some confusion, and they need to be distinguished from parameters and indexes. Parameters are upstream from the formulation of an indicator as they provide data to build the indicator. Indexes result from a collection of indicators combined mathematically. From this point of view, indexes can be seen as downstream of indicators. Nevertheless, an index can itself be used as an indicator, by simplifying the complex information contained in all its constituent parts (IISD, 2000).

Huang et al. (2007) affirm that spatial metrics are a series of quantitative indices representing physical characteristics of the landscape mosaic. A set of metrics may represent dimensions of the urban form, i.e. compactness, centrality, complexity, porosity and density. Porosity, previously defined as index, is here a dimension that we could describe with a set of indices or metrics.

Xu et al. (2017) define BCR, BH, BVD, FAI and SVF as parameters in the abstract and as indicators in the review section. Moreover, while SVF is considered an important indicator for UHI, so to indirectly measure an environmental performance, BH is simply identified as morphology indicator.

The above-mentioned acronyms, considered as parameters, convey a further degree of ambiguity generated by the fact that words as “ratio”, “height”, “density”, “index” and “factor” are put at the same hierarchical level.

The naming of what we could temporary call metrics presents the same amount of variety (Floor space Index, Form Factor, Connectivity Measure, Control Value). The Section *Taxonomy* will deepen this aspect with the goal of defining a common rule for the definition of names and acronyms of the new spatial metrics implemented in the research.

Following the previous citation, we discover that, the more we explain, the higher is the risk of using some words in an uncertain position:

In general terms, an indicator is derived from data - i.e. values that can be measured or observed - and can be defined as a value that provides information about a phenomenon. It is, therefore, a measure of its given state and evolution, which is able to summarise the characteristics of systems or highlight what is happening in a system (IISD, 2000).

An indicator is a statistic or parameter that, tracked over time, provides information on trends in the condition of a phenomenon and has significance extending beyond that associated with the properties of the statistics itself (OECD, 1994; EEA, 2002)

This short extract contains almost all the possible sliding words that we had better define before starting dealing with this argument. Initially I focused only on the terms Index, Indicator, Metric, Parameter and Value. By looking at their definition I found it necessary to expand the research to other terms connected to these like Attribute, Characteristic, Data, Dimension, Factor, Feature, Measure, Property, Quality, Quantity and Variable: 16 words dealing with the calculation of some aspects of the object of study.

In the following, I present an attempt to determine a hierarchy among these terms by grouping them according to their definition and electing the most convenient word to be used. Mutual citations are in underlined and in italic format.

DEFINITIONS

Attribute: a *quality* or *feature* regarded as a *characteristic* or inherent part of someone or something; a real *property* which a statistical analysis is attempting to describe

Characteristic: a *feature* or *quality* belonging typically to a person, place, or thing and serving to identify them.

Data: facts and statistics collected together for reference or analysis; the *quantities*, characters, or symbols on which operations are performed by a computer; things known or assumed as facts, making the basis of reasoning or calculation.

Dimension: a *measurable* *extent* of a particular kind, such as length, breadth, depth, or height.

Examples: length, width, breadth, depth, area, volume, capacity; an aspect or feature of a situation.

"We must focus on the cultural dimensions of the problem".

Factor: a circumstance, fact, or influence that contributes to a result; a level on a scale of *measurement*; any of a number of substances in the blood, mostly identified by numerals, which are involved in coagulation.

"His skill was a factor in ensuring that so much was achieved"; "factor 30 sun cream"

Feature: a distinctive *attribute* or aspect of something.

Index: a sign or *measure* of something.

"Exam results may serve as an index of the teacher's effectiveness"

Indicere, to say; *indicare*, to make known

Indicator: a thing that indicates the state or level of something; a gauge or meter of a specified kind.

"Car ownership is frequently used as an indicator of affluence"

Measure: a standard unit used to express the size, amount, or degree of something; a standard *quantity* or amount; an *indication* of the degree, *extent*, or *quality* of something

Metric: a system or standard of *measurement;* a set of figures or statistics that measure results

"The levels of branching are arbitrary and no precise metric is applied to the distance between the nodes";

Parameter: a numerical or other *measurable* *factor* forming one of a set that defines a system or sets the conditions of its operation; a *quantity* whose *value* is selected for the particular circumstances and in relation to which other *variable* *quantities* may be expressed; a limit or boundary which defines the scope of a particular process or activity.

"There are three parameters by which a speaker is able to modify the meaning of the utterance: pitch, volume, and tempo";

Property: an *attribute*, *quality*, or *characteristic* of something.

Quality: the degree of excellence of something; a distinctive attribute or characteristic possessed by someone or something.

Quantity: the amount or number of a material or abstract thing not usually estimated by spatial *measurement*.

Value: the numerical amount denoted by an algebraic term; a magnitude, *quantity*, or number; the regard that something is held to deserve; the importance, worth, or usefulness of something.

Variable: not constant or having a fixed pattern; liable to change; (of a quantity) able to assume different numerical *values*; able to be changed or adapted; a data item that may take on more than one *value* during the runtime of a program.

CONCLUSIONS

One of the reasons for this semantic confusion is that all the studies, with very few exceptions, introduce spatial metrics to explain a certain phenomenon that inevitably influences the clearness of the measure. Urban characterization is s step often skipped or made quickly to jump to correlations with environmental implications. Each specific goal of concern would shape the analytical categories and approach (Alberti 1999). That's why metrics and measures are called indicators and indexes and every time that the same attribute is used to explain a different dimension, it has to change name.

This work tries to hierarchically order these concepts in the urban morphology characterization field. It follows an explanation of how the above mentioned words will be used in the research framework from now on.

Data are a clear concept. They are the first input for any kind of calculation or analysis. A data, without a qualification or specification is useless and can't be transformed into information. They can be numbers, strings, geometries or other kinds of entities. In order to distinguish the content of each attribute field from the analysed objects, this latter will be called **input data/layer** or simply input.

The definitions of attribute, characteristic, feature, property and quality refer to each other. Characteristic, feature and quality contain the word "distinctive" or "typical" and are probably not so correct to identify something that every object shares but in different quantities. Additionally, quality has an additional positive sense, that risks becoming ambiguous in a phase of simple characterization, when no early-stage evaluation has been made yet.
Property and attribute indicate information attached to an object or instance. This aspect is not exclusive but shared among various instances and can assume different values. They can be integers, Booleans, characters, floating-point numbers and alphanumeric strings.
Attribute seems the most promising and specific word to be used because of its role of descriptor of a property and the link with statistical analysis and the consequent numerical dimension. Moreover, it is currently used in the GIS and database software vocabulary.

Quantity and value express the numerical amount of something that could be measured. Factor has many meanings and result ambiguous. It ranges from a specific level on a measurement scale to something that has an impact. Quantity and factor could also be misunderstood with the object of the measurement itself according to parameter definition. Dimensions are properties of the objects and can be measured with different units. Dimension can also mean the perspective from which we look at data. The word measure is sometimes used with the meaning of indicator, as capable to directly or indirectly explain something else. The value of an attribute may become a parameter for a specific formula or procedure. Also variable is a quite clear concept and defines everything that may change during a process. So, being a parameter or a variable is a condition that could interest other above mentioned words depending on when and how they are used.
According to its first definition, a **metric** is a system of measurement. For the classical and common physical characteristics, metrics are already existing and well known. The International System or the Imperial British System are some examples. The second meaning is becoming more and more popular and indicates something that is quantifiable and representable and should help in the characterization or understanding of one property. It is possible to find it used as a synonymous of indicator.

Vocabulary definitions tell us that index and indicator are synonyms. The definition is quite generic but the sample sentences clearly show that they quantify something that is able, and used, to describe or explain another phenomenon. Literature definitions specify that an index results from indicators combined mathematically. A phenomenon can be described by many Indicator or indexes, but while indicators may be complementary, indexes are exclusive. Indexes risk to collapse complexity into a too synthetic measure and are not coherent with the research approach. **Indicator** will be used to express everything that can be not only measures but also clearly and univocally maximised or minimised.

PRACTICAL APPLICATION

An example can be useful to systematize the conclusions and define the appropriate hierarchy among the different words. A collection of 2D geometries representing buildings is taken as **input** data. These polygons are **instances** of the same **layer** and each of them has its own value for some **attributes**. The buildings' initial set of attributes (A_0) are: area (A), perimeter (P) and height (H). Area and perimeter are intrinsic **properties** of the polygon and, even if this information is already present in our input data, they can also be obtained by simply querying the instances. Other properties can be similarly extracted as for example the number of sides or vertices of the polygons.
Height is an additional attribute (A_1) that characterises the geometries and has been added manually after a survey. Two identical polygons may have a different height while they necessarily have the same area. Other similar attribute could be, in our case, the number of inhabitants or of floors, the civic number or the owner name.
A number of other attributes (A_2) can be derived by mathematical operations performed on A_0 and A_1 as for example the volume (A*H), the vertical surface (P*H), the average length of sides and many other. Some other geometrical operations can produce as result a new geometry, individually generated by each instance. These new polygons, lines or points are called **ancillary layers** as they are used for representation purposes or to increase the parent instance set of attributes**.** Some examples could be centroids, minimum bounding geometries (mbg) or buffers (bf). Their attribute (A_3) can be put in relationship with the attributes of the input (A_0;A_1), generating other attributes (A_4). A certain kind of A_2 and A_4 can be already considered a **metric** for the building itself, while others will allow the construction of a metric by the interaction with attributes of another input layer. To clarify, P/A, S/V or Ambg/A are metrics, while A, P, V or S are attributes.
Attributes allow the construction of metrics not only for the instance itself, but also for a **spatial unit** including more instances. In our case these units could be Blocks (BL), districts or even the whole city. The information transfer by instance to boundary layer is based on spatial join procedures that can aggregate instance attributes with different mathematical operation as sum, average, count or other statistical concepts.

5.2.2 Taxonomy of Spatial Metrics

METRICS NAMING

Now that a research lexicon has been defined, it is time to focus more on one of its core terms: metrics. The examined literature presents more than 100 different metrics if we only consider Volume, Void or Link component (no Transportation or Type of Uses). With so many disparate measures now used to operationalize the same constructs, Urban Form research would benefit from some standardization in the operational definitions and measurement protocols (Clifton et al. 2008). The word *metric*, here adopted to identify them, is not universally used, substituted sometimes with *index, factor*, or *indicator*. They can be univocally described by a name, an acronym (not always) and a formula. Additional information can be the year and the responsible for their discovery and the phenomena they have been proved to be correlated with.

The ambiguity in this field is notable because of different reasons. One of them is that it is possible to find the same formula called with a different name and acronym. The ratio between floor area of buildings and a plane portion of ground surface, for example, is currently called Floor Area Ratio (FAR), Floor Space Index (FSI), Floor Area Density (FAD), Building Intensity (FSId), Plot Ratio and Built Density. While the first three names clearly refer to the same physical quantity, the fourth and the fifth one are vague, and the last is totally wrong or at best generic. Built density could represent any of the dimensions of the Volume layer like footprint, floor area, volume or number of buildings. If we consider that the same value could be net, using plot area as reference boundary, or gross, using the whole sample area including streets, it becomes harder and harder to speak the same language.

AN ALPHABET OF URBAN STUDIES

Another aspect regarding the acronyms is that some letters are currently used for multiple words and others are "empty". The following alphabet collect all the meanings found for a specific letter in the reference literature acronyms.

A	Area, Asymmetry, average
B	Building
C	Compactness, Coverage, Canopy, Climatic, Catchment
D	Density, Digital
E	Elongation, Evaporating, Elevation
F	Floor, Front, Factor
G	Ground, Green
H	Height (2D), Height (3D)
J	
K	
I	Index, Inertia
L	Land, Leaf
M	mean?, Metric
N	Node
O	Open
P	Perimeter, Parameter
Q	
R	Ratio, Rugosity, Reach
S	Sinuosity, Sky, Entropy, Space, Shape, Surface
T	Total
U	Urban, Uniformity, Unit, Gradient
V	Volume, Void, View
W	Width, weighted
X	
Y	
Z	Zone

Some letters are "crowded", and some have room for meanings. Looking at the meanings associated with a letter we can notice that they include very heterogeneous things. Looking at the "A", *area* is a physical property, *average* is a mathematical operation and *asymmetry* is a system property. For "C", *compactness* is a physical property of an instance, *coverage* relates the area of two objects, *canopy* is a part of built environment, as could be buildings, *climatic* is a performance field and *catchment* is a geometry than contains other geometries. Letters like F (factor), I (index) and P (parameter) indicate something that should be already known, considering that we are looking at spatial metrics, and can be seen as redundant.

If we try to distinguish these objects we can divide them into classes:

- object of study, what the metric is referred to and built on (building, sky)
- part of, or perspective on an object, (floor, front, view)
- system property (porosity, sinuosity, asymmetry)
- dimension, physical quantity (area, perimeter, volume)
- mathematical operator (average, mean, ratio)
- redundant (index, factor)

A TAXONOMY OF SPATIAL METRICS

The taxonomy is the branch of science concerned with classification, especially of organisms. The word dates to the early 19th century and was coined in French from the Greek *taxis* (arrangement) + *nomia* (distribution). A taxonomy classifies information in an ordered manner to indicate relationships, as well as to bring clarity to complex issues. A good example is the Taxonomy of density by Boyko & Cooper (2011).

For the creation of the taxonomy of density, the authors brainstormed ideas, looked at the definition and thought about all the different kinds of density with which they were familiar and wrote them down. They also spoke with nine experts who were able to generate additional density types and validate the ones developed by the authors. The authors then clustered the different density types according to similarity and level of specificity and then gave each cluster a heading (Boyko and Cooper 2011). Figure 35 gives a synthetic representation of this work.

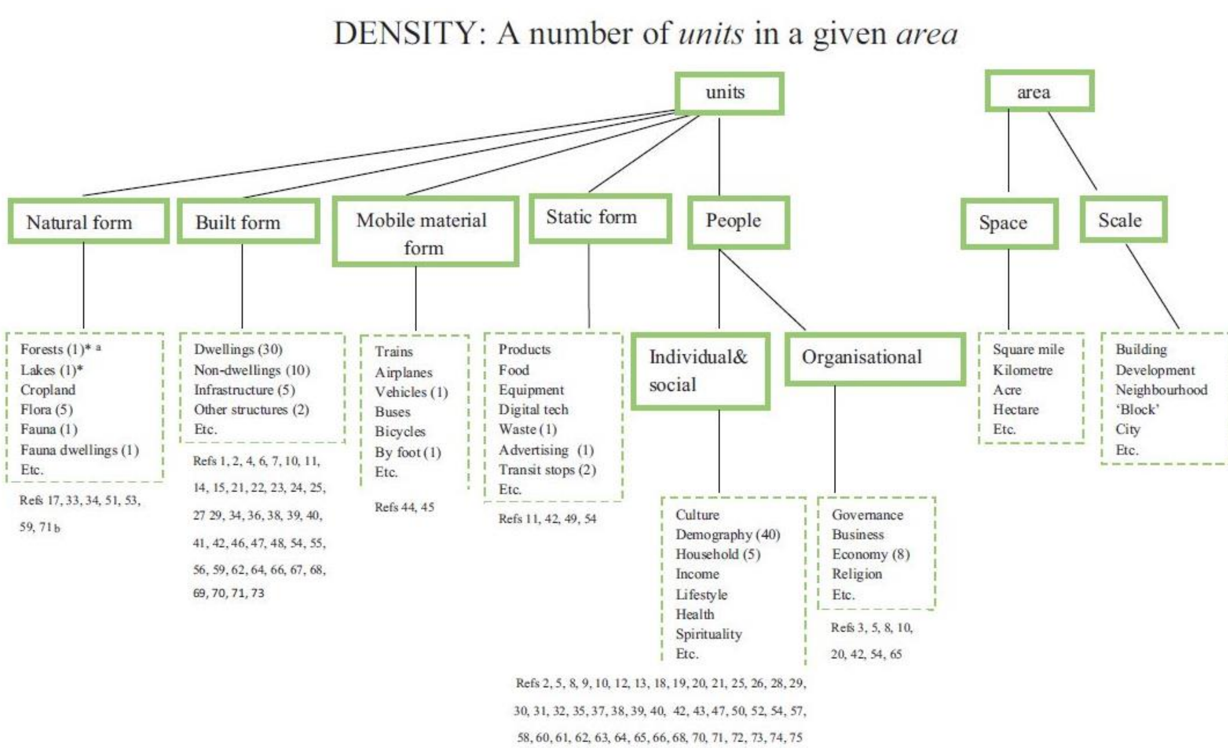


Figure 35 A taxonomy of density, populated with information from 75 studies. Numbers in parentheses refer to the quantity of studies exploring a particular type of density (Bokyo & Cooper, 2011)

The attempt of this work is to define the rules for a taxonomy of spatial metrics to be applied for the creation of new metrics, and to choose the most suitable name for multi-labelled metrics (FAR,FSI,FAD…). In comparison to the taxonomy of density this attempt is more abstract and deals with very heterogeneous objects.

Looking at the criteria currently used to label a metric we can find the following:

- synthetic name of the described property (Compactness, Entropy, Inertia) usually followed by what we defined "redundant" words as index, measure, factor and parameter
- ordered parameters and operators of the formula (BCR, FAR, ND)
- inventor name (Cbottema)

The first approach has the problem that a single metric can become a descriptor of more than one phenomenon, generating the initial labelling conflict that we are trying to avoid. The second one seems promising but when formulas become too complex and involve many non-standard parameters the risk is to have very long and strange names. The inventor is obviously not appropriate because the same person could discover more metrics, there could be homonymies, and the content of the metric remain hidden.

Re-naming the existing metrics is out of the scope of this research especially because a solid principle to do it doesn't seem to exist yet. By the way some basic rules should be defined in order to guide new researches in this field. We take as example one of the metrics implemented in this research to explore the different possible labelling techniques.

METRIC DESCRIPTION

Ratio between the number of unique buildings (models) and the total number of buildings. Is a metric constructed to represent how diverse is an area in terms of buildings size and shape. A rationalist neighbourhood with standardized buildings will show a low value, an historical city centre with irregular and plots and typological mix will show a high value.

Possible names

Bunique/Btot – Bu/Bt – Bu/B – N°Bunique/N°B – Ub/Tb – M/B – Mod/B – Bdiv – Db – MBR – UBR – BuBR – BuTB – Bmod/B …

With "U" standing for unique, "B" for building, "M" or "Mod" for model, "N" for number, "R" for ratio, "T" for to or total, "D" or "div" for diversity.

RESULTS

The following graph collects the preference of PhD candidates from the ABC Department for the best naming of the above mentioned metric (Figure 36).

Someone added as possible answers also the following acronyms:

UBM; MoDiv; Uniqueness Coefficient / Singleness Coefficient

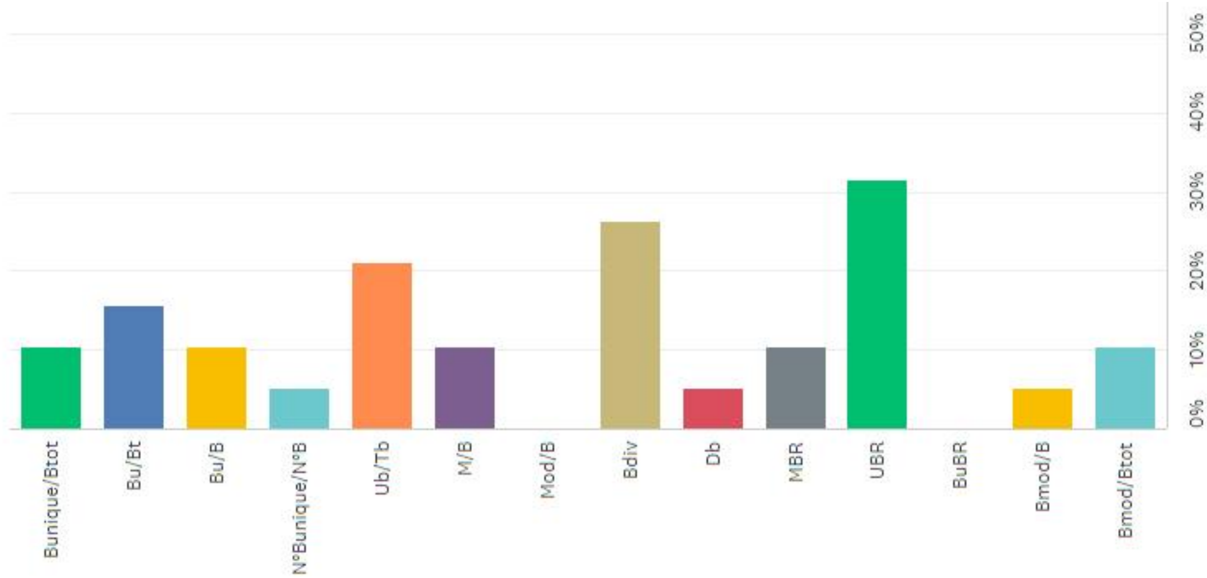


Figure 36 Metric acronym survey results. Investigation between PhD candidates from ABC department of the most appropriate name for a metric based on its description.

The results show little agreement on the naming logic for a metric. We can anyway learn something:

- adding *N°* before an instance to express its count seems redundant. When a specific measure is not mentioned (area, perimeter, volume…) we are dealing with instances count. In mathematics, moreover, the number of items in a set S of objects uses to be indicated with |S|, so eventually this notation can be used.
- to call a subsystem of a larger system with a totally different name can be dangerous. *Mod* and *B* seems different objects.
- an acronym should be short and preferably not including mathematical symbols
- both "synthetic descriptive" and "formula based" acronyms are accepted (Bdiv; UBR)
- the highest percentage of agreement on a name is 32% so none of them is considered acceptable by at least the half of the surveyed.

PROPOSAL

Without the presumption of being exhaustive, this dismantling and classification process of metrics produced some useful insights. We are now able to define a wording strategy for the new metrics that will be introduced with the research. Among the above mentioned labelling criteria, the ordered parameters and operators has been selected. The main advantage is possibility to create univocal acronyms that immediately cast some light on the involved attributes. The best scenario for its application is a shared and ordered alphabet of urban studies or, even better, of system theory.

In order to distinguish the different meanings associated to the same letter it's suggested to use subscripts and lower case characters, as already happens. These smaller texts permit to add information to an initial capital letter or specify the measure or ancillary layer related to it.

In literature it's possible to find two opposite usage of letters and subscripts. An example is the easiest way to understand this conflict. The attribute area (A) of the instance building (B) use to be expressed both as *Ab* or A_B and *Ba* or B_A. These methods are both acceptable but we believe that the second one is more appropriate because it put at the first place, so immediately recognizable, the instance under investigation.

5.3 Implementation

5.3.1 Morphological Investigation

This paragraph represents the practical application to Volume, and partially Void, of what have been described in Chapter 3 as an IMM reconceptualization of the role of components. The theoretical entity Component, in order to be analysed, need to be represented. Volume component is represented by prisms called Volumetric Unit (UV) as finer grain layer. UV can be associated and aggregated to buildings (B) bringing into a simpler geometry a more complex set of attributes. For example, the volumetric complexity and articulation of a building cannot be expressed by one single geometry and its attributes but needs to be dismantled into smaller geometries that can represent parts of the building with different heights (Figure 37).

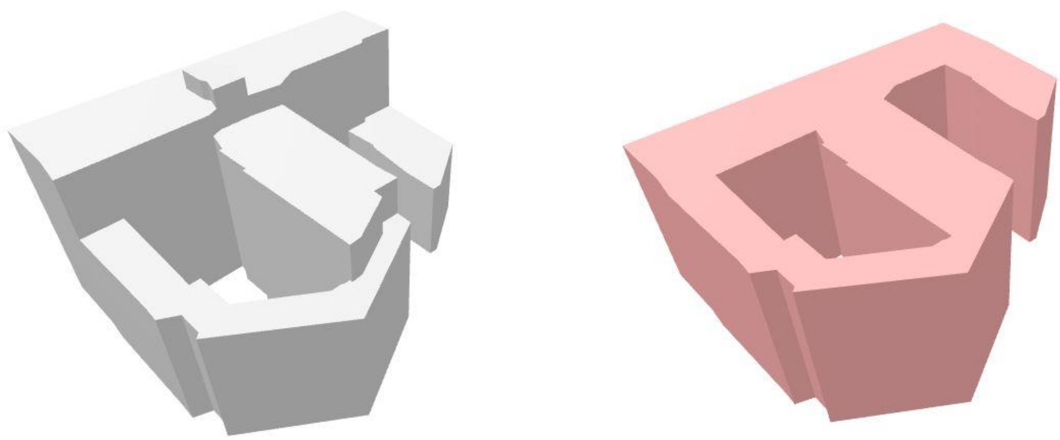


Figure 37 The same building represent by Volumetric Units (UV) on the left, and as a single geometry with average height on the right

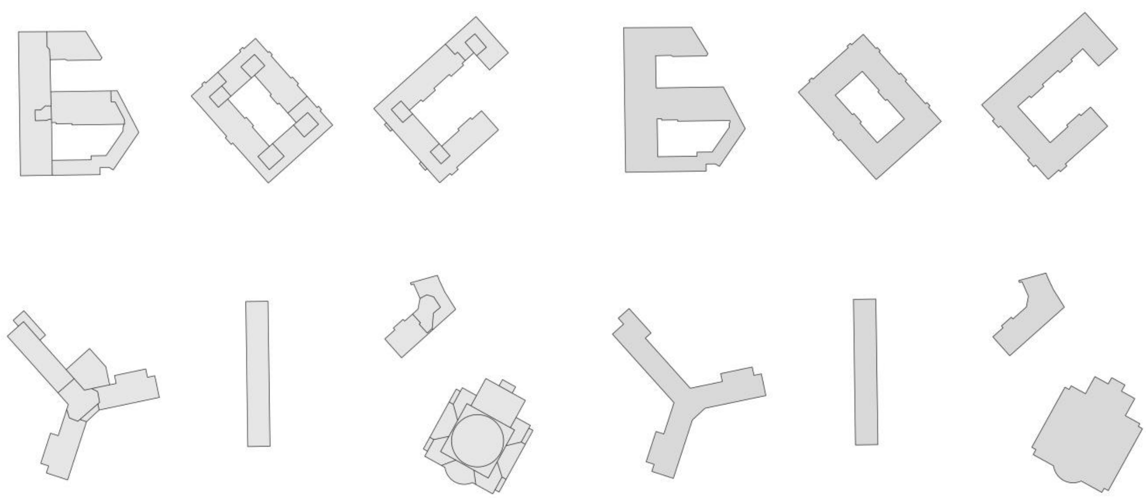


Figure 38 Set of 7 buildings represented as UV (left), and buildings (right)

A building can be composed by more UV and must be composed by at least one. Working with buildings as a class of objects offers the possibility to investigate them individually in addition to their overall unspecified mass. Buildings are the morphological unit of the Volume component and can be obtained from the input layer UV (Figure 38).

Considering the assumption of working only on the formal aspects and physical consistency of the investigated elements, the number of possible attributes seems limited to the basic geometric dimensions of solids as Area (A), Perimeter (P), Height (H), Volume (V) and Surface (S). Also number of faces, edges and vertices can be obtained by deconstructing B-rep, a simple operation in a CAD software but not trivial in GIS as 3d geometries are only represented starting from 2d polygons. Moreover the geometries are often composed by many small segments due to lack of accuracy during the digitalization procedures. For example, what may seem a rectangle (4 sides), could be in reality a rectangular-like irregular polygon with a higher number of sides (11, i.e.).

In order to increase the modelling complexity more attributes are needed. Given the fact that the formal intrinsic properties of whatever kind of shape are the above mentioned ones, the only possible way is to generate additional geometries performing spatial operations on buildings, the parent class. This gives the possibility to create Ancillary Layers than can be useful for both measuring and representation purposes. In this case two families of command have been mainly used: Minimum Bounding Geometry (MBG) and Buffer (Bf). MBG can be of 4 kind: circumscribed circle (Circle), convex hull (CH), oriented rectangle (OR) and envelope or non-oriented rectangle. Only the first three will be considered in this thesis and are showed in Figure 39.

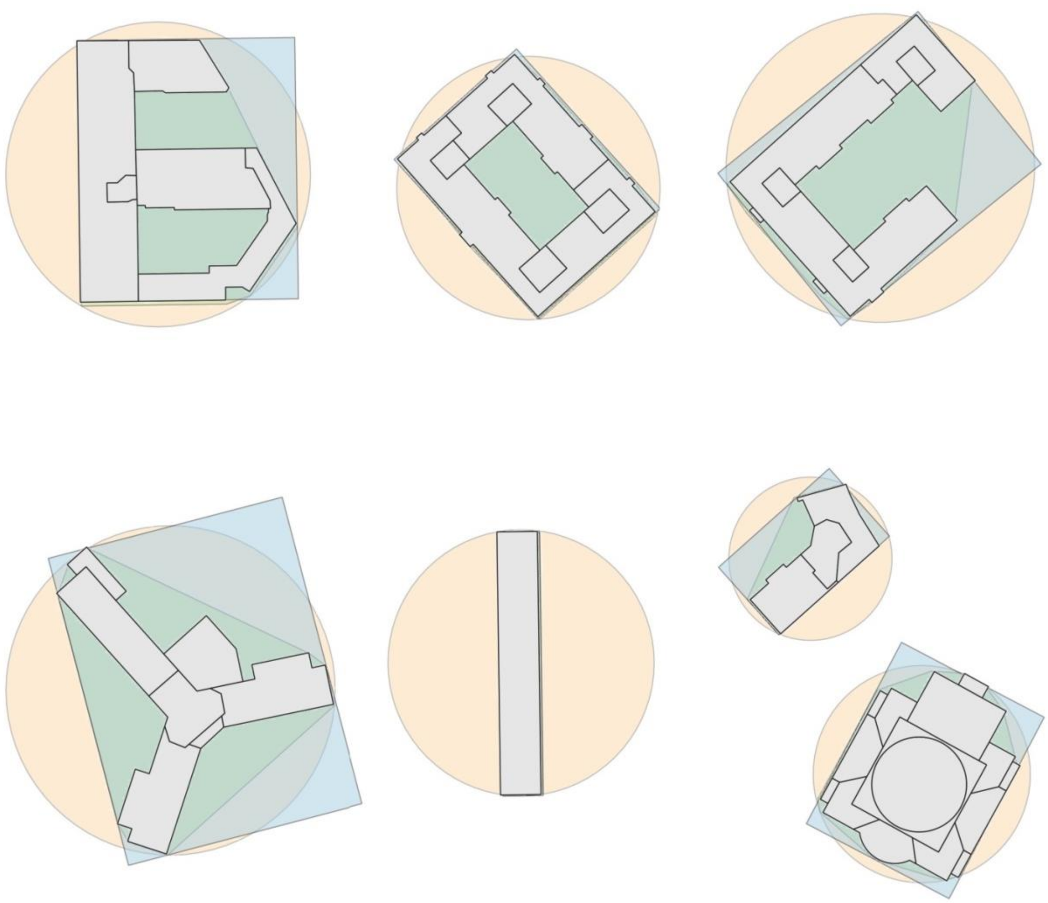


Figure 39 Ancillary layers visualization. On the same 7 buildings used above the different ancillary layers are displayed. Circumscribed circle (orange), Convex Hull (green) and Oriented Rectangle (light blue).

They are all polygons of minimal area containing the building shape and respecting different simple geometric rules. Each of them has its specific attributes that can be directly transferred to the parent building. OR, in light blue, represents the domain of the building and is the richest source of additional data. It has an A and P attributes, as CH and Circle, but also an Angle, the azimuth of the longest side, a minimum (Dmin) and a maximum (Dmax) side length. We can notice that CH, in green, is always contained in OR and Circle, in orange, and so smaller than them. The creation of these ancillary layers adds 8 new attributes to the building layer. Two or more geometries, including parent building, might overlap but one will always be different.

Bfs are simple offset with round corners of the input building geometry. They can be performed by any given distance. Negative values will produce a shape shrinking while positive values return a sort of inflated shape. The Dissolve (DS) operation can be seen as a buffer at distance 0m as it doesn't modify the original shape while merging together its constituents. From this perspective B is a DS or Bf0 of UVs. Buffers have been used with 4 different values for two reasons. The first value (-6m) simply helped to calculate the Passive Volume metric using the A attribute of the parent and child geometries. The other values (0m, 2.5m and 5m) are used to investigate the reciprocal distance of buildings. If on the perimeter of two buildings there are two points closer than the buffer distance, the two instances will merge in a single geometry. This new geometry doesn't represent a real urban object so investigating its area and perimeter could provide ambiguous results. In order to get some attributes it remains the number of distinct, or single part, elements between parent and child layer. Only the attributes coming from the buffers of null or negative value can be joined to the parent layer. For example B can get as attribute the number of UV it's composed by (DS), or the A of the -6m buffer, but can't be related to Bf5 and Bf10 as they go outside from its perimeter. In reality, this is possible but not useful in the study of a single B. Working on a block or a district makes the information of how B are aggregated more interesting and so these larger spatial units are the appropriate place to collect the remaining buffer attributes. The following picture tries to clarify the opportunities and the limits of this approach (Figure 40).

The fact that the number of B_DS corresponds to the number of blocks is due to the morphological characteristics of the sample, extracted from Milano city centre. Every Block may contain more than one B_DS. Thanks to this scalar hierarchy the downstream larger layers (on the right) may inherit all the attributes of the upstream smaller layers (on the left). These attributes will help in the construction of metrics describing the relationship between a whole and its parts at different stages or resolution.

The block (BL) is by definition equal or bigger than a building and can so become the first collector of it attributes. Considering that one BL usually contains more than one B, B attributes need to be summarized with operators as the mean, the maximum, the unique, the count or other more articulated processes. In addition, BL is also a key morphological unit strongly affecting the structure of an area in terms of flowing. This allows and suggests to apply to it some operations similar to the one used to create the ancillary layers of buildings. In order not to exceed with the amount of attributes, expecting that some could be redundant, the only operations performed were the OR and a sequence of Buffers of equal distance first positive and then negative.

This last operation has been used to pass from the real block shape to what Pafka & Dovey (2017) use for the calculation of AwaP metric. This new shape that I called Virtual Block (VBL) consists in the perimeter of the block ignoring internal dead end streets (Figure 41). OR instead follows exactly the same logic of the previous application to buildings.

Figure 40 Sample area in Milan city centre represented by UV (top-left), B (top-right), B_DS (bottom-left), Bf5 (bottom right. Each representation contains numeric information regarding the number of displayed geometries. UV (206), B (43), B_DS (10), Bf5 (4).

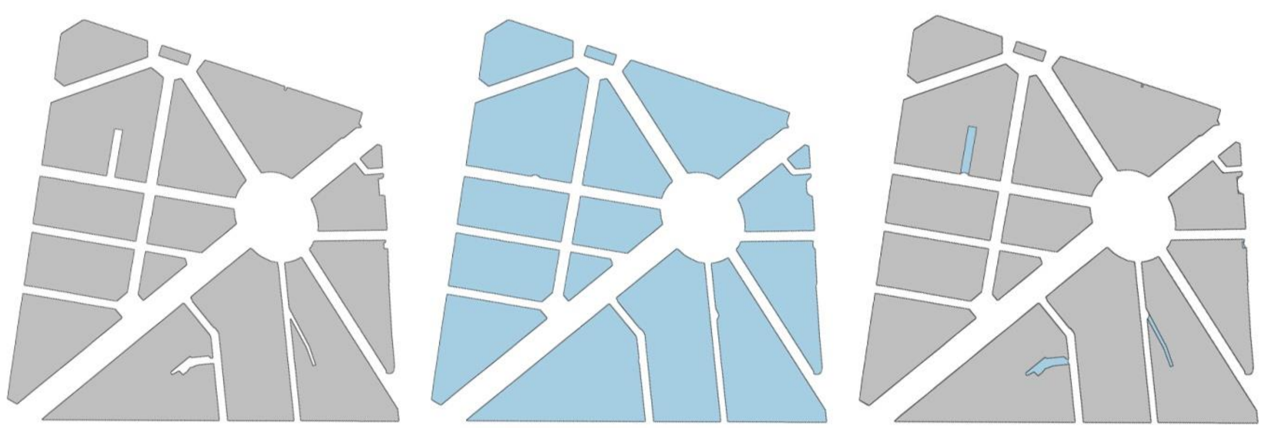


Figure 41 From Block to Virtual Block. Mazzini neighbourhood in Milan (upper part of Porto di Mare area. Real block (left), VBL (middle), Real block and VBL overlapped to show how the cul de sacs have been filled by the double buffer process.

After these self-learning procedures I explored the possibilities coming from the geometrical interaction of B and BL shapes. Inspired by the Interface Catchment (IC) metric by Pafka & Dovey (2017), I decided to find a way to quantify how buildings were facing the street or, from another perspective, which percentage of block perimeter was occupied by a building front. To overcome possible digitization mistakes instead of using B I used Bf10, intersecting it with BL contour line. This means that every part of a building closer than 5 m to block perimeter will be considered as facing it. This attribute is called BL_BP (Block Built Perimeter) (Figure 42).

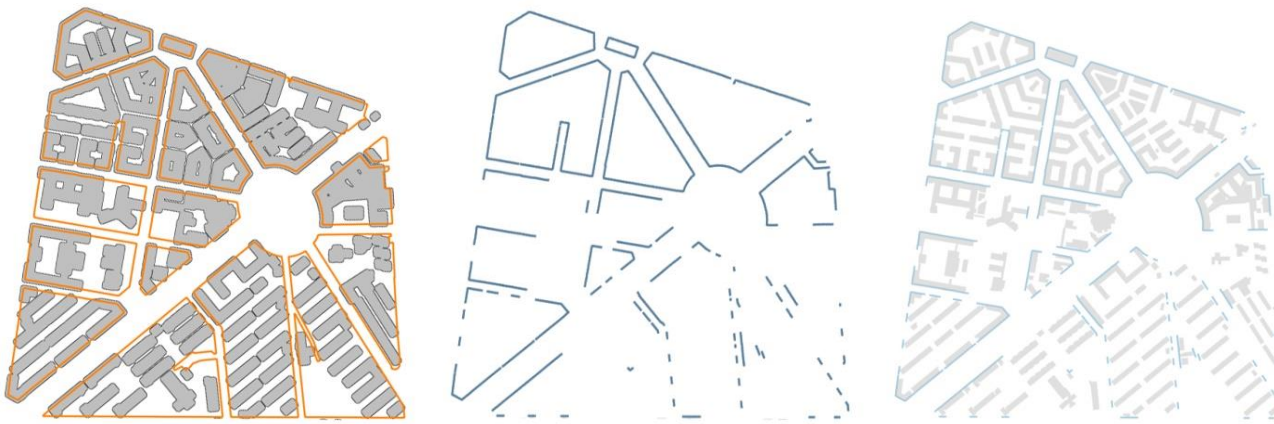


Figure 42 BL_BP construction. Mazzini neighbourhood in Milan (upper part of Porto di Mare area. Block perimeter (orange) and Bf10 (grey) (left), BL_BP middle), Buildings and BL_BP overlapped to clarify the meaning of the representation

The other urban element that will be taken into account are closed courts (CT). CT are visible as negative of B but are almost never considered from an object oriented perspective also because they are not included in common databases. CT can be easily obtained by performing a difference between B and their envelope as a whole. This method identifies only closed courts and enclosed shapeless spaces. Once obtained the CT layer, as for every polygon, the previous operations for the creation of ancillary layers can be performed. These operations in fact help to characterize a shape no matter its size or field of study. Considering the huge amount of attributes already added, only OR has been applied to CT. Is not possible to assign a CT to one and only B, as they are often shaped my multiple B, but their attributes can be gathered inside the block they belong. The following picture (Figure 43) represents different morphologies from the city of Milan. It’s clear how the presence, or the absence, of courts can be representative of different building typologies and also block shape and dimension.

Figure 43 Courts representation of three different areas in the city of Milan. The presence, or absence of courts is a clue for the morphological configuration of urban areas.

The complementary relationship between Volume and Void show that they have the same importance and it's not possible to determine which the negative of the other is. This picture recalls the famous cover of Colin Rowe Collage City (Rowe and Koetter 1983) by comparing two areas not far from the city centre of Milan, Chinatown and Maggiolina (Figure 44).

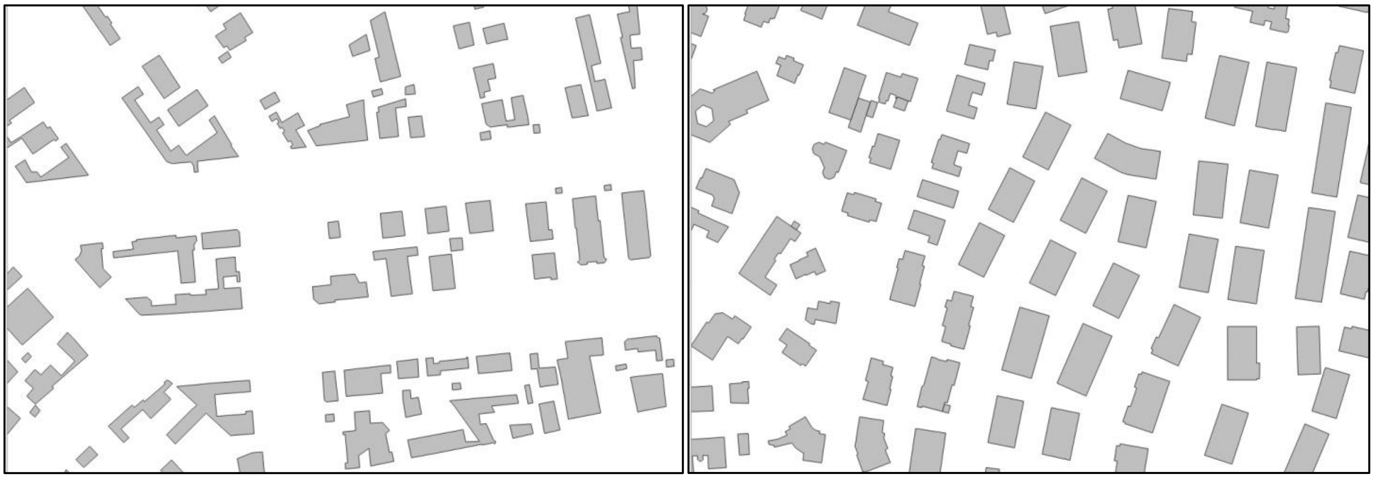


Figure 44 Courts - Building comparison between two Milanese areas. The same visualization symbology is used to represent courts in Chinatown area (left) and buildings in Maggiolina district.

We used UV and Ancillary layers to increment the number of attribute of B, and B,CT and other Ancillary layers to enrich Block attributes set. The above mentioned process is articulated in 4 QGIS graphical models. The first three return the morphological units (B,BL and CT) starting from UV and Street Area (SA), the negative of blocks, while the last one collects all the above mentioned attributes into landing geometries like blocks or districts.

Figure 45 represents the full process to pass from Volume input layer (volumetric unit) to a hypothetical building classification passing through ancillary layers, morphological units, attributes and metrics. The approach extended to the other components is graphically showed in the following tree structure, including some hints in terms of input layers also for the two remaining components and possible ancillary layers and relative attributes for the Link one (Figure 46).

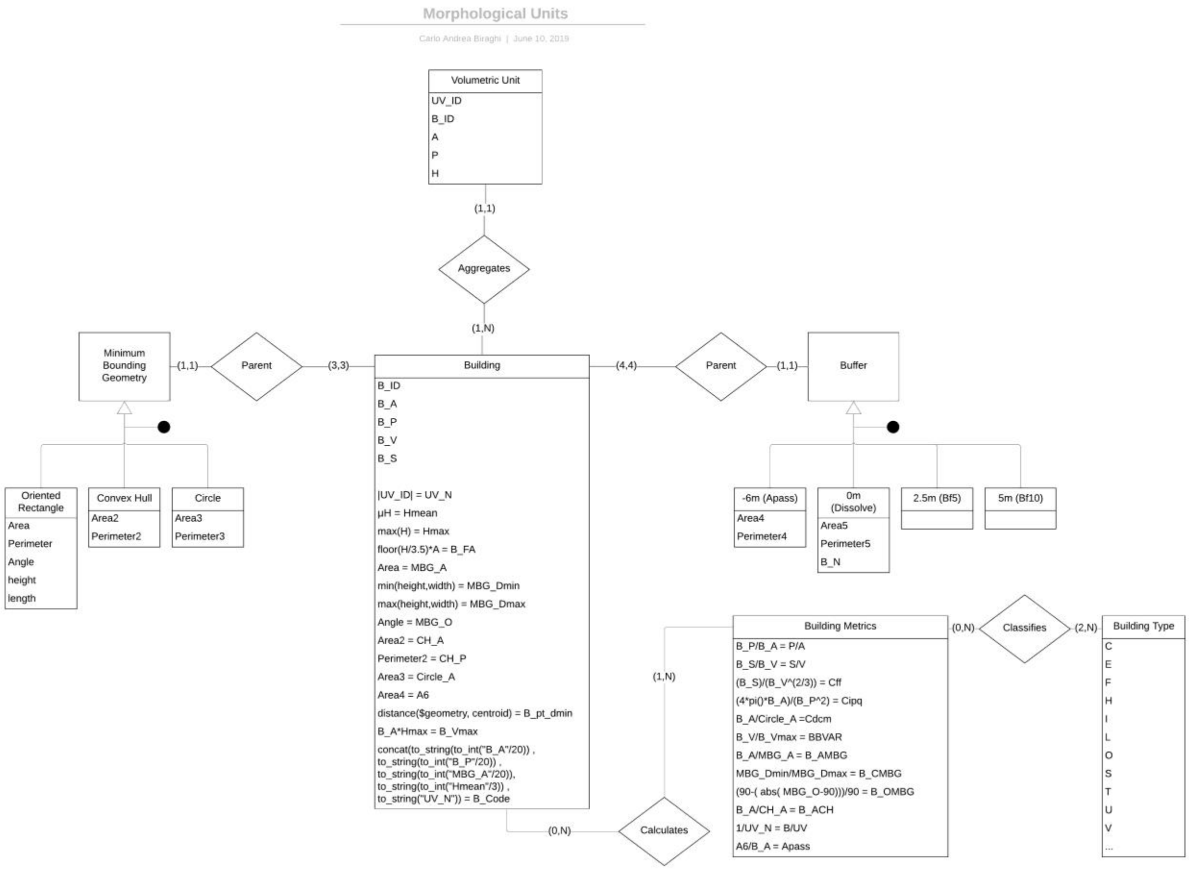


Figure 45 Layer to Metrics. The scheme shows the how to generate attributes and metrics performing spatial operations on Volumetric Unit (Volume input layer). Building attribute set is implemented with the use of ancillary layers and used to generate metrics that allow a classification process.

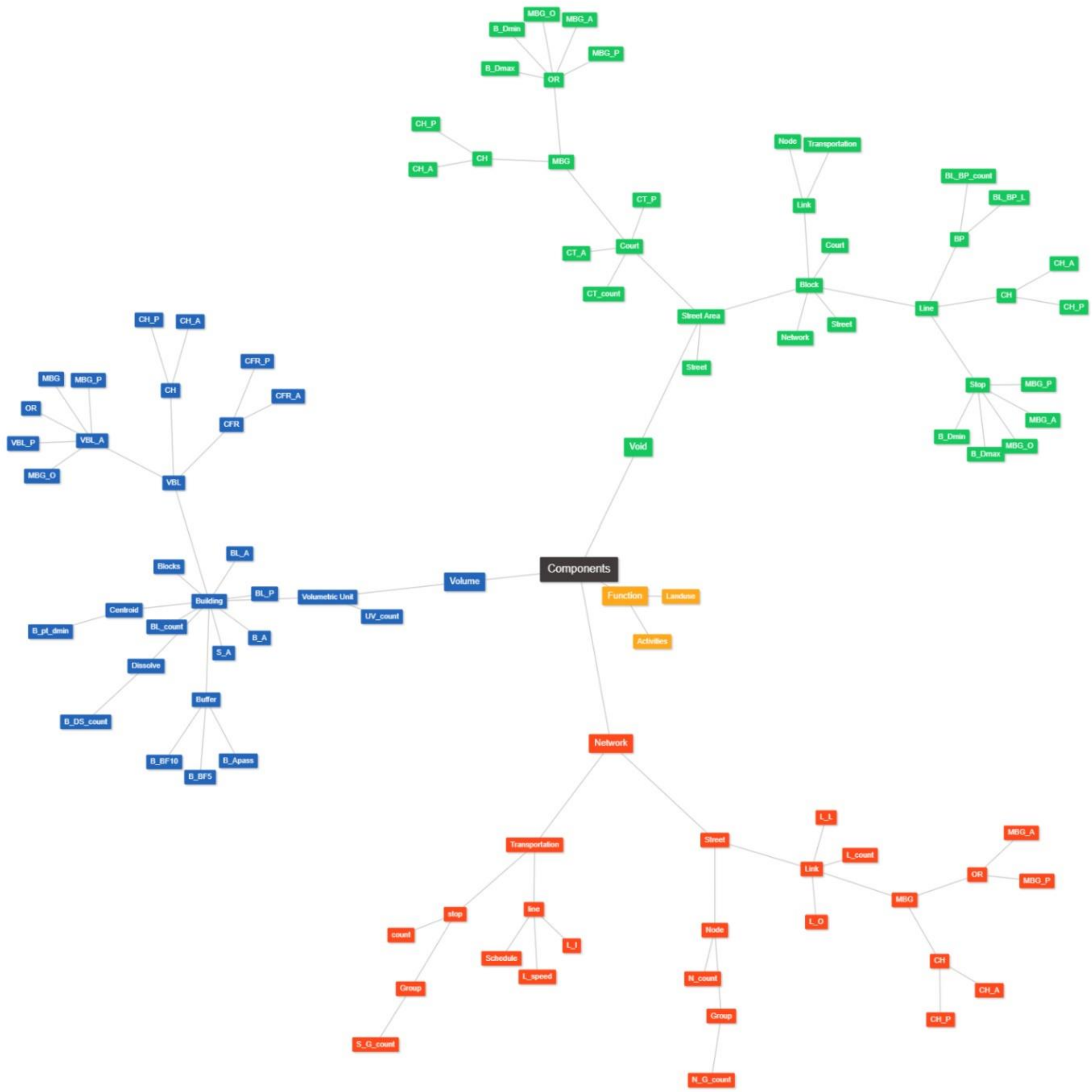


Figure 46 Components tree diagram. The tree start from the 4 IMM Components as main branches, splits in Input Layers and then in morphological unit, ancillary layers and attributes in order to display the highest possible number of attributes related to a specific component. Function branch is not developed as out of the research topic and Network's attributes are only supposed

5.3.2 Metrics

The new and the old attributes, also belonging to different layers, can now be combined in number of ways in order to create spatial metrics. These spatial metrics, investigating the relationship between Volume and Void component can be calculated at different scales and for different morphological units. While all of them can be applied at the district and city scale, as these scales necessarily comprehend the other smaller units, only some can be calculated at finer grain scales. Blocks can be characterized by all metrics based on courts, buildings and block itself but not from the one dealing with streets, as they obviously fall outside the single block they define. Following the same principle, building metrics can catch only building and sometimes courts attributes. This is an important aspect and open interesting perspectives. In fact, even if the main purpose of the research was to define a method to be applied at neighbourhood scale, the actual strategy permits to enrich the possible criteria to classify also buildings, courts and blocks according to objective and quantitative measures. The generation of types or classes requires a segmentation process where the investigated building stock is divided into groups according to a certain number of attributes (Loga 2009; Tuominen 2015). Increasing the number of non-redundant, valid and consistent attributes increases the classification possibilities especially using data mining methods and software.

It's important to remember that even if the research only focuses on Volume and Void component, it works in a systemic and larger framework covering all the remaining structural aspects of the city. This means that the final number of available attributes that could be generated by a small amount of standard input layers is more than twice bigger than the one presented here. The capability to appropriate model complexity is definitely increased as we multiply the number of possible connections and interactions. Always referring to IMM infrastructure, we notice that Volume and Void components, clearly important for the definition of Porosity and Permeability KCs, play a minor role also in the definition of the other KCs. To play a role can be practically translated in having one or more metric based on them that help to characterize other KCs. For this reason, after the definition and the explanation of the new metrics, the most appropriate position inside IMM theory will be indicated. More than one KC can be indicated as there's the possibility of overlapping among them. It's important to notice that at this stage of the research, the KCs listed below are deducted intuitively by the author. In the future, after testing the selected metrics and performances indicators on a larger set of case studies, there will be possible to demonstrate how much every metric is able to affect each single KC. The smallest application scale is also mentioned.

The new metrics introduced are here listed as done for the existing one at the beginning of this chapter. In order to make it more readable and understandable they have been gathered into groups that are either thematic or geometrical.

Multi-scale

The following list of metrics relates different morphological units or different representations of the same unit. They are an innovation in the field. In addition to the mentioned KCs, all the metrics of this section could be used to determine an additional KC yet to be revealed dealing with the multi-scalar aspects of the system. Possible names could be Resolution, Definition, Scalarity or Fractality but its implementation is out of the scope of this research.

- Building Volumetric Unit Ratio (BUVR)

Is the number of buildings divided by the number of volumetric units in an area. If applied to a single building it becomes one over the number of volumetric units. Is the inverse of the number of volumetric unit per building. It represents how a building volume is complex, non-reducible to a single simple shape. Volumetric units are used as an indicator of shape complexity. High values are for simple extruded buildings, low values for complex multipart buildings. Low values highlight monuments, high values modernist units, middle values XIX and XX century city.

KC: Porosity, Diversity Scale: Building

- Dissolved Building Ratio (BDSR)

Is the number of dissolved buildings divided by the number of buildings in an area. Names as Building continuity, match, agglomeration or attachment could be used to express its role. It represents how buildings are attached one to the other creating a continuous urban fabric. High values represent fabrics with completely isolated buildings, low values urban canyon like environment made of multiple attached buildings. High values for sprawled residential area, low values for city until XIX century made of block houses

KC: Porosity, Proximity Scale: Block

- Buffer Building Ratio n (BFRn) / BFR5 & BFR10

Is the number of single part clusters at a given buffer distance (5m) divided by the number of buildings in an area. The role of buffers operation and of the clusters they generate is to fill small voids in between buildings grouping together objects that are almost attached. It describe the same aspects of BDSR but at a given buffer distance. It should be read together with it and with other buffer distance as 10m. This metric can be computed incrementally for an infinite number of distance values obtaining the function of building distances in an area. This process is computationally demanding and complicated so only discrete selected values have been used. These values must be significant context-based measures. For Milan, 5m is the minimum distance between a building and another lot and 10m is the minimum distance between two facades with windows (Building Regulation).

KC: Porosity, Proximity Scale: Block

- Unique Building Ratio (UBR)

Is the number of unique buildings, or models, divided by the total number of buildings in an area. For unique building is intended a building with non-identical copies in the selected area. To be more precise we can refer to the concept of model used in the typological debate, in contrast with that of type. Two buildings of the same type can have different size and proportions while two copies of the same model are identical objects. To test the similarity of two buildings I relied on their A, P, OR_A, Hmean and UV_N, concatenating them into a string (B_Code) so that only objects with very similar values for all these attributes will be considered identical. In order to apply this idea to the existing datasets, drawn with a certain level of approximation to be expected, there's the need of simplifying the building shapes in order to ignore these accidental drawing mistakes. Based on a code coming from area, perimeter and height treated to hide/ignore drawing mistakes. High values mean very diverse environment, low values represent standardized fabric. High values for historical city centres and irregular fabric, low values for modernist linear or sprawl areas

KC: Diversity Scale: Block

B_Code formula QGIS: concat(to_string(to_int("B_A"/20)) , to_string(to_int("B_P"/20)) , to_string(to_int("MBG_A"/20)), to_string(to_int("H_mean"/3)) , to_string("UV_count"))

B_Code formula ArcMap: Int ([POLY_AREA]/20) & Int ([PERIMETER]/20) & Int ([MBG_Area]/20) & Int ([MEAN_un_vo]/3) & [COUNT_FID]

- Block to Building Ratio (BLBR)

Is the number of blocks divided by the number of buildings in an area. The logic of dividing the smaller number by the larger one is adopted as before in order to have a metric ranging from 0 to 1. High values mean huge monolithic buildings and quite small block size, low values may mean very small buildings or very large blocks.

KC: Accessibility Scale: Block

- Block to Dissolved Building Ratio (BLBDSR)

Is the number of blocks divided by the number of dissolved buildings in an area. It tells almost the same thing of the previous one.

KC: Accessibility Scale: Block

Volume and Surface

Many measures dealing with Volume and Surface have already been developed. The proposed new metrics try to simplify some of them and to answer the question of how to define the total volume (including built and void) of an area. Some of them are very similar and the most appropriate could be determined after the metrics retrofitting phase.

- Canopy Area Ratio (CAR)

Is the total sample area divided by the sum of the total area and the free vertical surfaces of buildings. It could be called also Blanket Area Ratio (BAR)as for canopy is intended an imaginary layer covering both built and void part as a tightly fitting blanket. Low values for high and fragmented buildings, high values for regular small buildings. If applied to a single building, sample are will overlap with building area.

KC: Porosity, Interface, Effectiveness Scale: Building

- Building Surface Ratio (BSR)

Is the building surface divided by the total surface including open spaces and the building previously counted. High values for high and fragmented buildings, low values for regular small buildings. It’s almost the inverse of the previous metric.

KC: Porosity, Interface Scale: Building

- Front Surface Density (FSD)

Is the building free vertical surface divided by the sample area. As a concept is simpler than the previous one because people are more familiar with density measures but has the disadvantage of not having one measure necessarily bigger than the other.

KC: Porosity, Interface Scale: Building

- Building Surface Area Ratio (BSAR)

Is the building vertical surface divided by the building ground area. Is like BSR when applied to a building. Its calculation on wider areas is an average of building measures. Is strongly dependent by perimeter and height and will be probably highly correlated with other metrics using the same attributes.

KC: Porosity, Interface Scale: Building

- Built Volume Ratio (BVR)

Is the built volume divided by the total volume of an area (volume+void). This metric easily applicable to other object with a defined outline presents some criticalities for city. The question of how to calculate the total volume of a city will be wider discussed in the next chapter for the porosity investigation. Here the maximum building height has been taken as the upper limit for our sample. High values may mean high coverage values and an even distributed building heights, low values can be due to the presence of higher buildings emerging from small one or by low coverage values. The risk for this metric is to be strongly affected by the presence of high buildings having often very low values due to the disproportion between built and void volume.

KC: Porosity Scale: Block

- Building Built Volume Ratio (BBVR)

This metric moves from BVR but tries to overcome its limit. Is the building volume divided by the building maximum volume (B_Vmax). With B_Vmax is intended the volume obtained by multiplying building area by the maximum height of volumetric units composing a building. High values for buildings with uniform height and no holes at the ground floor, low values for very articulated buildings with passages. It describes the porosity of the single building more than the global one

KC: Porosity Scale: Building

Box or Bounding Geometry

The differences between the three kinds of bounding geometries, as well as their attributes, have been explained in the previous paragraph. This set of metrics describes the shape and the orientation of buildings comparing them with their ancillary layers. Some of them will inevitably be redundant but I preferred not to discard any before the retrofitting. These metrics can be applied to any kind of shape or urban object and some of them will be used to characterize also blocks and courts. In that case, in the following sections, the explanation will be shorter, referring to the building application

- Building Box Area Ratio (BmbgAR)

Is the building area divided by the area of the OR. OR area is necessarily larger or equal to building one. OR can be used to simulate the plot when missing even if there is no clear or fix geometrical link between them. High values for rectangular like buildings, low values for court type or L,C,U,S,T types. There is a correspondence of certain ranges with particular elementary shape and typology.

KC: Porosity, Diversity Scale: Building

- Building Box Perimeter Ratio (BmbgPR)

Is the building perimeter divided by the perimeter of the OR. Differently from area, OR perimeter is not always bigger than building one. This may lead to ambiguous results. Low values for regular triangular like shape, close to 1 for rectangular like shapes or regular L shapes, higher for concave or fragmented shapes

KC: Porosity Scale: Building

- Building Box Orientation (BmbgO)

Is the orientation of OR longer side. In order to make the value ranging from 0 to 1, taking into account the way in which azimuth angles are calculated inside GIS, the below mentioned formula has been used. This solves the ambiguity of very different angles representing very similar conditions (1° and 179°). Low values for East-West orientation, high values for North-South orientation. In an area, extreme values, either high or low, represent uniformly oriented buildings, mid values a mix

KC: Permeability, Diversity Scale: Building

Formula QGIS: (90-(abs(MBG_O-90)))/90

Formula ArcMap: [90-(|MBG_ORIENT-90!)]/90

- Building Box Compactness (BmbgC)

Is the minimum side of the OR divided by the maximum side of the OR. High values for square like boxes, low values for elongated shapes. It has typological implications, low values for deep block houses or modern slabs, high values for single family independent houses or towers. Mid values for an area may mean typological mix while extreme values mono-type. It could be possibly correlated with orientation in modernist districts

KC: Porosity, Diversity Scale: Building

- Convex Building Area Ratio (BchAR)

Is the building area divided by the CH area. This measure is similar to BmbgAR but based on a different shape. High values for convex shapes, low values for concave shapes, mid values for fragmented shapes. It may have typological implications

KC: Porosity, Diversity Scale: Building

- Convex Building Perimeter Ratio (BchPR)

Is the CH perimeter divided by the building perimeter. CH perimeter is always bigger or equal to the building one. High values for convex shapes, low values for concave shapes, mid values for fragmented shapes. It may describe also how complex is the perimeter of a shape and its fractal dimension

KC: Porosity, Permeability, Diversity Scale: Building

- Convex building to box area ratio (BchmbgAR)

Is based on ratio between the CH area and the OR area. It's a sign for the typological identification of buildings. High values for rectangular like box shapes, not necessarily rectangular buildings but also C or U shapes, low values for wing made buildings as L,T,V,X types. This ratio can never be smaller than 0.5 as CH can't be smaller than half of the OR triangle. So, in order to enlarge the possible span between 0 and 1, the formula becomes [(CH_A/MBG_A) - 0.5]*2.

KC: Porosity, Diversity Scale: Building

After looking at these metrics is clear how they together can contribute to building classification, but taken independently, they have poor implication with Diversity KC. One way to overcome this limit, which will not be verified in this thesis, is to use them for the classification purpose and then investigate the presence of homogeneous or mix typologies inside an area similarly to what have been done with the UBR metric.

Centroid

To conclude the building based metrics we use its centroid as ancillary layer.

- Building Point Distance (BptD)

Is the minimum distance between building centroid and building perimeter. It expresses the concavity of a building. To be precise is more an attribute than a metric as is not put in relationship with other values. I decided to include it in this list for the capability to describe a very specific aspect that could be helpful for the definition of building typologies. Null values for buildings with centroid inside their area, high values for C or U shape buildings or concave profile like closed courts buildings. The only problem with this metric appears when dealing with F or E type or buildings with an even number of courts inside. In this case, despite the presence of voids, the centroid may fall inside the inner wing.

KC: Porosity Scale: Building

Block

- Block Built Perimeter (BLBP)

Is the built perimeter of a block divided by the total block perimeter. As introduced into the attributes paragraph this metric is inspired to Pafka and Dovey (2017) IC metric. It tells which portion of block perimeter has buildings on it. High values for blocks with prevalence of buildings aligned on the perimeter or at close distance, low values for buildings located and oriented independently from the block. High values for historical blocks, low values for modern one

KC: Permeability, Interface, Effectiveness Scale: Block

- Virtual Block Area Ratio (VBLAR)

Is the block area divided by the VBL area. VBL is necessarily bigger than BL as it fills up the inner dead end streets through the buffer operations. High value for convex like blocks, low values for blocks with many internal alleys

KC: Permeability, Interface Scale: Block

- Virtual Block Perimeter Ratio (VBLPR)

Is the VBL perimeter divided by the block perimeter. Respect to the VBLAR the order of the parameters is inverted ad VBL perimeter is always smaller that BL one. It’s an alternative to the previous one and the retrofitting will tell which is the most suitable

KC: Permeability, Interface Scale: Block

- Block Box Area Ratio (BLmbgAR)

BmbgAR applied to the block. High values for rectangular like blocks, low values for triangular, concave or irregular shapes

KC: Permeability, Interface Scale: Block

- Block Box Perimeter Ratio (BLmbgPR)

BmbgPR applied to the block. Low values for regular triangular like shape, close to 1 for rectangular like shapes or regular L shapes, higher for concave or fragmented shapes

KC: Permeability, Interface Scale: Block

- Block Box Orientation (BLmbgO)

BmbgO applied to the block. Low values for East-West orientation, high values for North-South orientation

KC: Permeability Scale: Block

- Block Box Compactness (BLmbgC)

BmngC applied to the block. High values for square like boxes, low values for elongated shapes

KC: Permeability Scale: Block

- Block Built Perimeter Mean Length (BLBPLmean)

Is the length of block built perimeter divided by the number of segments it's composed by. To make an example, a block with a perimeter of 400m, has 300m of BL_BP (buildings facing the street). This 300m can be continuous, a unique segment, or split into many different smaller portions as 50m,100m,75m,75m. The mean length of the block built perimeter in this case is 75m. High values for uninterrupted built block curtain, low values for void-volume alternate patterns

KC: Porosity, Permeability, Interface Scale: Block

- Block Built Perimeter Frequency (BLBPLR)

Is the normalized version of BLBPLmean, divided by the block length. These are both measure of the frequency of volumes along the block perimeter. High values for uninterrupted built block curtain, mid values for void-volume alternate patterns, low values for buildings located and oriented independently from the block

KC: Porosity, Permeability, Interface Scale: Block

Courts

Due to the fact the courts have been rarely studied, this section contains also very simple metrics usually applied to buildings or other objects.

- Courts density (CTD)

Is the total number of courts in an area divided by the sample area in ha. High values for historical city centre, low values for open built form.

KC: Porosity Scale: building

- Net Courts Area Ratio (CTAR)

Is the total court area divided by the total void area inside the block. The choice of using only void area internal to blocks is to enlarge the possible span of the values covering completely the 0,1 domain. High values for historical city centre, low values for open built form.

KC: Porosity Scale: Block

- Courts to Building Ratio (CTBR)

Is the number of courts divided by the number of buildings in an area. At the building scale is a very simple measure highlighting the presence of courts inside buildings, at the block or district one the values are more heterogeneous. High values for court or multiple courts type buildings, mid values for courts made by multiple block houses, low values with no courts

KC: Porosity Scale: Building

- Courts to Dissolved Building Ratio (CTBDSR)

Is the number of courts divided by the number of dissolved buildings in an area. The metric is similar to CTBR but with higher values considering that B_DS_N is always smaller or equal to B_N.

KC: Porosity Scale: Block

- Courts to Block Built Perimeter Ratio (CTBLBPR)

Is the court perimeter divided by the built perimeter of the block. Is an attempt to relate court length instead of simply area and number. Extreme value should represent historical fabric or modern one (1 and 0), mid values some hybrid block type, typical of transition zones.

KC: Porosity Scale: Block

- Courts Block Perimeter Ratio (CTBDSPR)

Is the court perimeter divided by the dissolved buildings perimeter. Is an attempt to relate court length instead of simply area and number. B_DS_P is always larger that CT_P as the second, when present, is part of the first, usually not more than the half.

KC: Porosity Scale: Block

- Court Box Area Ratio (CTmbgAR)

BmbgAR applied to the court.

KC: Porosity Scale: Court

- Convex Court Area Ratio (CTchAR)

BchAR applied to the court.

KC: Porosity Scale: Court

- Convex Court Perimeter Ratio (CTchPR)

BchPR applied to the court.

KC: Porosity Scale: Court

- Court Box Orientation (CTmbgO)

BmbgO applied to the court.

KC: Porosity, Permeability Scale: Court

The box metrics applied to the court can hardly be representative of a whole area except in very particular cases. For this reason the most relevant application may be in a study focusing particularly on courts at a scale smaller than the district.

Other

In addition to the above mentioned one, other metrics have been introduced seeking for the assessment of Permeability KC. These metrics are based on Links (Directness, Topography, All_N) Street Area (SAR) and Rasters (Tortuosity, Constrictivity) and require, up to now, the use of additional software. For this reason they have not been retrofitted together with the others but tested on 3 different areas in 3 different cities for a total of 9. Definitions, formulas, meaning and representations will be presented in the next chapter in the Permeability paragraph.

METRICS RETROFITTING

These metrics have been proposed after making some minor test on sample invented agglomeration of volumes. In order to test their behaviour on the real city and to understand if they are truly suitable to be used in urban studies, what we could call a metric retrofitting process has been performed. The goal is to reduce the number of metrics, both existing and implemented, from 60 to a more manageable quantity. The criterion is to have complete, valid, consistent and non-redundant metrics. Considering that these metrics can be used for different purposes at different scales, all of them should be retrofitted and the results compared.

The best application scale was block especially for computational reasons. In order to study the correlation among metrics a certain number of records need to be compared and, as it’s easy to understand, running the analysis on hundreds blocks is more manageable than doing it on hundreds of cities. Also district is quite manageable and represents an interesting compromise scale similar to the one of small cities. For the retrofitting process the city of Milan has been investigated, using NIL (Local Identity units) for district scale, Municipi (zones) for larger sector scale, and blocks as smaller unit.

The set of tables resuming metric correlation and descriptive statistic are in the Appendix A. The criteria used for the selection are linear correlation (better if not too high), domain (better if ranging from 0 to 1), interval (better when it covers the full domain) and data distribution (Asimmetry and Curtosi). More precisely, metrics with an interval lower than 0.6 and higher than 1 (with a domain between 0 and 1) where discarded. In case of two or more metrics describing the same aspect (BchAR and BchPR) or being extremely correlated (more than 0.8) only the best performing one has been kept. Some of the existing metrics with a domain exceeding 1 as upper limit have been maintained as already well consolidated in the literature while the newly introduced one tried to stay within this limit.

To facilitate the reading of the values a conditional formatting in excel has been done, colouring with darker tones of blue (positive) and red (negative) highly correlated values. For every investigation scale both correlation and descriptive statistic sheets are presented. Also the statistics sheets have been coloured in order to facilitate the reading. Metrics have been divided in Perfect, respecting the criteria independently from the sample, Accepted, good metrics able to properly describe morphological aspects with need of normalization to fit the diagrams or minor improvements, Discarded, valid metrics excluded for their redundancy with other better one, and Not Acceptable, metrics not able to satisfy the minimum quality requirements.

The results show how while many metrics work at the block scale, the number progressively decreases by enlarging the investigation sample. Municipi scale is so too big for allowing the emergence of differences and also to imagine an intervention able to affect the values of such a large area. District and block scale are the most appropriate with the second permitting finer grain analysis. Another interesting aspect is the number of newly introduced high quality metrics, not all used in the following KCs assessment, falling under the Perfect category at all the investigation scales (CTAR_N; BDSR; BUVR; UBR; BLBP; BSR). This result can be considered on its own a great achievement in the assessment of urban morphology with numerical values. The first research question, how to characterize urban morphology, is here answered in a satisfying way with the proposed metrics and the strategies adopted for the creation of new and the evaluation of the existing ones.

This process of filtering and selection of metrics, here performed manually, can be implemented using data mining software and techniques. The following table contains only the metrics selected for the characterization of urban morphological features (Table 4)

In the next chapter we'll see how some of these metrics can be used to assess IMM KCs. It's important to remember than they can be used also independently, for any purpose related to urban design, outside IMM framework, the systemic approach and even outside this disciplinary field when possible. The creation and validation of spatial metrics represents a contribution to the whole discipline for any possible approach.

Table 4 Selection of validated metrics divided by section. For each metric Acronym, Formula, Domain, IMM KC collocation and minimum application scale are indicated.

	Acronym	Formula	Domain	IMM KC	min scale
multi-scale	UBR	Bu/B	[0,1]	Diversity	block
	BUVR	B/Buv	[0,1]	Porosity,Diversity	building
	BDSR	Bds/B	[0,1]	Porosity,Proximity	block
	BFR10	Bbf10/B	[0,1]	Porosity,Proximity	block
	BTBL	1-(BL/B)	[0,1]	Accessibility	block
	BDSTBL	1-(BL/Bds)	[0,1]	Accessibility	block
V - S	BBVR	Bv/Bvmax	[0,1]	Porosity	building
	BSR	(Bs+Ba)/(Bs+La)	[0,1]	Porosity,Interface	building
box	BmbgAR	Ba/Bmbga	[0,1]	Porosity, Diversity	building
	BmbgO	(90-(abs(MBG_O-90)))/90	[0,1]	Permeability,Diversity	building
	BmbgC	Bmbgdmin/Bmbgdmax	[0,1]	Porosity,Diversity	building
centroid	Bptdist	Bptdist/B	[0, infinito]	Porosity	building
block	BLBP	BLbp/BLp	[0,1]	Permeability, Interface,Effectiveness	block
	VBLPR	VBLp/BLp	[0,1]	Permeability,Interface	block
	BLmbgAR	Bla/BlmbgA	[0;1]	Permeability, Interface	block
	BLmbgO	(90-(abs(MBG_O-90)))/90	[0;1]	Permeability	block
	BLmbgC	Blmbgdmin/Blmbgdmax	[0;1]	Permeability	block
court	CtD	CT/A	[0;infinito]	Porosity	building
	CTAR	CTa/(Bla-Ba)	[0;1]	Porosity	block
	CTBdsP	CTp/BLp	[0;infinito]	Porosity	block
	CTBR	CT/B	[0;infinito]	Porosity	building
	CTmbgAR	CTa/CTmbga	[0;1]	Porosity	court
existing	BCR_G	Ba/A	[0,1]	Porosity, Permeability	block
	FAR_N	Bfa/Bla	[0;infinito]	Porosity	block
	BD	B/A	[0;infinito]	Porosity, Accessibility	block
	BLD	BL/A	[0;infinito]	Permeability, Interface	district
	S/V	(Bs+2Ba)/Bv	[0;1]	Porosity	building
	Cdcm	Ba/Circlea	[0;1]	Porosity	building
	Apass	A6/Ba	[0;1]	Porosity, Effectiveness	building
	AwaP	BLp*(Bla/A)	[0;infinito]	Permeability, Interface	district

5.3.3 Maps

Coherently with the approach followed during the map survey paragraph, some representation suggestions will be presented here. Except for one case, most of the following representation doesn't represent a significant innovation considering their production rules, but they can still be a useful hint for further implementations. Moreover, the new metrics can feed existing representation techniques as FCC, gradient map or simple graduated or classified symbologies.

Equivalent Grid

The equivalent grid is a morphological abstraction of a real urban fabric. It's based on average values of link length and street width or, alternatively, average number of blocks and their size in an area.it literally reduce every possible morphology to a square grid. This is an extremely powerful tool to visually compare very heterogeneous portion of urban fabric as shown in the following example (Figure 47).

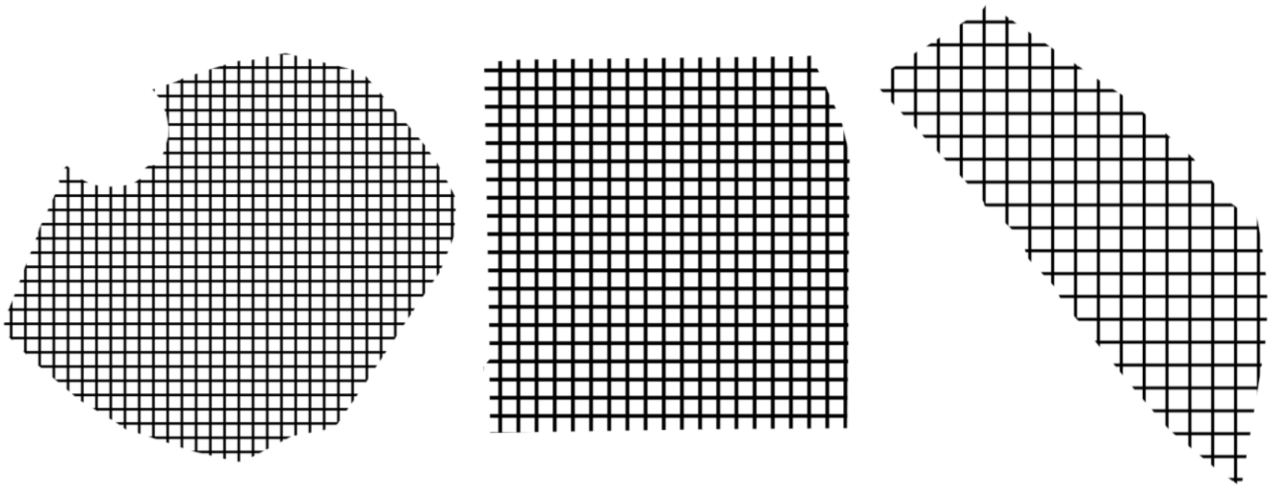


Figure 47 Equivalent street grid for 3 areas in Milan. City centre (left), Città Studi (middle), Porto di Mare (right). This representation gives an intuitive understanding of the average block size

BL_BP

The BL_BP representation, showed in the previous paragraph, is not a new mapping method as the innovative part is in the construction of the layer itself, then simply represented as a line layer inside GIS software. Anyway it deserves to be mentioned for its synthetic power to represent the relationship between buildings and streets and the presence and continuity of urban canyons (Figure 48).

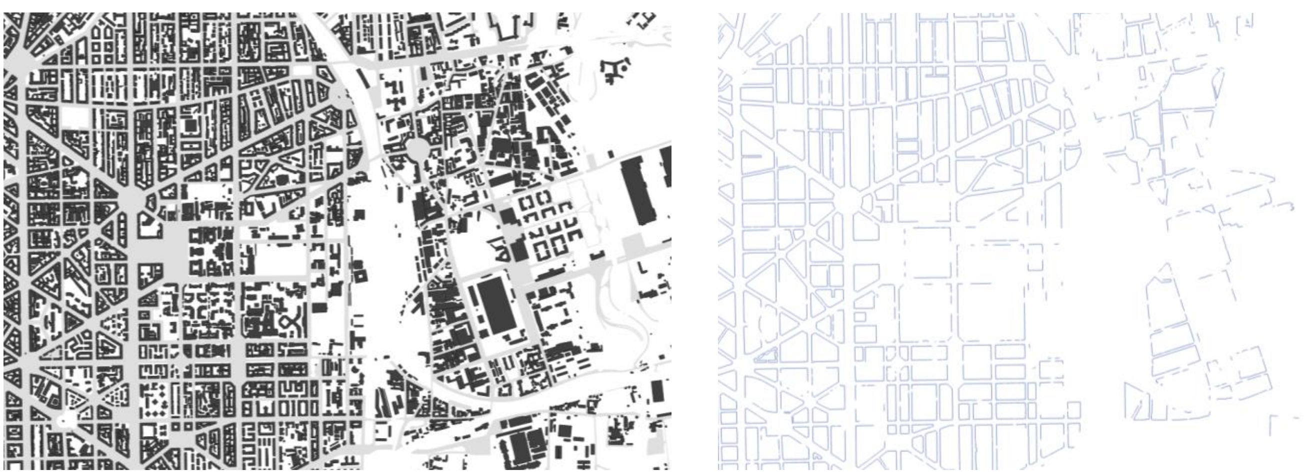


Figure 48 BL_BP representation. Buildings and streets (left) BL_BP map (right)

Binary images

A binary image is a digital image that has only two possible values for each pixel. Typically, the two colours used for a binary image are black and white. It's a simple matrix made of 0 and 1 that, as raster, discretizes a vector layer. It's used for image processing and some application will be showed in the permeability section. Even if for most of people dealing with programming or coding this is absolutely normal, for people with an architectural background, looking at a city as a collection of 0 and 1 is not so common. The image below represents the Dome of Milan as a binary image. Nothing new has been invented but I tried to offer to the readers a new perspective (Figure 49).

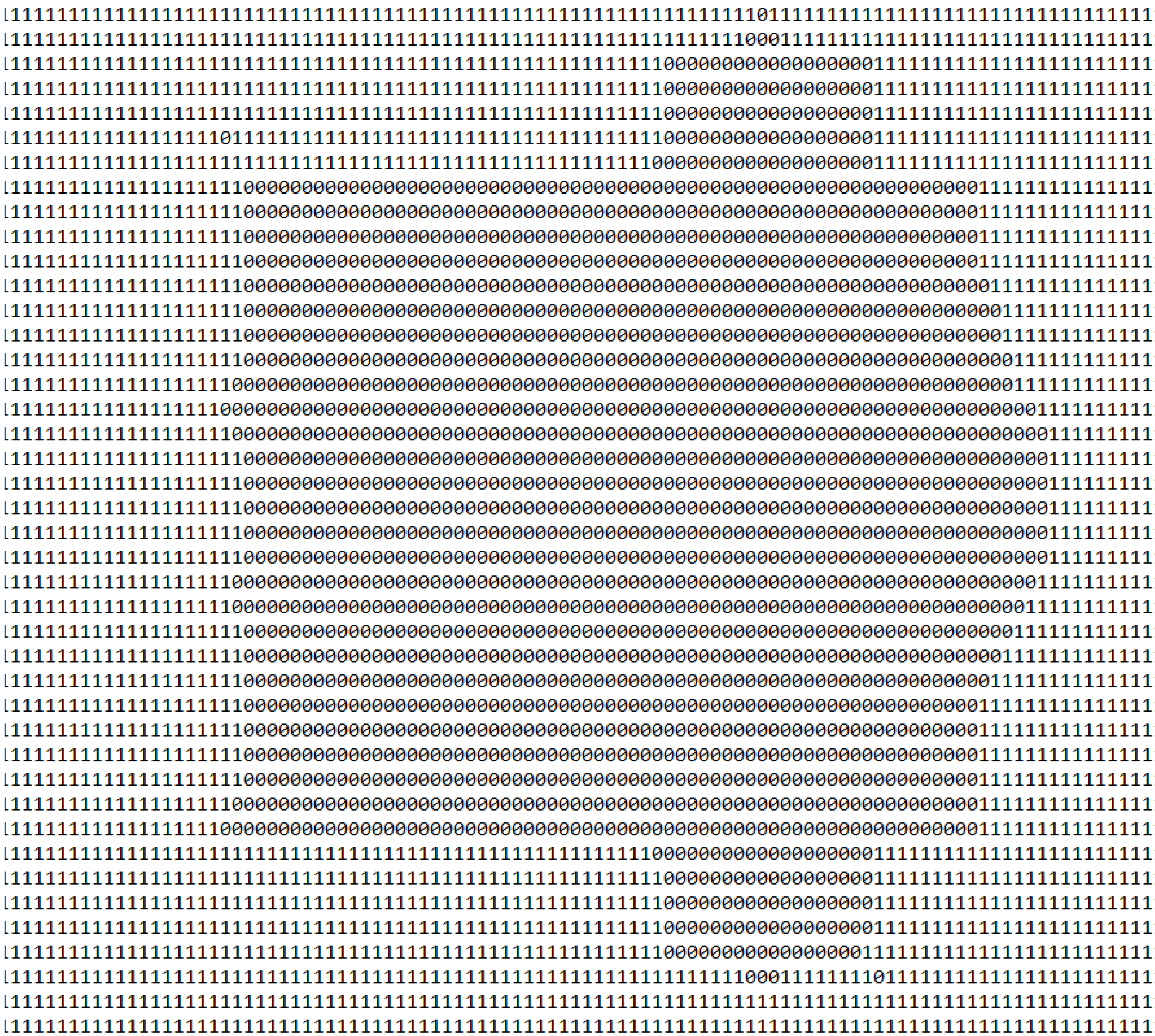


Figure 49 Binary image representing the Milan Cathedral. 0 are built-up spaces while 1 void spaces.

Thematic theory map: Sitte's enclosure

Many authors in urban studies defined some concepts with the words contained in their books. Sitte is surely one of the most popular with his work focusing mainly on squares. The topic of enclosure emerge as a key factor for the definition of a square and its positive perception (Sitte 1889). Trying to interpret in a geometric meaning its word, there is a relationship between building façades height and the depth of the void space they face. Visually, is like if we rotate each façade by 90° along its base side towards the void space. Inside GIS software, this operation corresponds to a buffer according to building height. Figure 50 shows darker areas as more enclosed as many buildings overlook them, and white areas as not framed or shaped by any surrounding volume with the required height. What has been roughly done for this concept, can be replicated for almost all the existing literature.

Figure 50 Sitte's enclosure map. Buffer equal to building height with 25% of transparency

Other

Few other maps have been used for the KC assessment and they will be presented contextually in order to let them the appropriate space. The Directness map is based on a graduated link representation increasing their width according to a specific attribute. Tortuosity map is a gradient map obtained through a simulation of particles movement processing a binary image.

5.3.4 Tools and algorithms

The research has been carried out using QGIS as main software. Among available GIS it has been selected because considered the most advanced and widely used open source alternative to property software. A set of algorithms has been developed through the graphical modeller unit to cover all the previously described process from components to KCs, passing from input layers, morphological units, attributes and metrics. In Appendix B it's possible to find all the codes and formula used, here I briefly resume the main characteristic of every model and its purpose.

Volume_Filter: it takes as input UV and filters them according to area and height attributes in order to remove from the analysis all the independent minor volumes not attached to any building. In addition it computes V and FA attribute. The filtering criteria can be manually decided by the final user and may vary from context to context. Here 25mq for the area and 2m for the height has been used. The output maintain the input attribute names

UV2B: it takes as input UV_Filtered (works also with non-filtered UV) and returns buildings as main output plus the different ancillary layers used for the implementation of buildings attribute set (MBGs, Apass). It renames and reorganizes the fields in order to have simpler names for the following steps

Courts: it takes buildings (or UV) as input and returns enriched attributes courts as output. A plane containing all buildings is cut with a geometrical difference operation leaving only closed courts. After that, ancillary layers are used to add attributes to the morphological unit just obtained

Blocks: it takes as input the Street Area (SA) layer and Buildings. Blocks are obtained, as did for courts, as the negative of street area. An additional condition to respect is to contain at least one building. This has been made to exclude from the analysis marginal areas of huge dimension hosting only natural landscape and so no more urban. As done for Buildings and Courts, also block set of attributes is enriched through the creation of ancillary layers, exportable to be visualized.

Surface: this is the only operation that up to now needs to be performed inside ArcMap instead of QGIS. It's also the most demanding operation from a computational point of view. Running the algorithm for the whole city of Milan took almost one week. This is due to the huge amount of input geometries that exponentially increase after the first two steps of the process. The most critical step combines more than 800'000 lines with slightly less than 3'000'000 points. Fortunately, the process takes only few minutes when applied to a neighbourhood scale. The purpose of this process is to compute free vertical surfaces of buildings. This data, apparently simple, is not usually available and require a certain creativity to be extracted in a GIS environment. The same operation is extremely easier inside a 3d modelling software as it's sufficient to merge together or perform a solid/boolean union between buildings Brep and then deconstruct the results considering only faces.

Attributes: it takes as input the output of all the previous algorithms plus the limit area we want to analyse. It's structured in a way that permits to manage a layer with multiple instances at the same time, as for example all the NIL of Milan. Blocks, because of their double nature of morphological and landing unit, can be used as input both for the block and for the limit box. Attributes from morphological units are joined and summarized according to their position into the geometry that intersects them. Other ancillary layers are generated here to create additional attributes and may be exported.

Metrics: It simply takes the attribute output and computes all the required metrics by combining the different attributes. The input and output geometry is the same, but metrics are added to attributes.

Metrics (buildings): it's a simplification of Area_Metrics algorithm. It doesn't require the attribute step as no summarization is needed because buildings are the smallest possible unit of analysis. In addition, not all the metrics can be computed at the building scale, so only part of them is maintained.

The following Data Flow Diagram resumes the whole process from a systemic perspective. Computer science language and graphical convention have been chosen for their clarity, transmissibility and possibility to be translated into an operative tool (Figure 51). As indicated in the legenda on the top right corner, white circles are the algorithms implemented for this research. Their inner structure, together with additional visual scripting achievements, can be explored in Appendix B.

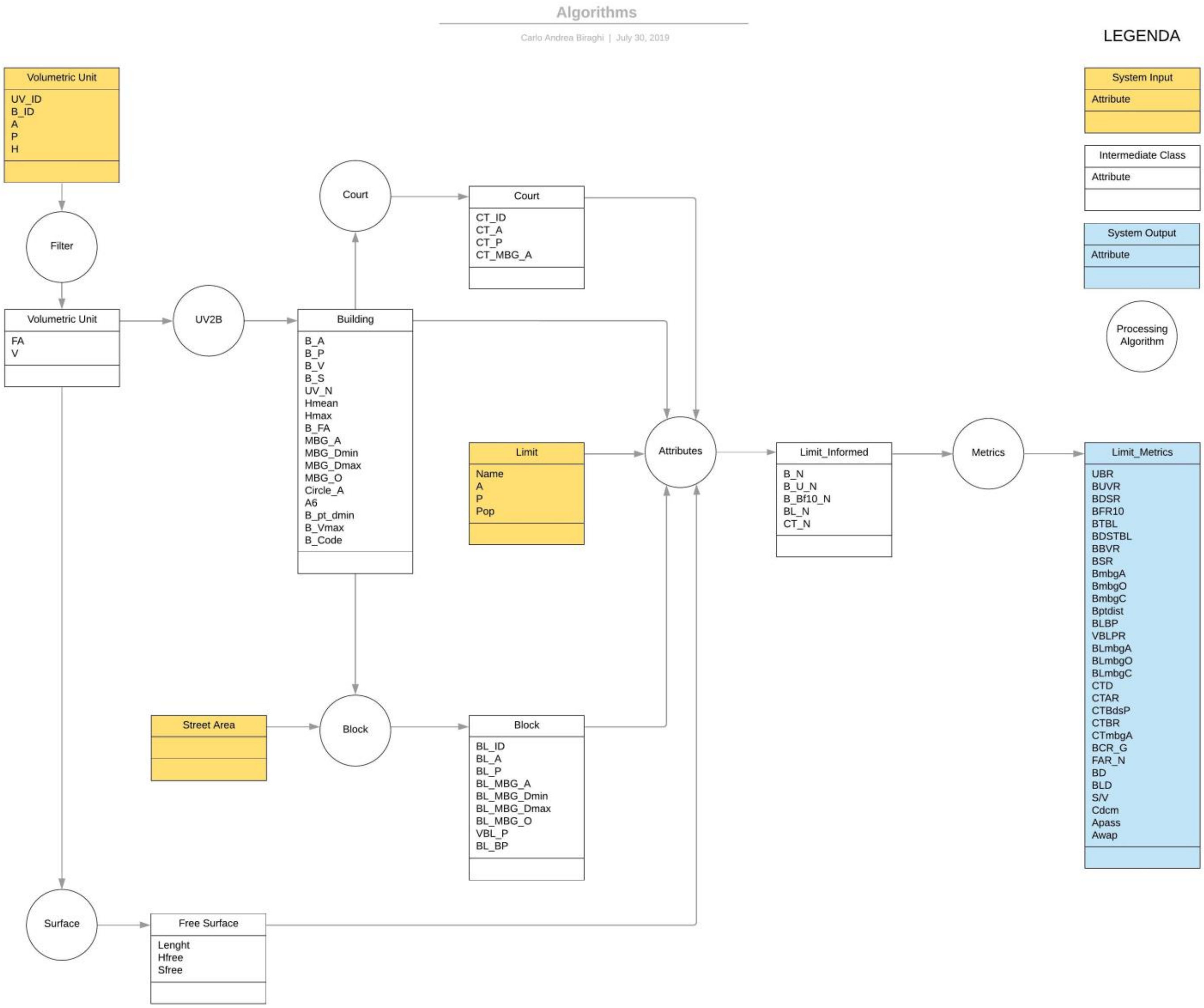


Figure 51 UML data flow diagram showing the whole reconceptualization process from input layers to spatial metrics. Circles are the above mentioned algorithms, orange classes are the input required by the user and blue one is the final output

6 Urban Compactness

As previously explained in chapter 3, it's not possible to directly address Compactness Determinant for its level of complexity. Its definition is postponed to subchapter 6.3 after having defined calculation and interpretation methods for Porosity and Permeability KCs. The chapter starts explaining why Porosity can be considered a system property (KC) and not simply an urban design feature reaffirming its importance for morphological issues. It follows a literature review showing the ambiguity of current porosity definitions and a part exploring its nuances related to the physical aspect and consistency of buildings. All the metrics collected in chapter 5 (Table 4) related to Porosity KC are organized in the larger possible radar diagram showing the full porosity pattern (19 metrics). Given the complexity of this representation, a selection of six metrics is taken and tested on heterogeneous case studies. The results already published by the author (Tadi et al.,2017) are presented with additional conclusions as results of the revision of that paper content.

The same structure and approach is repeated for Permeability KC with the only difference that new metrics, previously not presented, are here introduced. Through a set of six metrics, coming both from urban studies and hydraulics, a diagram able to represent all the different aspects of Permeability, emerging from the literature, is produced and tested on the same case studies used for porosity. This part, taken by Biraghi et al. (2019), is integrated by the results coming from chapter 5 (table 4) in order to draw the same kind of extended radar diagram done for porosity (13 metrics).

The other face of the coin is, the performance one, need to be investigated and the first approach is a literature review on indicators in general discussing when they became popular, the principles for a good indicator, the debate between global/local and the issues raised by the multiplicity of heterogeneous actors asked to handle them. Moving to environmental sustainability indicators, the results from existing literature are presented. The concepts of density and compactness are here joined because of the ambiguity they are currently used with in urban studies. Their advantages and disadvantages are explained together with the possible reasons for these contradicting results. Then, a deeper attention is given to existing studies correlating environmental aspects of urban microclimate (surface temperature, energy potential, ventilation, pollution) to one or more spatial metric. IMM performance indicators are introduced as a tool able to overcome the most critical aspects emerging from the literature as the global/local debate, the obsession to find a finite number of best possible indicators. UN Sustainable Development Goals (SDGs) are taken as a larger framework and the possibility to use IMM indicators as an operative tool for the achievement of their targets is explained. The common ground for this application is, once again, system theory.

Finally, Compactness as system Determinant is defined in a theoretical as the integration of the above mentioned KCs plus an additional one (Proximity), not included in the research. This perspective refuses any possible simplification coherently both with the increased modelling complexity achieved and with the concept of optimization. A critical point of view on optimization is offered highlighting the difference from a maximization and the contradictory position between compactness and life itself. The importance of a multi-scale approach is stressed as well as the need to iteratively perform the presented process on a number of case studies to improve our understanding of Compactness. The research can be seen as a learning process that traced the way for solutions in a short/medium time. Investigation paragraph represent a first step in this direction and consists in an explanation of Appendix C, containing a diagnostic of all Milano 88 NIL measuring both their structural arrangement and environmental performances.

6.1 Porosity Key Category

The term porosity is used in multiple fields including pharmaceutics, ceramics, metallurgy, materials, manufacturing, hydrology, earth sciences, soil mechanics and engineering. This makes clear that this property is not a simple urban design quality but a true systemic property.

Porosity in IMM is a fundamental morphological characteristic of urban systems, integration of two basic components of urban space: Volumes and Voids. Porosity plays a key role in the relationship between urban morphology and environmental-energy performances. 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. 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 (Tadi et al. 2017).

6.1.1 Porosity Definition

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% (Encyclopaedia Britannica).

Porosity as a concept in urban studies can be traced to an essay on the slums of Naples in 1924 by Benjamin and Lacis (1978). Much more than simply street permeability, porosity is the social and spatial interpenetration of public and private spaces – socially and spatially (Pafka and Dovey 2017). Despite some authors tend to hybrid porosity with concepts related to activities and social life, it remains a purely structural property. Volume and Void are integrated in a sponge like structure (Vahabzadeh Manesh 2012) and constitute the rigid solid skeleton of the city (Adolphe, 2001). The dialogue between urban void and urban volume is the key element of the urban morphology and its sustainability. There should be a balance between these two elements in the urban system, where each one completes the other one. In the oversized modernist housing projects there is no balanced relationship between the empty spaces and the solid masses because they are not designed as two equivalent forms, one full and the other empty (Vahabzadeh Manesh 2012) .

Urban Porosity is defined variously in the existing literature, and in many cases, these definitions contradict each other (Guaralda et al. 2011). 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 (Kotsopoulos 2007). 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 (Tadi et al. 2017).

6.1.2 Understanding Porosity

Before looking at the selected metrics is better to further investigate the topic of the relationship between built and void parts. 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.

In order to literally apply the above mentioned porosity definition, it’s necessary to define what can be considered the total volume (Volume + Void) of an urban sample. There are some possible alternative and each of them produces a different value for the same ratio.

Figure 52 Urban total volume definition. Explanation of different methods to define the upper boundary of a sample area in order to determine its volume. Urban Canopy layer (1st image from top), building weighted- average height (2nd image), building maximum height (3rd image), building’s UV maximum height as for BBVR metric calculation (4th image)

Similar to studying the Urban Heat Island Effect (UHI), here, the peripheries of the study areas could be identified according to the local Urban Canopy Layer which is the warm layer of air near the ground level (Figure 52, 1). This blanket like layer is not so easy to be obtained despite its visual clarity. Trying to simplify it, maintaining nearly the same quantities, a simple extrusion according to weighted average building height has been tested (Figure 52, 2), but the resulting value is equal to BCR_G metric and so redundant. Everyone agrees that there's no upper limit than the highest building in the area (Figure 52, 3), but extruding the sample area till that height will produce unbalanced values for volumes (too low) ad voids (to high). The final and decisive attempt is a mix of 1 and 3. It takes the maximum building height but extruding only the corresponding building area, leaving void spaces at the ground level (Figure 52, 4). This calculation method, at the basis of BBVR metric, has the advantage of describing building porosity in plan and section, and the limit of neglecting the open spaces and streets impact. In order to have a better result, void could be extruded by a fix amount (i.e. 4-5m, the height of a ground floor) or, even better, up to the closest building front

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 Figure 53 two alternative building arrangements having the same volume but different footprint are shown.

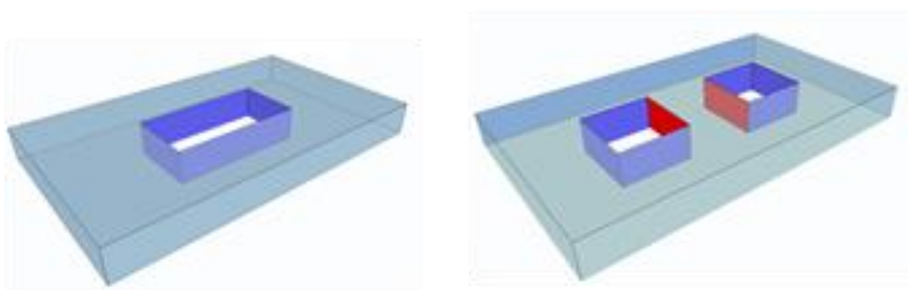


Figure 53 Volume / Surface comparison. Example of two buildings with the same volume but different surface values (Tadi et al., 2017)

In order to include the shape of the buildings in studying porosity the free vertical surface of the buildings has been studied here. 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. The following scheme shows three buildings attached in order to clarify which surfaces need to be counted. Attached buildings must be considered as a solid mass ignoring the contact surfaces between them (Figure 54).

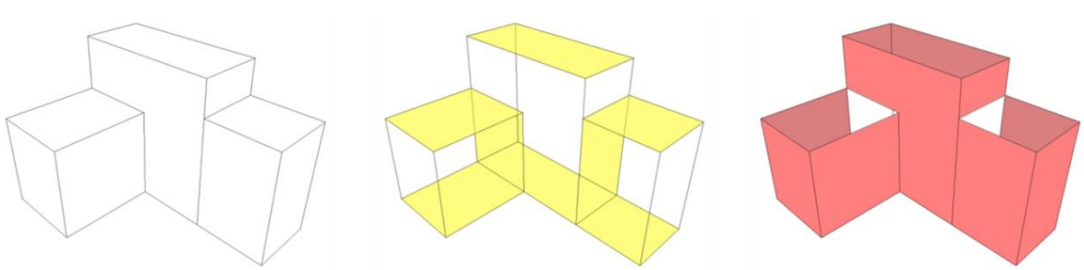


Figure 54 Free vertical surfaces identification. Building volumes in white (left), discarded surfaces in yellow (middle), free vertical surfaces (right)

Passing from masses to buildings and units, we meet the density concept. 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 (Tunney et al. 2011). Density, solely, does not illustrate the urban context characteristics sufficiently (Frankhauser 2004). Morphologically speaking, far different contexts could share the same value of urban density so, we need to select some metrics that could be considered the morphological interpretations of urban density. One difference between the above example, characterized by the same dwelling unit and volume density, is the number of buildings (Figure 55). Even more extreme cases can be found in the real world (Figure 56).

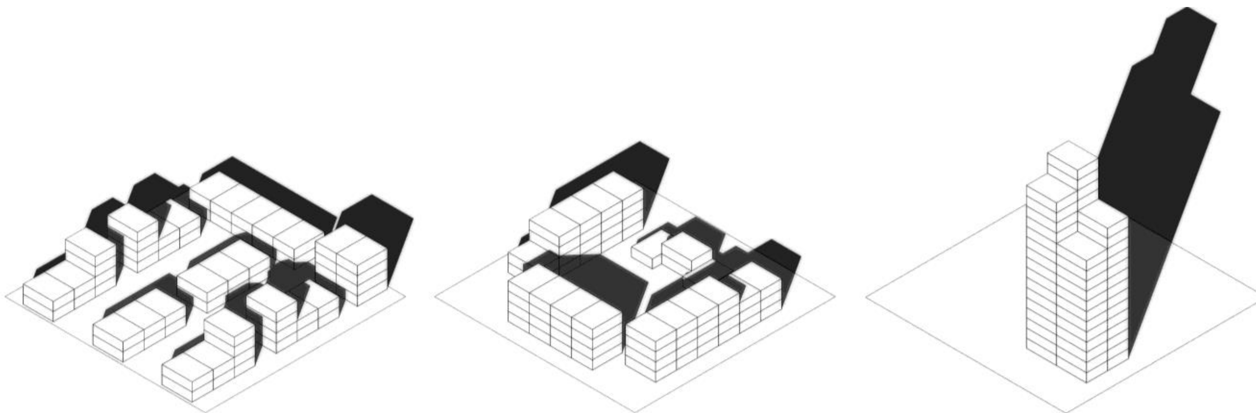


Figure 55 Same density in terms of volume and dwelling units distributed in low (left), medium (middle) and high buildings (right) (Tadi et al., 2017)

Figure 56 City comparison. West Bay, Doha presents high rise buildings separated by huge shapeless empty spaces (left), in Venice, myriad of smaller buildings of different typologies create a thick web of small regular-like private and public voids (Tadi et al., 2017)

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.

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, buildings' position and their mutual distance should also be considered. Similarly to the patch approach, we can group together buildings below a certain mutual distance, as done by the BFRn metrics (Figure 57).

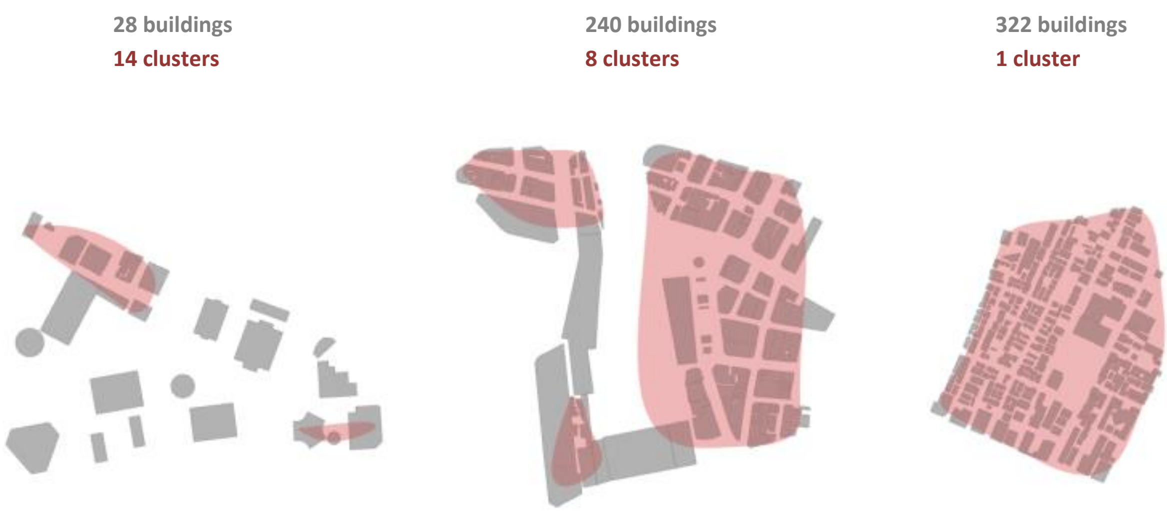


Figure 57 Buildings and Clusters, comparison of three areas in Tokyo, Japan. Buildings (grey) are grouped in clusters (red) according to their mutual distance. Buildings with no red halo around belong to their own single element cluster. According to the drawing method clusters with less than 3 elements are not visualised.

6.1.3 Metrics and Diagrams

In the previous chapter all the valid metrics have been listed. Among them only some can be assumed as able to affect the porosity of an area in a significant manner. KCs are the result of components integration and this integration, in practical terms, moves from metrics. A set of metrics describe a KC both from the quantitative and the qualitative side. The full list of porosity metrics is the following:

BCR_G; FAR_N; BBVR; BSR; B_AMBG; B_CMBG; B/UV; B_DS/B; BDF10; Apass; S/V; Cdcm; Concavity; CTTB; CTAR_N; CTBLPR; CT_AMBG; CTD; BD

Inside this list we can distinguish metrics related to Building Volume, Surface, Area, Distribution and Typology, and Courts presence and size. There are existing and new metrics working together to give the more exhaustive possible picture of this emergence. IMM representation for KC provide radar diagram composed by an open and flexible number of metrics. The larger possible consistent diagram, according to this research, is the following one (Figure 58), presenting Porosity pattern for three of the area already investigated by Tadi et al. (2017):

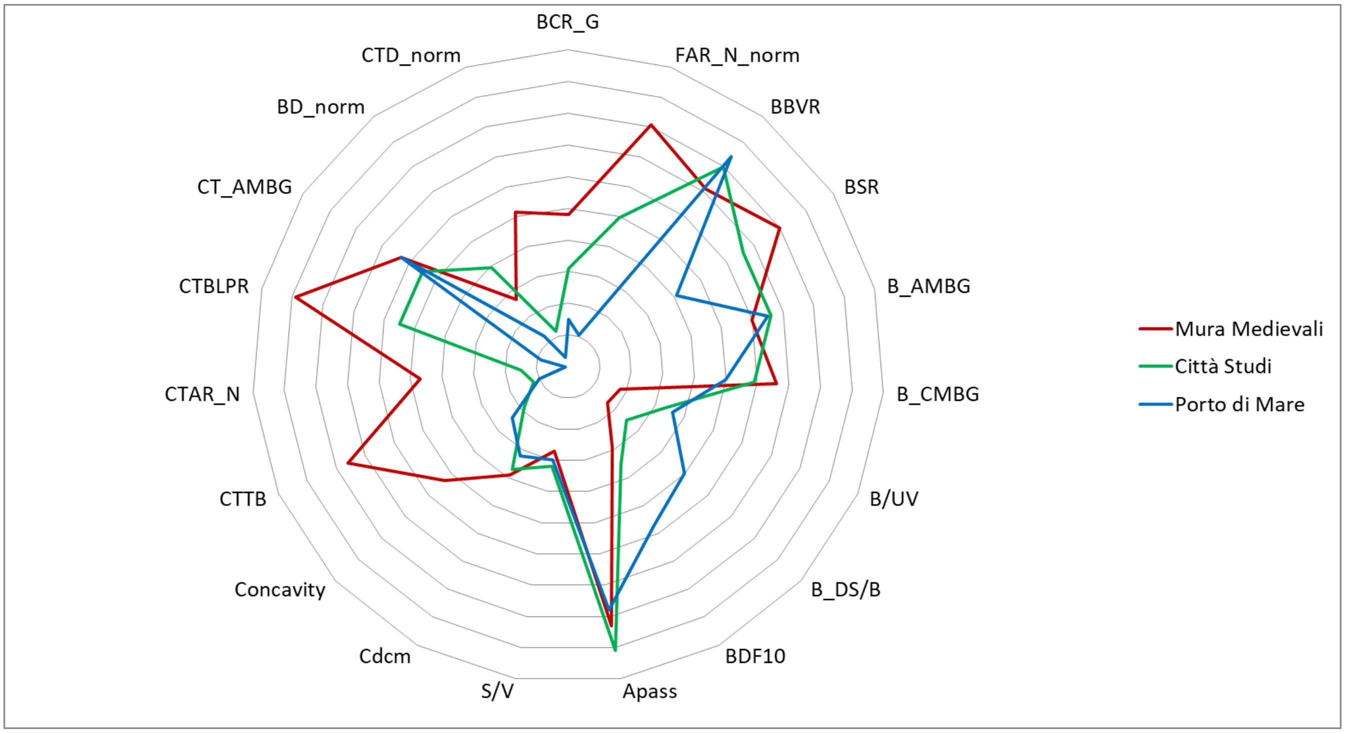


Figure 58 Porosity pattern radar diagram including all related metrics. Metrics are ordered by the categories used in Table 4, going clockwise from the top (BCR_G) we meet existing one from urban studies, volume and surfaces, box, multi-scale, geometry, centroid, courts and density. The suffix "_norm" stands for normalized and indicates those values that have been divided by a constant in order to fit the radar diagram.

The result is particularly accurate but hard to be easily interpreted in a glance. What is immediately visible is how the consistent role played by courts in the city centre decreases moving to more peripheral areas (CTTB, CTAR_N, CTBLPR). The same trend can be noticed is classical urban studies metrics mainly assessing quantitative aspects as BCR_G, FAR_N_norm, BSR and BD_norm. Geometry measures present similar values for all the three areas (Apass, S/V, Cdcm).

This diagram is unweighted but can be modified by using a NURBS curve instead of a polyline and assigning different weights to some metric that is believed are more representative than others. To orient this selection we can move from previous similar works. Yoshida & Omae (2005), without specifying the word Porosity, rely on 6 metrics related to building Area, Height, Surface, Volume and Density to characterize morphological properties. Clifton et al. (2008) also uses building heights as a measure of human scale and spacing to describe enclosure. Also our previous work (Tadi et al. 2017) considered only 6 metrics adding distance to Yoshida & Omae (2005) values. It's important to notice than the relevance of a metric can be dependent by the context where is applied. For example, if no courts are present in a whole city, all those metric will inevitably become redundant and useless, whilst, in cities like Milan, Wien or Copenhagen, they can really help in distinguishing one area from another.

In the next session the results of the work performed by the author in Tadi et al. (2017) is presented. The metrics used for determining porosity are comprised in the one presented between survey and implementation paragraphs in chapter 5. Void Volume Ratio (VVR) has been calculated as the inverse of BVR using the second image from Figure 50, using building weighted average height. BFRn has been calculated at distance 20m obtaining BFR20.

In Appendix C and D a different set of six metrics will be used to draw the Porosity diagrams. This to say that the most important aspect is not identifying the best possible metrics, but the idea of representing them on a diagram that allows to transform numerical values into shape patterns that facilitate morphological comparisons and understandings. That justifies the use of different metrics provided that they are picked from the one that has been already validated and assigned to the KC under investigation. The same will be done for Permeability to overcome some calculation problem on large samples with the metrics presented in the following subchapter.

6.1.4 Case Studies

To investigate the ability of the proposed metrics to characterize the Porosity of morphologically different urban areas, we consider nine different case studies (Figure 57). The first row illustrates the three districts chosen for the city of Milano, i.e., Mura Medievali (MM), Città Studi (CS), and Porto di Mare (PM). The second row reports the three districts chosen for the city of Bergamo, i.e., Città Alta (CA), Valtesse (VA) and Sentierone (SE). Finally, the third row, displays the three districts chosen for the city of Brescia, i.e., Centro Storico (CS), Stazione (ST), and Cascine Beretta (CB). These districts are selected because they have developed in three diverse historical phases of city growth and therefore allow assessing the proposed procedure to identify key features associated with specific historical periods. The test cases can be grouped chronologically as follows.

The districts Milano MM, Bergamo CA and Brescia CS correspond to the most ancient part of three cities which were typically delimited by walls during the medieval times and they constitute now the core of the city. The shape of these districts is irregular, built-up part represent a uniform mass following the block perimeter where single buildings' shape is not recognizable. A mix of different typologies constitutes a compact urban fabric. Larger buildings are usually civil or religious places determining the shape of the relative square. Voids have a clear and regular shape.

The districts of Milano CS, Bergamo SE and Brescia ST are modern urban areas which were developed during the cities' expansion in the 20th Century. Both voids and buildings become larger and more regular as they are the result of a planning activity.

The areas of Milano PM, Bergamo VA and Brescia CB are the most recent ones among the investigated case studies and are located on the border of the three cities. These are mainly characterised huge shapeless void spaces, higher distances and a larger dimension span between the smallest and the biggest buildings.

The spatial limitation 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 centres, 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 shape and dimension, ranging from 50 to 300ha, but this is not a problem as all measures are not scale sensitive. For our case studies, all located in Lombardy region (Italy), we rely on the DBT (Topographic Database) of Lombardy, using the layer Volumetric Unit (A020101). (http://www.geoportale.regione.lombardia.it/).

The same case studies will be used for the Permeability investigation, for this reason, their plan is reported only once in the following page (Figure 59). The maps are followed by the diagrams (Figure 60) and the table (Table 5) collecting the graphical and numerical results of the analysis. This section is concluded with a discussion on the morphological evidences emerging from the diagrams.

Figure 59 Black and white map of selected case studies. Starting from the top left and proceeding horizontally: MI Mura Medievali, MI Città Studi, MI Porto di Mare; BG Città Alta, BG Sentierone, BG Valtesse; BS Centro Storico, BS Stazione, BS Cascine Beretta

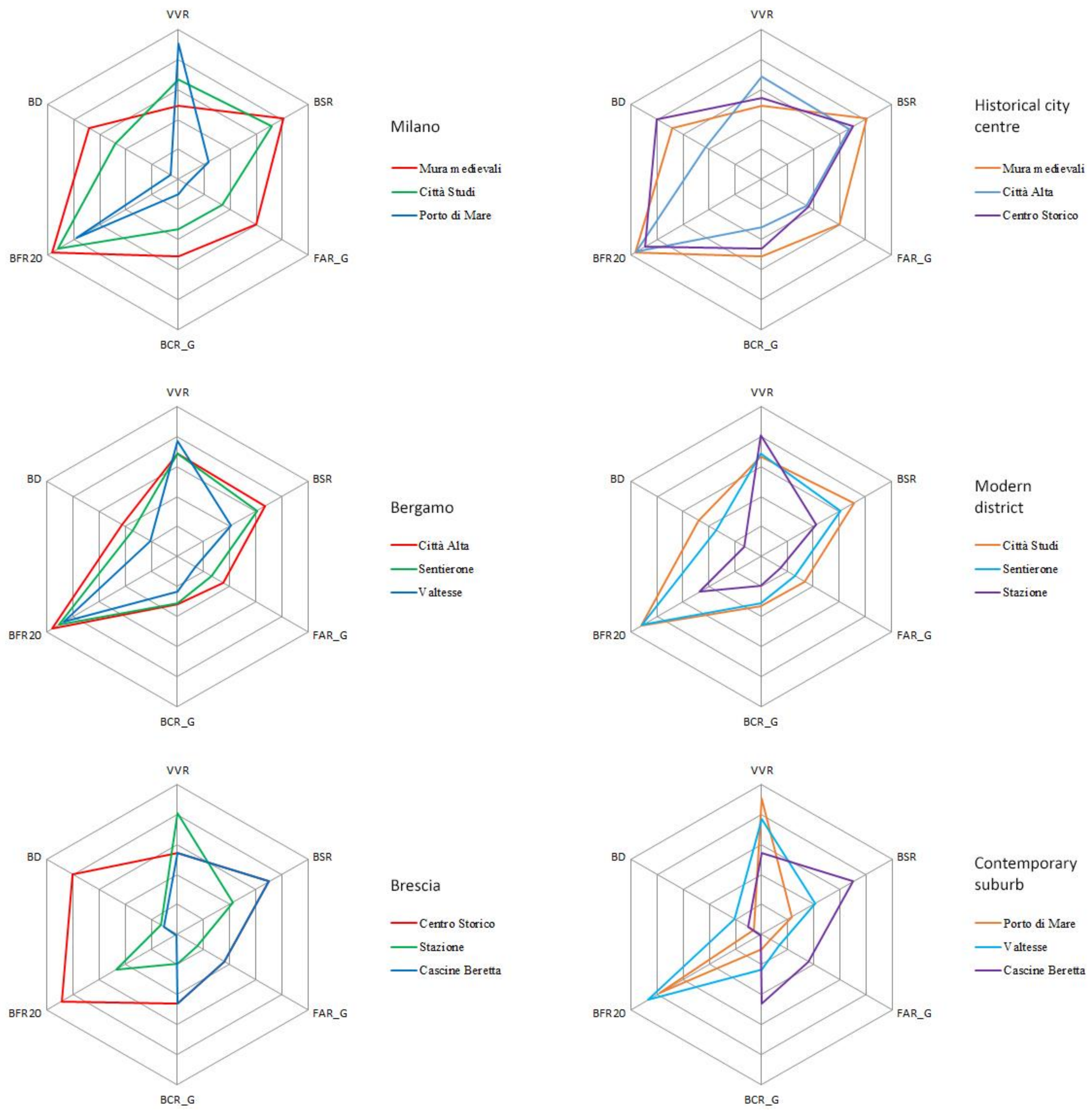


Figure 60 Results of Porosity investigation by means of radar diagrams grouped in case studies (left) from Milano (top), Bergamo (middle) and Brescia (bottom), and grouped by historical period of development (right) historical city centre (top), modern district (middle) and contemporary suburbs (bottom)

Table 5 Results of Porosity investigation on the nine different case studies

City	District	Area (ha)	VVR	BSR	FAR	BCR	BFR20	BD
MI	Mura Medievali	269	0.48	0.81	0.60	0.51	0.97	0.68
MI	Città Studi	275	0.68	0.72	0.35	0.33	0.92	0.48
MI	Porto di Mare	169	0.92	0.23	0.08	0.10	0.78	0.06
BG	Città Alta	45	0.69	0.67	0.35	0.32	0.96	0.43
BG	Sentierone	68	0.67	0.61	0.27	0.31	0.91	0.35
BG	Valtesse	84	0.76	041	0.17	0.23	0.87	0.21
BS	Centro Storico	177	0.56	0.70	0.35	0.46	0.89	0.80
BS	Stazione	180	0.81	0.42	0.17	0.19	0.47	0.13
BS	Cascine Beretta	177	0.53	0.70	0.39	0.46	0.01	0.10

Some of the extremes expressed in the diagrams bear only theoretical meanings. For example, the value of BCR_G can hardly exceed 75% in practice. Hence there are mainly two ways to read the diagrams: first is to morphologically interpret different fabrics within a certain city. For example Milano MM and CS clearly represent one city in two different historical periods. CS has more void, due to hygienically policies, and all other values decrease in order to achieve it. FAR_G follows coverage because building height is almost constant, BSR loss from regularization in building shapes is mitigated by an emptying of courts. Larger buildings for a lower BCR_G make Building Density value reduce sensibly. The great distance that Leonardo Campus holds with the other buildings probably drives BFR20 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 Milano PM is almost divided in two parts, large empty areas with few volumes 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 BFR20 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 BD, Brescia CB provides as much BCR_G 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 Brescia ST area is not as straightforward as the other cases, but the existence of larger building units - in comparison with Brescia CS - is clearly recognizable from its lower BD value.

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 20th century development, and some suburbs 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 can be explained looking at the construction sites conformation and properties and to the overall city size. Bergamo lower values for BCR_G and FAR_G are due to the presence of a large steep natural area that can't be built. The same can be said for 20th century expansions as Milano CS and Bergamo SE, almost perfectly overlapping, while Brescia ST is something in between these examples and more sprawled/modern one collected in boundary diagram. The case study areas have been selected according to the previously mentioned criteria and picked by the authors looking at city maps. For this reason, anomalies in the correspondences between diagrams expected to be similar can be explained as a partially wrong reading by the authors. Even if sometimes maps and metrics seem to explain the bleeding obvious (Pafka and Dovey, 2017), this is the proof that even something apparently similar can hide structural differences that emerge with the comparison of these two means of representation. 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 metrics used here for evaluating the urban porosity are independent from but related to each other. 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.

6.1.5 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 neighbourhoods 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 (Lee 2017). To investigate Porosity means to do more than just mapping black-and-white spots indicating buildings and open space. 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.

6.2 Permeability Key Category

Permeability, is the capacity of a porous material for transmitting a fluid; it is expressed as the velocity with which a fluid of specified viscosity, under the influence of a given pressure, passes through a sample having a certain cross section and thickness. Permeability is largely dependent on the size and shape of the pores (Encyclopaedia Britannica).

Permeability is a concept that finds a place for itself also in the field of urban design as in many areas such as physics, chemistry, geography and medicine. This makes Permeability not only a Space Determiner (Yavuz and Kuloglu 2017) but also a property able to characterize a system.

Permeability in IMM is a fundamental morphological characteristic of urban systems, integration of two basic components of urban space: Voids and Volumes. It can be seen as complementary to Porosity and characterized by a more dynamic nature. It controls the flows of people, vehicles and materials, including wind for example. Various researches have revealed that permeability provides a positive contribution to the use of space and that this kind of space affects the users positively (Yavuz & Kuloglu, 2017). Optimizing urban permeability is a major design problem faced by city planners and architects (Yuan & Ng, 2012).

6.2.1 Permeability Definition

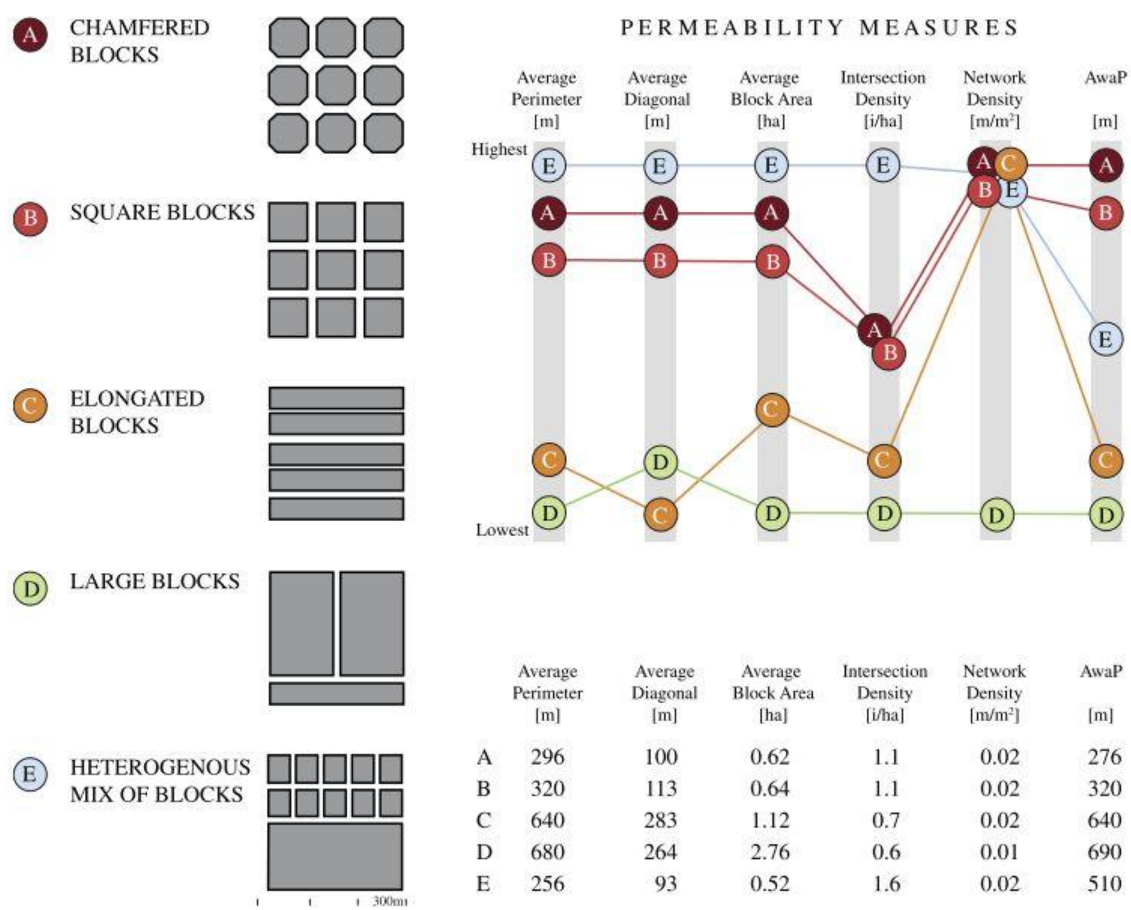
The concept of urban Permeability is still debated in literature and alternative definitions have been provided. The literature presents two possible interpretation of the concept of urban Permeability: the visual and the physical one. Visual Permeability is related to the visibility of open and public pathways as opposed to private spaces which are excluded from visual contact with public spaces. In this work, we focus only on physical Permeability, as defined by Bentley (1985), i.e. the ability of the urban structure to allow people a choice to move into the urban network.

Previous works interpret the physical Permeability as the extent to which a two-dimensional plan area embeds accessible space (Marshall 2005) or allows pedestrian movement (J. Jacobs 1961). In this context the concept of Permeability becomes equivalent to the one of urban connectivity (Kusumastuti et al. 2017). A suite of different methods have been proposed to quantify urban connectivity through various indicators, such as the intersection density (number of intersection per given area) (Berrigan, Pickle, and Dill 2010), block density (number of blocks per given area) (Oakes, Forsyth, and Schmitz 2007) or block size based measure and route directness (Randall and Baetz 2001). As reviewed by Ellis et al. (2016), each one of these indicators has its own weaknesses and limitations in providing consistent explanations of the urban Permeability. Indeed, Kusumastuti and Nicholson (2017) and Pafka and Dovey (2017) demonstrate that the concepts of Permeability and connectivity are related but not interchangeable as an urban morphology can present a good street connectivity indicator and, at the same time, a poor level of Permeability.

More recent studies (Stangl 2019) revise the concept of Permeability highlighting that Permeability is not only a measure of the existence of a link between any two points of an urban area (i.e., the urban connectivity) but it should also embed the multiplicity of route choices between those points (Pafka and Dovey 2017). Montgomery (1995) defines it as the capacity of entering an area and moving there easily. Then, Permeability should contemporary quantify the directness of links and the density of connections in a transport network (Ewing and Handy 2009). This gives to urban Permeability concept a more general meaning and significant role in relation with the walkability potential which is associated with movements of people within the city, whether by foot, bike, public transport or car (Ewing and Cervero 2010). There are also authors mixing the physical consistency of Permeability with qualitative aspects of urban design at the street scale. K. Campbell and Cowan (1999) define permeability as the degree of variety of the pleasant, convenient and secure ways that an area owns, whereas according to Lennard, Lennard, and Bert (1987), permeability is one of the four qualities consisting of legibility, diversity and sensitivity.

The complexity and the multiple aspects associated with the concept of urban Permeability are still a subject of debate in the current literature and a general consensus on methodological quantitative framework to assess Permeability on the basis of a single measurable property is still lacking. The synthesis of this KC in a single value may be limiting and incomplete, similarly to what observed for Porosity, as discussed by Tadi et al. (2017).

This study aims at providing quantitative measures that can pinpoint significant features of the spatial organization of the urban elements in order to characterize the concept of urban Permeability. There are studies reviewing existing block and network metrics in order to identify the best possible one for the characterization of this and other features (Clifton et al. 2008; Pafka and Dovey 2017), with the purpose of defining a better performing one, showing contextually the need of confronting more measures to have a clearer picture of the topic (Figure 61).



	Average Perimeter [m]	Average Diagonal [m]	Average Block Area [ha]	Intersection Density [i/ha]	Network Density [m/m²]	AwaP [m]
A	296	100	0.62	1.1	0.02	276
B	320	113	0.64	1.1	0.02	320
C	640	283	1.12	0.7	0.02	640
D	680	264	2.76	0.6	0.01	690
E	256	93	0.52	1.6	0.02	510

Figure 61 Comparison between Permeability measures based on block size and geometry (Pafka & Dovey, 2017). Six measures are tested on five different sample contexts to see their descriptive capacity

In addition, other metrics can be found in different disciplinary fields. To this end, we define a set of six quantitative metrics: Street Area (SA), Normalized Average Link Length (ALL_N), Directness (D), Constrictivity (βN), Tortuosity (Tor) and Topography (Top). These metrics are not included in the previous chapter as they deal with Link component, raster maps and require specific software to be computed. This implies that, at this stage, their calculation requires more time that the other metrics and can't be automatized on large samples as, i.e., Milano NIL.

Each one of these addresses a different aspect of the concept of Permeability of an urban area. For each proposed metric, we provide a quantification procedure that is reproducible and easily exportable to any case study of interest. For testing the applicability of the proposed metrics, we implement them on a set of selected case studies. The six metrics for each case study are presented through radar diagrams. The concept of Permeability can be then characterized, quantified and discussed by collectively reading the six metrics together and in relation with each other. Through the implementation of the proposed characterization on different case studies, we discuss the ability of the suite of proposed metrics to describe and quantify the main features of urban Permeability for diverse urban structures, spanning from medieval to recent urban contexts.

6.2.2 Metrics and diagrams

All these quantities are, on purpose, defined to vary between 0 and 1 which is helpful when the metrics need to be post-processed, interpreted and compared among different case studies. Some of these quantities are introduced here specifically for the characterization of Permeability on urban context (i.e., SA, ALL, D and Top). Tortuosity and Constrictivity are, instead, parameters that are commonly employed to characterize porous media across different scientific fields, e.g. in chemical engineering or geosciences. These parameters are here exported to cities under the assumption that the urban structure can be assimilated to a bi-dimensional porous medium. Indeed, there is a clear correspondence between morphological structures observed for bi-dimensional porous media and urban plans where buildings are represented by solid elements and open spaces (as streets and squares) can be interpreted as the voids of the porous domain (Figure 2). These latter are routinely characterized by a number of effective parameters which describe and quantify the impact of porous medium properties on a wide range of physical processes of practical interest taking place in porous domains such as fluid flow, solute transport, chemical reactions, solid deformations (Bear and Cheng 2010).

In the following section we introduce each one of the metrics concurring to Permeability description by providing its definition and the operational procedure employed to compute it. Along with the methodology presentation, we display some illustrative examples of the computed metrics which might help in visualizing the physical meaning of each quantity. The methodologies proposed for computing these metrics are reproducible and exportable to any case study since they make use of information that are typically found in topographical database and rely on freely available software. For our case studies, all located in Lombardy region (Italy), we rely on the DBT (Topographic Database) of Lombardy, using the layers Street Network (L010107), Street Area (A010104), Street Nodes (P010108) and Volumetric Units (A020101).

Street Area

Street Area (SA) quantifies the portion of void space, which is open, continuous and accessible to urban flows. The open void space is spatially complementary to the joint area identified by buildings and bounded open spaces. These latter are isolated spaces completely enclosed by buildings, such as courts or other urban cavities.

We define the Street Area (SA) as

$$SA = \frac{A_S}{A_v} \qquad (1)$$

The quantity A_S indicates the accessible void area which can be extracted from the street area layer included in the DBT database (Topographic Database) or, alternatively, by computing it by summing the extension of streets, sidewalks and other paths. The quantity Av is the total void urban area computed as

$$A_v = A_t - A_b \qquad (2)$$

where A_t is the total urban area covered by the chosen case study and A_b is the building footprint. According to its definition in (1)-(2), the SA metrics can only range between 0 and 1 since A_S constitutes a portion of Av and, thus, always smaller than Av.

Figure 62 provides an exemplificative illustration of the portion of accessible void area in a real urban context which corresponds to one of the case studies investigated in this work, i.e., the one labelled Milano. It compares the amount of accessible void space (in black) and the surface associated with the not accessible space which includes both enclosed urban cavities and buildings (i.e., Ab). The resulting value of SA = 0.56 which means that the 44% of the void space in this urban structure is not freely usable by persons and/or vehicles for moving within the city.

Figure 62 Visualization of the accessible void area As, indicated by black colour, in the context of Milano MM case study

Average Link Length and Normalized Average Link Length

The Average Link Length (ALL) represents the average distance existing between connected street intersections. This metric can be interpreted as a proxy of the connectivity of the urban matrix (Ellis et al. 2016), which corresponds to easiness of changing routes and finding alternative paths between points lying in the accessible urban areas.

We define the Average Link Length (ALL) as

$$ALL = \frac{\sum_{i=1}^{nL} L_i}{nL} \tag{3}$$

where L_i is the length of the ith link (with i= 1,..., nL), defined as the segment of street connecting two intersection, and nL is the number of links identified in the urban structure investigated.

We can visualize the ALL associated with a chosen urban area by displaying a fictitious street network composed of nL links shaped as a regular grid of squared blocks with a side equal to ALL metric. In Figure 63, we depict this fictitious street network for one of the case studies investigated in this work, i.e., Milano MM where ALL = 55 m.

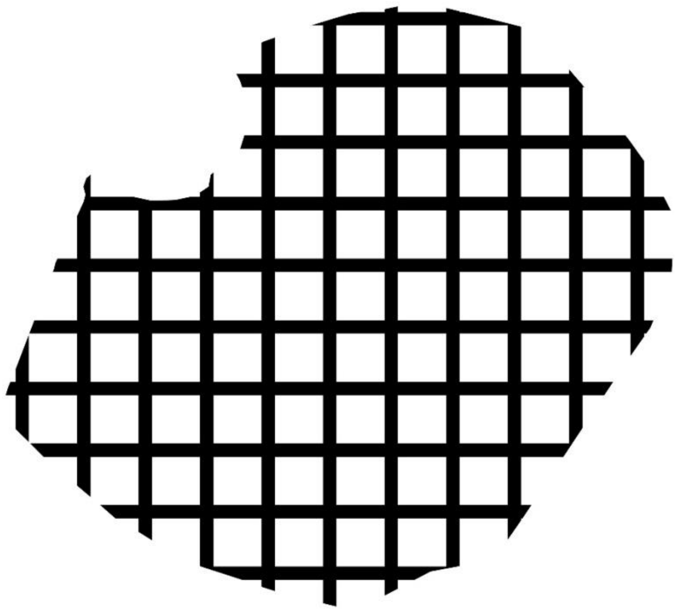


Figure 63 Visualization of Milano MM street network assuming that the length of each street link is equal to the ALL measure (i.e., 55 m). The street width is equal to 12 m, computed as the ratio between A_S and Total Link Length. The number of intersections here corresponds to the one observed in the real urban structure (nL)

The quantity ALL is dimensional, it is defined positive but it is not limited by an upper bound. This might lead to some difficulties in interpreting this measure

Then, we introduce a Normalized Average Link Length (ALL_N), which rescales ALL between 0 and 1, as

$$ALL\_N = \frac{ALL}{K_{ALL}} \tag{4}$$

where K_{ALL} is an a priori defined upper bound based on preliminary investigations. We set K_{ALL} = 150 m as a representative upper bound for European urban morphologies.

Note that urban areas characterized by deeply different link length distribution may present close ALL_N and ALL values, similarly to all average quantities. For example, peripheral areas, located at the boundaries of the metropolitan area, typically host few but very long links corresponding to extra-urban infrastructures surrounded by urban structures characterized by very short links which were developed in a second moment, after urban expansion. The presence of these long links may have a strong influence on the ALL_N metric. Then, this metric, after computed, needs to be critically interpreted considering the specific case study under investigation.

Directness

Directness (D) is a measure of how close is the shortest path following the street network that connects two points located on the border of a considered urban area to their Euclidean distance.

Chosen two points P_i and P_j (with $P_i \neq P_j$) on the border of the investigated urban area, the Directness value associated with these points (D_{ij}) is defined as

$$D_{ij} = \frac{\overline{P_i P_j}}{SP_{ij}} \qquad (5)$$

where $\overline{P_i P_j}$ is the Euclidean distance between the points and SP_{ij} is the length of the shortest path connecting the two points following the street network. This measure of Directness is generalized for characterizing an urban area as

$$D = \frac{\sum_{i=1}^{P_B} \sum_{j=i+1}^{P_B} \overline{P_i P_j}}{\sum_{i=1}^{P_B} \sum_{j=i+1}^{P_B} SP_{ij}} \qquad (6)$$

where P_B is the total number of points located on the border of the urban domain.

According to definition (5)-(6), it is expected that urban structures characterized by a street network shaped as a regular grid presents high D values and the presence of diagonals contributes positively to the Directness measure. On the contrary, the presence of large urban cavities or non-permeable elements such as railways or obstacles deviates linear connections between urban points decreasing the Directness value.

Figure 62 shows the street network of Milano MM case study where each street link width is weighted proportionally to the number of times that is contributing to a shortest path connecting two points on the boundary.

Figure 64 highlights possible limitations affecting this metric. We observe that the streets which lie on border of the selected area frequently act as shortest path, because Directness is computed considering couples of points lying on the border. This means that the Directness measure might be biased by the chosen shape of the boundaries of the case study, which is subjected to choice of the analyst. Moreover, the evaluation of Directness might encounter some difficulties when concave shapes are considered as there might be the risk to artificially increase the path length with respect to reality by excluding some links external to the selected area.

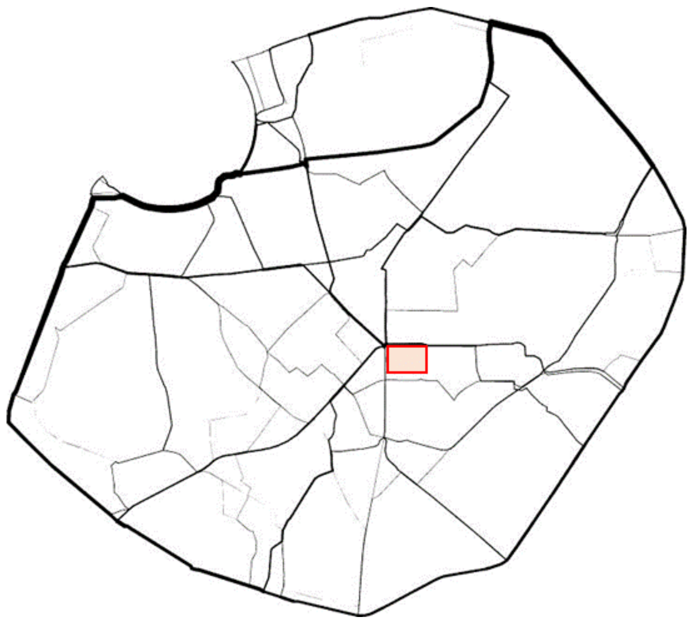


Figure 64 Street network of Milano MM case study (see Section 3 for further details) where each street link width is weighted proportionally to the number of times that is contributing to a shortest path connecting two points on the boundary.

Tortuosity

Tortuosity is a parameter routinely employed for the characterization of solute mass transport in porous domains. Solute mass dissolved into a fluid undergoes diffusion leading to the progressive dilution of solute concentration forced by the solute concentration gradient. According to Fick's model (Bear and Cheng 2010), the diffusion of a solute in a free fluid can be characterized through a single molecular diffusion coefficient Dm [m2 s-1]. However, in the presence of a porous medium, the diffusion process is limited by the presence of solid boundaries. The effects of the porous spatial structure on the diffusion process are lumped in an effective dimensionless parameter labelled as tortuosity (τ [-]). In other words, the tortuosity quantifies, on average, how tortuous is the path of a molecule of solute that diffuses into the fluid phase of a porous sample. The tortuosity ranges between 1, corresponding to a free fluid situation (no solid boundaries), and infinite, corresponding to a medium where transport by diffusion is not possible along a specific direction (i.e., an impermeable or non-percolating geometry). Tortuosity is a geometrical parameter (Bear and Cheng 2010), yet analytical quantification of τ is possible for simple geometries or, alternatively, empirical correlations have been proposed for estimating tortuosity relying on the void-solid volume ratio (e.g. (Tomadakis and Sotirchos n.d.; Akanni and Abramson 1987; Ho and Striender 1981; van Brakel and Heertjes 1974; Weissberg 1963; Lerman 1979; Ullman and Aller 1982; Torquato 2002). We rely here on a quantitative method that can lead to a direct numerical estimation of tortuosity from a chosen geometry, upon relying on the implementation of the freely available TauFactor Matlab (The MathWorks 2016) software (Cooper et al. 2016). TauFactor numerically computes the diffusive flux (F) of a solute across a two-dimensional porous domain. The solution is obtained applying a unit concentration gradient along a given direction and solving the corresponding diffusion process.

A challenge posed by the use of tortuosity as a lumped numerical indicator is that its value is dependent on the direction of transport considered, which implies that the complete characterization of the tortuosity of a bi-dimensional domain is a second rank symmetric tensor (Bear and Cheng 2010). To overcome this element of complexity, we set the x and y-axes to coincide with the North and East directions and evaluate the tortuosity along these directions. Then the trace of the tortuosity tensor (τ_T) is computed as

$$\tau_T = \tau_x + \tau_y \tag{7}$$

where τ_x and τ_y are the tortuosities computed along the x and y directions, respectively. For simplifying the analysis and the results interpretation and the comparisons provided in Section 4, we introduce the quantity Tor defined as

$$Tor = 1 - \frac{2}{\tau_T} \tag{8}$$

The measure Tor embeds both the effects of τ_x and τ_y and it is bounded between 0 and 1. The metrics Tor attains a value of 1 when the solid phase is not percolating while Tor =0 corresponds to a porous medium which does not have any impact on the diffusive process. TauFactor estimates the tortuosity by comparing the quantity F against the reference diffusive flux (FH), which would be obtained in a free fluid. Figure 65 provides an example of the results provided by TauFactor for one of the study case investigated in this work. i.e., Milano MM. Figure 65 shows the diffusive flux computed in presence of the solid phase (F), i.e. the buildings of Milano MM, normalized to FH corresponding to the diffusive flux without any solid obstacle. It emerges that the diffusive flux distribution is inhomogeneous and a few pathways are characterized by very high value of , i.e., the diffusive flux in presence of the solid structure is remarkably deviated compared to free fluid system. The tortuosity τ_y for the case study depicted in Figure 65 attains a value equal to 2.87, which means that effective diffusion is reduced by a factor 2.87 with respect to a non-porous domain.

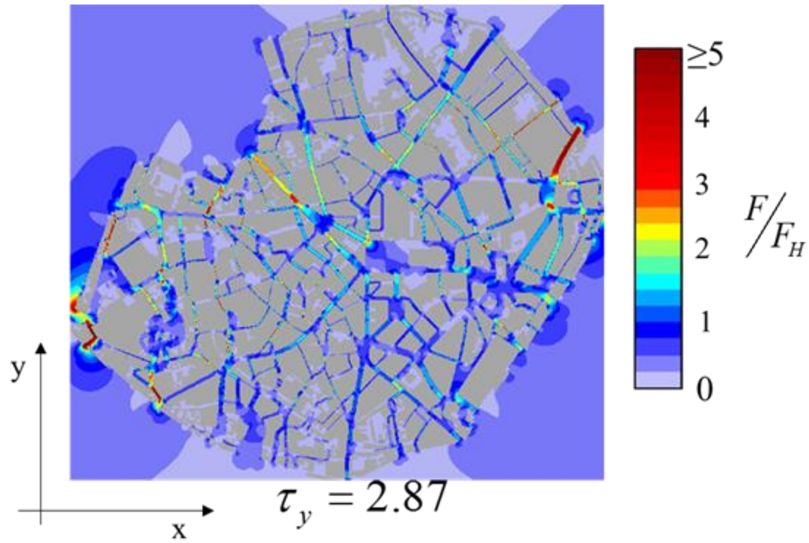


Figure 65 Flux (F) computed for the Milano MM study case (see Section 3 for further details on the study case) normalized over the FH computed in free fluid in y-direction.

Constrictivity

The constrictivity parameter β was first introduced by Petersen (1958) and is computed as

$$\beta = \left(\frac{r_{\min}}{r_{\max}} \right)^2 \qquad (9)$$

for a single pore with periodic constrictions. In such a simplified geometry, the symbol r_{min} indicates the radius of the most constricted area of the pore (the bottleneck), while r_{max} refers to the characteristic radius of the bulge. In natural porous media, and similarly in urban structure, a single value of r_{min} and r_{max} is not trivial to identify. To estimate the values of r_{min} and r_{max} in the urban context, we implement the procedure proposed for porous media by Holzer et al. (2013). This procedure identifies r_{max} as the 50% quantile of the Continuous Pore Size Distribution (c-PSD, for details see (Münch and Holzer 2008)) while r_{min} is the 50% of Pore Size Distribution estimated by simulating mercury intrusion porosimetry (MIP-PSD, for details see (Garboczi and Bentz 1991)). The c-PSD and the MIP-PSD are two conceptually different techniques to characterize pore-size distributions that can be seen as the cumulative distribution function of pore sizes in a given porous geometry. The c-PSD determines the portion of total void volume that can be potentially covered by circles of a fixed radius r. On the other hand, the MIP-PSD, fixed the radius r, quantifies the amount of volume of void that can be explored by a circle of radius r starting from a boundary. The MIP-PSD and c-PSD are built by varying the radius r within an opportunely selected range. A detailed explanation of this methodology can be found in (Holzer et al. 2013). Based on definition of MIP-PSD and c-PSD, r_{min} always attains values that are smaller than r_{max}. Therefore, the constrictivity parameter is naturally bounded between 0 and 1: when β tends to 0 this indicates that bottlenecks are predominant features in the geometry and vice versa. We then introduce here the quantity β_N

$$\beta_N = 1 - \beta \qquad (10)$$

such as, more intuitively, the higher is the value of β_N the more intense is the street constriction effect. To numerically estimate both MIP-PSD and c-PSD, we employ the freely available software ImageJ/Fiji extended with the free plug-in provided by (Ferreira and Rasband 2012). To exemplify the computation of the constrictivity metric, Table 6 reports the estimates of rmin, rmax and βN for Milano MM, Milano CS and Milano PM.

Table 6 Values of rmin, rmax and constrictivity computed for three different studies cases considered in these work: Milano MM, Milano CS and Milano PM

Urban Structure	r_{min} [m]	r_{max} [m]	β_N
Milano MM	2.1	5.1	0.83
Milano CS	6.8	9.4	0.47
Milano PM	9.4	18.7	0.75

Topography

Topography has an important impact on street network properties and has a critical role in driving flows of people and vehicles. An aerial view only shows elements projected on a plane, shrinking distances and hiding differences in heights. To keep the same topology of connections respecting link lengths it would be necessary to unroll the ground mesh, obtaining a distorted and trimmed map, not useful for representation or other purposes. The more or less intense inclination of a street affects the connectivity and morphology of the urban space and therefore should be included in the Permeability characterization. To this end, we introduce a specific metric devoted to the characterization of the topography of an urban system

We first characterize each ith link of the investigated study case by estimating its slope (ϕ_i) as follows

$$\phi_i = \arccos \frac{L_i}{L_{3D,i}} \tag{11}$$

where L_i is the length of the ith link (i= 1,…, nL) as measured on urban plan while $L_{3D,i}$ is the length of the same link considering a 3D model.

The metric Top is then defined as

$$Top = \frac{\sum_{i=1}^{nL} \phi_i}{nL \cdot K_\phi} \tag{12}$$

where K_φ is a normalization factor included in (12) in order to limit the interval of variability of Top between 0 and 1 which simplifies the metric assessment and interpretation. In this work, we fix K_φ to 17° which corresponds to a street inclination of 35%, i.e., the highest inclination observed for an urban street (Baldwin Street, Dunedin, New Zealand).

6.2.3 Case Studies

To investigate the ability of the proposed metrics to characterize the Permeability of morphologically different urban areas, we consider nine different case studies, the same used for Porosity KC.

The districts Milano MM, Bergamo CA and Brescia CS correspond to the most ancient part of three cities which were typically delimited by walls during the medieval times and they constitute now the core of the city. The shape of these districts is irregular and the street network is dense and intricate which is a feature commonly observed in those parts of city that were originally developed for pedestrian traffic (i.e., before the broad diffusion of vehicles). In the case of Milano MM and Brescia CS we can observe the tendency of the street network to follow an overall radial configuration which, from the border of the district, conducts to a central major square. The case of Bergamo CA is peculiar because of the influence of the orography of the territory (this urban area lies on the top of a hill).

The districts of Milano CS, Bergamo SE and Brescia ST are modern urban areas which were developed during the cities' expansion in the 20th Century. These areas are indeed characterized by a more regular and planned street network and the street width tends to be larger compared to medieval areas.

The areas of Milano PM, Bergamo VA and Brescia CB are the most recent ones among the investigated case studies and are located on the border of the three cities. These are mainly characterised by isolated buildings and wide extra-urban streets.

For our case studies, the DBT layers used for this analysis are Street Network (L010107), Street Area (A010104), Street Nodes (P010108) and Volumetric Units (A020101). (http://www.geoportale.regione.lombardia.it/).

The numerical values of the metrics computed for the nine case studies presented are listed in Table 7. The same data are also displayed in Figure 66 by means of radar graphs. Figure 66 compares different districts belonging to Milano, Bergamo and Brescia on the left side. On the right column, the data are rearranged to compare Permeability results of districts developed in similar historical period: the Historical city centres, the modern districts and the contemporary suburbs. The representation via radar diagrams facilitates the contextual reading of all the metrics identifying general trends as a function of the historical development period within the same city and site specific features by comparing areas grown in the same historical period but in different cities.

We can observe that the cities of Milano and Brescia present a similar trend of SA moving from the ancient district (Milano MM and Brescia CS) towards the most recent ones (Milano PM and Brescia CB). This trend express the progressive increment of portion of void space occupied by inaccessible areas to traffic flows, such as countryside and industrial sites, when moving from the city core to the border. This consideration is in agreement with the visual inspection of the maps reported in Figure 59 and the function of the different city areas. We can also note that, on average, the city of Milano is characterized by higher values of SA compared to Brescia which might be an indicator of the spontaneous adaptation of the two cities to economic, political and social drivers: Milano is characterized by an extremely high motorized traffic pressure, therefore void space is preferentially devoted to accessibility, as compared to other cities. The case study of Bergamo CA represents an outlier in this context. The SA metric, in this district, is remarkably controlled by the presence of large parks, accounted as inaccessible void space, which are clearly visible as white spots on the East-hand side of Bergamo CA area.

The quantity ALL_N shows a similar quantitative and qualitative trend for Brescia and Milano, increasing when moving from the city core to the peripheries. This is consistent with what expected for the different districts since this reflects the diverse type of traffic that characterized the different historical periods. The city cores are characterized by shorter Average Link Length favouring the possibility of changing direction for people walking, while the city borders tend to facilitate the nowadays high speed and motorized traffic. Once again, Bergamo CA presents a result contrasting with the other two case studies presenting a value of ALL_N = 0.52 which is, at least, 10% higher than Milano MM and Brescia CS (0.37 and 0.42, respectively). However, Figure 66 allows to compare the values of ALL_N and Top for Milano MM, Brescia CS and Bergamo CA: we observe that Brescia CS and Milano MM are located in flat areas as suggested by low Top values while for Bergamo CA Top is very close to 0.5. This indicates that the orography has limited the development of an articulated street network and that the direction of the streets was adapted to the territory natural slope, especially in those parts of the city pre-existing the advent of motorized traffic.

Directness (D) presents quite high and similar values for all the case studies. Radial road networks (e.g., Milano MM) as well as those characterized by rectangular blocks (e.g., Milano CS) exhibit a good level of Directness. The radial streets, indeed, acting as diagonals, favour the shortening of the paths to connect the points on the border of urban areas. See, for example, the map of Milano MM reported in Figure 64 where the radial streets are frequently contributing to the shortest paths. The presence of a radial network, is commonly observed in ancient cities, since it helped to convey the flows from the borders to most important location for the human activities and for aggregation such as the major square and/or a cathedral. In the specific case of Milano MM, indeed, the centre of the radial structure corresponds to the Duomo cathedral square marked with a red rectangle in Figure 64. A particularly high value of D is associated with Milano PM (D = 0.91) which, from its plan in Fig. 5c, appears as a square-like cell with two diagonals.

Even if the concepts of Tortuosity (Tor) and Directness (D) might appear complementary to each other, this is contradicted by the numerical values obtained on our case studies. Note, indeed, that Brescia CS is a remarkable example since it is associated with high values of both D (= 0.84) and Tor (= 0.67). This apparent contradiction might find a possible explanation by looking at the planimetry of Brescia CS. Along the North-South direction, we can easily identify a number of almost straight streets which connect the upper border to the lower one and this clearly contributes to increase the D value. At the same time, these streets are surrounded by many small tortuous streets that, similarly to river tributaries, transfer their fluxes into these larger arteries. The Tor metric, then, increases accounting for both the main direct streets and the lateral tortuous ones. Coherently to our perception from the maps reported in Figure 59, the Tor value increases form more recent districts (i.e., the contemporary suburbs of Milano PM, Bergamo VA and Brescia CB), characterized by a regular street network and repetitive building block shapes, to the more ancient core of the cities, presenting an irregular and tortuous street system.

The smallest value of constrictivity is associated to the modern urban area of Milano CS (β_N = 0.47), whose conformation is characterized by a limited variability of street amplitude as confirmed by the short difference existing between bottlenecks and bulge sizes We emphasize that a small value of constrictivity does not mean that the voids are on average larger, but only more uniform. In this sense high values of β_N can be seen as a proxy of the variability in local characteristic dimension of open spaces as in the city cores (Milano MM, Brescia CS and Bergamo CA) where wide urban spaces (e.g., squares and parks) coexist with a lattice of narrow streets. The result obtained for the suburbs whose β_N values are included between 0.71 and 0.75 can be intuitively explained upon observing that these areas include remarkable portions of non-urbanized open-space areas (which correspond to large pores) or very wide streets being extra-urban connections. These have an important planar extension and therefore increase the radius r_{max} and, at the same time, the urban expiation has introduced a number of narrower streets which determine a small value of the characteristic bottleneck apertures r_{min} (see definition (10)).

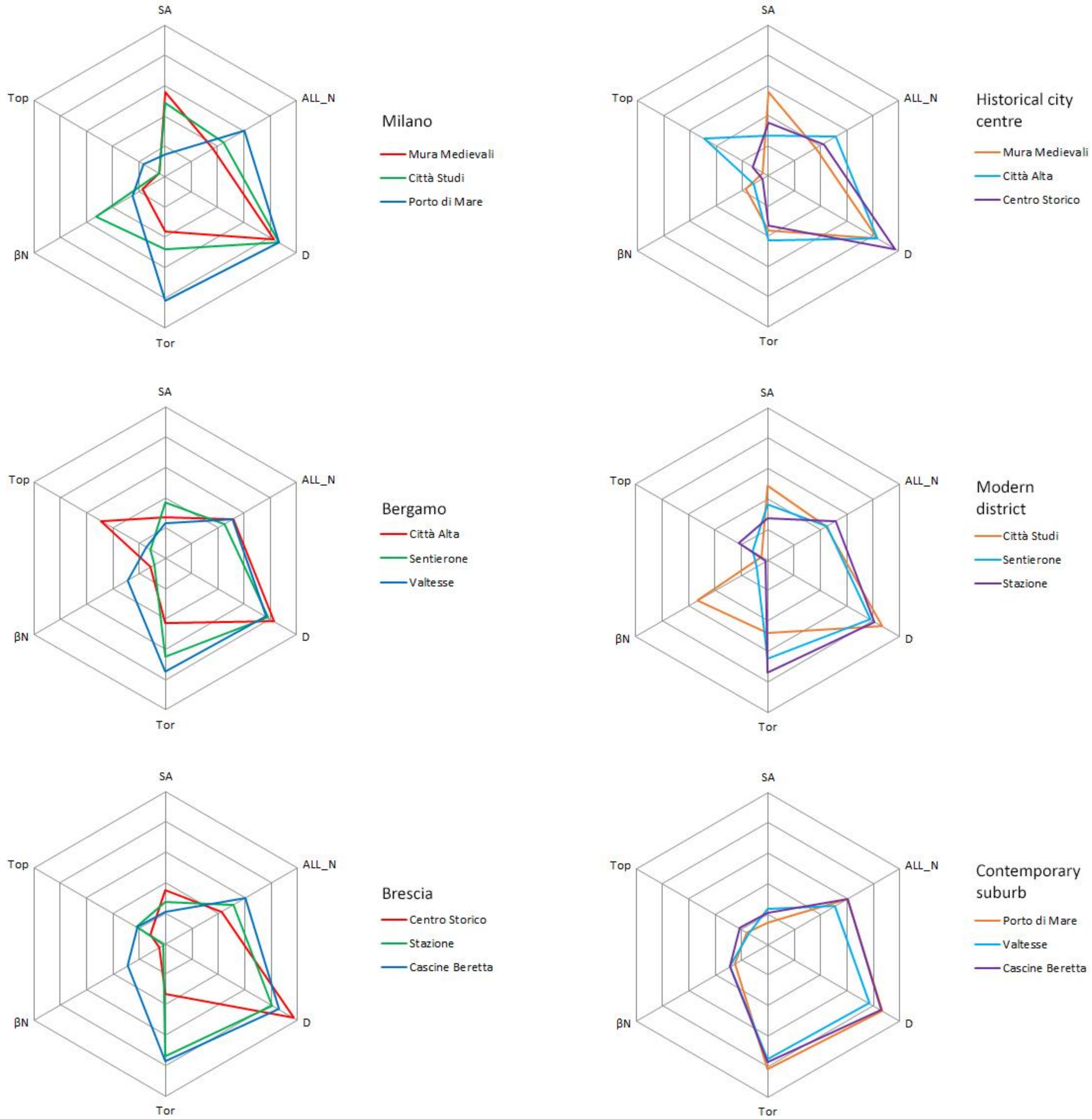


Figure 66 Results of Permeability investigation by means of radar diagrams grouped in case studies (left) from Milano (top), Bergamo (middle) and Brescia (bottom), and grouped by historical period of development (right) historical city centre (top), modern district (middle) and contemporary suburbs (bottom)

Table 7 Results of Permeability investigation on the nine different case studies

City	District	Area (ha)	SA	ALL_N	D	Tor	β_N	Top
MI	Mura Medievali	269	0.56	0.37	0.82	0.64	0.83	0.04
MI	Città Studi	275	0.48	0.44	0.87	0.52	0.47	0.04
MI	Porto di Mare	169	0.14	0.60	0.91	0.18	0.75	0.16
BG	Città Alta	45	0.27	0.52	0.84	0.57	0.89	0.49
BG	Sentierone	68	0.37	0.45	0.76	0.35	0.91	0.11
BG	Valtesse	84	0.23	0.51	0.87	0.25	0.71	0.14
BS	Centro Storico	177	0.35	0.42	0.84	0.67	0.95	0.12
BS	Stazione	180	0.27	0.51	0.88	0.26	0.98	0.22
BS	Cascine Beretta	177	0.21	0.60	0.69	0.23	0.71	0.22

A key result is that the graphs associated with suburban case studies (Figure 66) almost overlap with each other. Our quantitative results support the notable similarities existing between suburbs in completely different cities. Suburbs are indeed a transversal issue of global concern in Italy and worldwide. In such areas local streets turn into long roads which favour the motorized traffic while hindering the pedestrian movement and losing their social role of a meeting place. At the same, relatively high values of constrictivity (typically lager than 0.7) show that the street network may undergo to intense phenomena of congestion: the ongoing urbanization expansion, progressively occupying the void extra-urban spaces, provokes the development of an ordered (as indicated by low values of tortuosity) network of narrow streets that converges into the extra-urban arteries and then affecting the viability from/to the city centres.

We finally briefly comment the moderately high value of Top observed for the case Milano PM (Top = 0.16) which is apparently an outlier since Milano is notoriously located in flat area. A closer inspection of the area reveals that the presence of few overpasses where road crosses the railway network, then, impacts on street slopes.

6.2.4 Conclusions

The metric numerical values computed on the nine case studies show good agreement to the expected results based on the visual inspection of the planimetries, thus reflecting in quantitative terms our perception of the urban Permeability.

Moreover, the quantitative assessment provided by our metrics helps in revealing important trends as a function of historical period of city's development, similarities and differences between the diverse case studies that might remain concealed to a visual qualitative inspection. As a general trend, we can observe that SA and Tor tends to increase while ALL_N to decrease when moving towards more ancient districts in the city reflecting if a urban context was developed to favour pedestrian or motorized traffic depending on the historical period (see the case studies of Milano and Brescia, Fig. 7a and c). The use of constrictivity metric may help in identifying urban structures more prone to traffic congestion or embedding important bottlenecks, i.e., where the width of street network is heterogeneous.

Interestingly, our analysis reveals that the Directness and Tortuosity are not complementary concepts but high Directness and Tortuosity can coexist in the same urban structure when straight and radial arteries are drown in articulated lattice of tortuous street network (see e.g., Milano MM, Bergamo CA and Brescia CS). The orography of the land might act as a limiting factor for the development of street networks as probably occurred in Bergamo CA which results to be characterized by larger Average Link Length and smaller SA compared than other urban areas developed in a similar historical period. The metrics computed for the three suburban areas are very close to each other and support a morphological similarity which is not immediately visually identifiable from planimetries. This supports the reliability of the proposed suite of metrics being the suburbs of different cities often affected by the same perceived lack of urban Permeability as a result of favouring the motorized traffic at the expenses of pedestrian viability.

In this sense, the methodology proposed provides a novel practical tool for urban permeability investigation, applicable by researchers, designers and stakeholders in all urban existing contexts or to explore the features of planned developments to investigate specific aspects of urban permeability and possible feedbacks on transport and energy performances.

6.2.5 Integration

As done for Porosity, it's possible to draw also a larger diagram including all those metrics that we assume may have an impact on Permeability assessment. As might be noticed, BCR_G is part of both Porosity and Permeability diagrams, even if its impact is larger on Porosity KC. The full list of permeability metrics is the following:

BCR_G; B_OMBG; BL_BP; BL_AMBG; BL_OMBG; BL_CMBG; VBLPR; SA; ALL_N; D; Tor; βN; Top

Inside this list we can distinguish metrics related to Building Area and Orientation, Block shape and orientation, Urban Canyon, Street length, width, elevation and pace. There are existing and new metrics working together to give the more exhaustive possible picture of this emergence. IMM representation for KC provide radar diagram composed by an open and flexible number of metrics. The larger possible consistent diagram, according to this research, is the following (Figure 67).

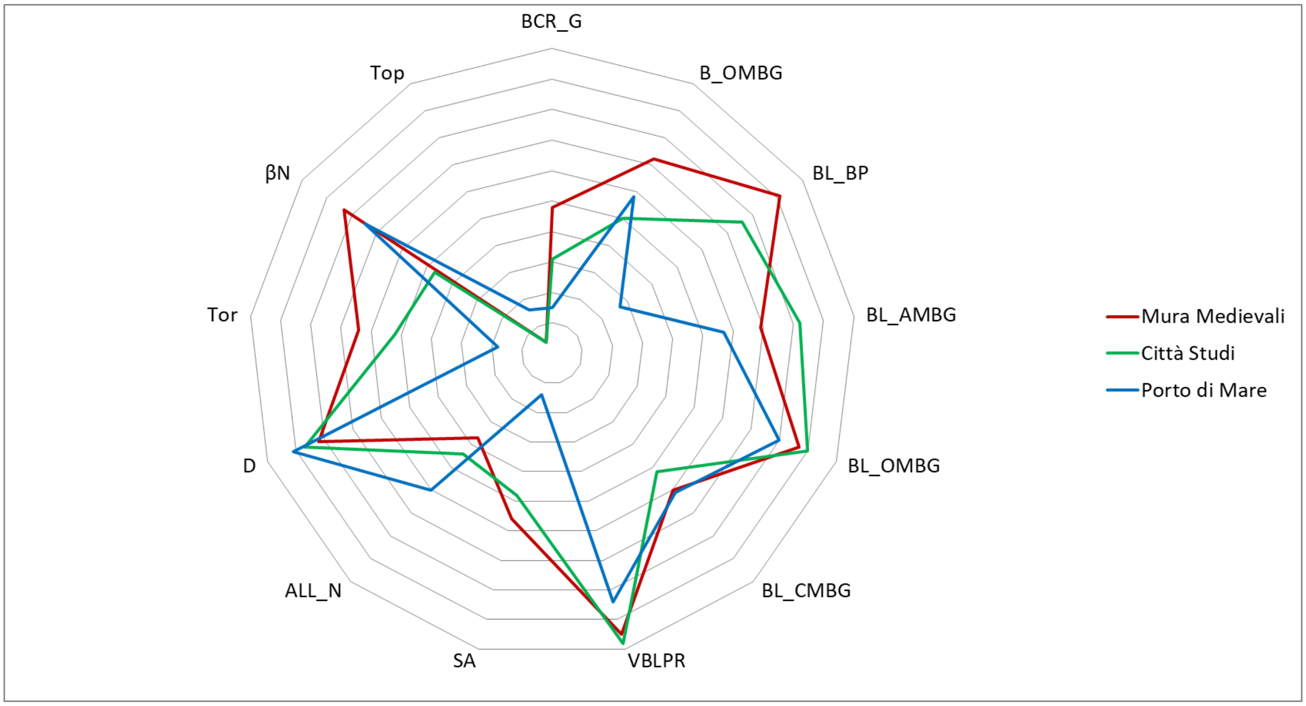


Figure 67 Permeability pattern radar diagram including all related metrics. Metrics are ordered starting from the building related one, moving to block, street area, link, hydraulics and topography.

It's important to notice than the relevance of a metric can be dependent by the context where is applied. For example, comparing regular grids will make constrictivity unnecessary whilst it can be crucial for contexts containing bridges, overpasses or other restrictions. Topography itself, limited to the Milan case study, is not so relevant because of the complete flatness of the area. As said for Porosity, in Appendix C and D a different set of six metrics will be used to draw the Permeability diagrams for all the 88 Milano NIL. In this case the main reason is the impossibility to automatize the calculation for Tor, β_N and D metrics on such a large sample. Top has been considered not able to highlight some differences on such a flat city. ALL_N deals with Network Component and in order to have some meaningful result, a cleaning operation, as performed on the 9 case studies would be necessary. SA has been excluded only for its correlation with the Street Cover Ratio (SCR) indicator, used among the others to assess performances. The remaining metrics, except BCR_G as already included in Porosity investigation, have been used gaining additional feedbacks on their descriptive capacity.

6.3 Compactness Environmental Implications

6.3.1 Indicators in literature

In the 1990s, an intensive debate about different definitions and models of sustainability occurred. This also marked the beginning of the relationship between sustainability and policies, and the development of sustainability indicators for modelling urban sustainability (Spiekermann and Wegener 2003; Berardi 2013).

There is an extended literature on sustainability indicators. An indicator is a way to measure a specific issue or condition that is relevant to the overall health of a community. A good indicator alerts you to a problem before it gets too bad and helps you recognize what needs to be done to fix the problem. Indicators of a sustainable community point to areas where the links between the economy, environment and society are weak (Schwartz 2008).

Indicators are useful tools since they are objective measurements on the contrary to ideals. They enable to compare cities during their evolution and to observe the results of politics or constructions, and to the consequences of some decisions or plans (Salat, Vialan, and Nowacki 2010). Indicators are a compromise between scientific accuracy and the demand for concise information (Verbruggen and Kuik 1991; EEA 2002)

However, selecting the appropriate indicator is not a simple task. In fact, there are many parameters that can be measured, but only a few of them are able to translate complex relationships about phenomena in a simple way (EEA, 1999).

A good indicator can be defined by five criteria:

- It must be handful and accessible, which means its analysis must be simple and the data needed to calculate it must be not too hard to access and not too expensive to get.
- it must be relevant, that is to say answering the right question.
- its results and their explanations must be simple. It must not make the problem even more complex.
- it must be comparable to other indicators and allow comparisons between objects thanks to its results.
- it must improve the global reflection.

(Salat, Vialan, and Nowacki 2010)

Indicator should be as easy as possible, since potential users include a wide range of people from city managers, local administrators and planners, up to international bodies defining regional or global development strategies.

At regional and local level, a number of sets of indicators have been identified to fit each specific situation. On one hand, there is a demand for the existence of a set of indicators that could be applied in each context in order to perform comparisons. On the other hand, at a local level, the scale of the approach to sustainability requires more specific and detailed information (EEA 2002).

Many efforts have been made to standardize indicators that aim to assess, monitor and compare sustainable development at different territorial levels. Arguments in favour and against the need to design common indicators are many and highly contested (Moreno Pires, Fidélis, and Ramos 2014).

6.3.2 Environmental Performance Implications

Pope et al. (2004) and Tanguay et al. (2010) have offered a review of available indicators for measuring sustainability. They showed that most of the currently used indicators are characterized by a strong environmental approach (Berardi 2013). The urban planning literature is perhaps the only source of empirical studies that have addressed this question, separately cross-examining a number of urban spatial structure and environmental variables (Alberti 1999). Expressing both environmental and morphological aspects in a measurable form allows to find some correlation between them, understanding how the second can explain the first. Many studies already did this focusing every time on a finite set of morphological metrics, often highly correlated, and few indicators on a specific theme. The reason is that indicators, unless when they are calculated via top-down process starting from census data, require specific instruments and data for every aspect (sun, wind, air, soil…). The result is that conclusions, when reliable, are often partial and contradicting as they strongly depend from the perspective used to look at the same problem. This makes also hard to compare the results and find some conclusions based on them. By the way they represent a huge collection of contexts, simulations and field experiments that if framed in a systemic approach, may help to understand the existing patterns between morphology and performances.

Urban morphology, is a significant driver of urban climate at the micro- and local scale (Stewart et al. 2012; Middel et al. 2014). It impacts air temperature (Oke 1981; Unger 2004), air flow, ventilation, turbulence (Grimmond et al. 1999; Salamanca et al. 2011; Ng et al. 2011), solar radiation (Johansson 2006; Lindberg, Holmer, and Thorsson 2008; Hofierka and Kaňuk 2009; Middel, Lukasczyk, and Maciejewski 2017), land surface temperature (Peng, Wang, and Guo 2018), and air quality (Marquez and Smith 1999; Stone 2008) in the urban canopy layer (Middel et al. 2018). The proper configuration of the volume and void could reduce the total energy consumption of the city considerably. Solar gaining, shading and natural ventilation and heat loss could be optimized solely by the volume and void integration (Salat 2010). In addition to the effect of the two integrated layers on thermal comfort level of the city, the void and volume layers integration has tremendous impact on the transportation layer (S Vahabzadeh Manesh, Tadi, and Zanni 2012).

COMPACTNESS ADVANTAGES

Even if in the previous chapters the difference between density and compactness has been highlighted, with a preference for the second term, considering that most of the existing studies refers to density, and that the two terms have more than something in common, the following list of environmental performance implications will refer to both terms.

Some studies relate residential and job density to energy consumption, transportation-related atmospheric emissions, urban air quality, and biodiversity (Owens 1986; MD 1991; Newman and Kenworthy 1989). Others use various elements of urban configuration to indirectly explain individual choices that have consequences for the environment (Gordon, Kumar, and Richardson 1989; Handy 1992, 1996; Holtzclaw 1994; Cervero and Gorham 1995; Naess and Sandberg 1996; Banister, Watson, and Wood 1997; Alberti 1999).

Urban densification reduces travel distances and therefore also emissions and greenhouse gases, transport expenditure (Jacobs 1961), pollution and heating costs without negative implications. It has a positive impact on the economic benefits and the tourist industry of a city (Jenks, Burton, and Williams 1996).

For example, Japan's urban population is five times as dense as Canada, with the former consuming 40% less electricity than the latter (Kamal-Chaoui and Robert 2009). Second, in terms of energy, higher-density buildings are more efficient than lower density buildings and emit less GHG (Boyko and Cooper 2011).

Other studies relate it with transportation and mode choice. Aggregate density is the highest and density gradients are steepest in Asian cities, where the dominant mode choice is walking and bicycling. Aggregate density is lower and density gradients are less steep in European cities where public transportation is most common. Aggregate density is the lowest and density gradients are the least steep in US cities where travel is dominated by the automobile (Clifton et al. 2008)(Figure 68).

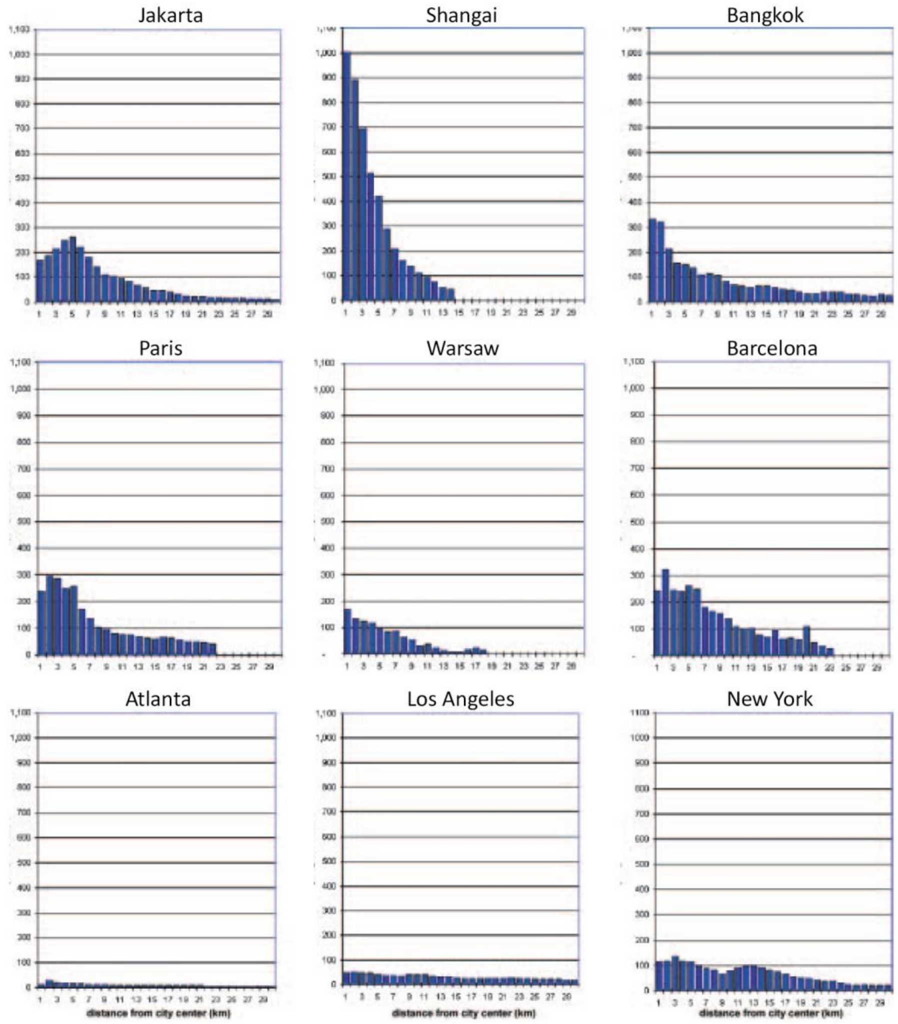


Figure 68 Density gradients showing the variation in population density with distance from the city centre in Asian, European and US cities (Clifton et al., 2008)

Ewing (1997) concluded that the doubling of neighbourhood density results in a reduction in Vehicles Miles Travelled (VMT) from 5% to 38% and doubling urban densities results in a 25-30% reduction in VMT. Using travel survey data Holtzclaw (1994) found that a reduction from twenty to five dwelling units per acre (i.e., urban to suburban densities) increases average vehicle travel by about 40%.

One of the most important reasons why people don't walk in a neighbourhood is because they are afraid of the speed people drive around. According to HMSBID (2000): 5% of pedestrians would die when struck by a vehicle traveling 20 mph, about 40% for vehicles traveling 30 mph, about 80% for vehicles traveling 40 mph, and nearly 100% for speeds over 50 mph.

According to the WorldWatch Institute, even shifting a small car trip to a short, four-mile round trip by bicycle keeps about 15 pounds of pollutants out of the air we breathe. Other studies show that each 1% shift of mileage from automobile to non-motorized modes tends to reduce energy consumption and pollution emissions by 2-4% (TDM Encyclopaedia; Schwartz 2008)

On the contrary, urban sprawl has unambiguous harmful effects on the same aspects of life (Clifton et al. 2008). It consumes farmland, disrupts habitat, increases VMT (thus degrades air quality), and increases impervious surfaces (thus degrades water quality) (Godron and Forman 1983; Chen, Franklin, and Spies 1992; Randolph 2004). Discontinuous urban growth is even more harmful, as discontinuity further fragments farmland and wildlife habitat (Randolph 2004). Low-density suburban development has a larger carbon footprint than an equivalent amount of dense urban housing (Ewing et al. 2007).

COMPACTNESS DISADVANTAGES

However there also contradicting results. Densification policies may bring to urban green space shrinkage having negative consequences on the urban quality of life (C. Zhao et al. 2011). UHI is correlated with urban density (Coutts, Beringer, and Tapper 2006; Hui 2001; Oke 1988; Skinner 2006). Increases in urban density also may reduce air flows in streets and, thus, natural ventilation in buildings (Skinner 2006; Givoni 1998; Hui 2001), and could negate the behaviour of sky views and altitude in allowing vegetation to lower outdoor temperatures (Giridharan et al. 2008). These issues may extend seasonal exposure to unfavourable climatic conditions (Coutts, Beringer, & Tapper, 2007), and may exacerbate urban storm water runoff because more surface area may be pervious (Skinner 2006; Lin and Lin 2010; Boyko and Cooper 2011). Social problems in town can be related to the effect of “crowding”, due to the heights of buildings as well to their uniform architectural realization (Frankhauser 2004). High densities might be accompanied by high rent and property prices, transportation system congestion (Duranton and Puga 2005; Melo et al. 2016; Ahlfeldt 2011),low air quality and a discomforting urban microclimate (Krehl et al., 2016). However, policy advocates in many cities and countries have pushed for higher densities, believing it to be the panacea for sustainable living (Boyko and Cooper 2011).

The fact that many correlations have been seen as possibly both positive and negative also shows how extreme values of metrics inevitably lead to undesired results, while values in an appropriate range may have an higher probability of producing a more balanced system. In addition, the context where these studies where performed inevitably influences the results. The same system structure can perform differently depending on its agent (people) behaviour.

URBAN MICROCLIMATE

Urban climate knowledge should be a crucial aspect in the urban planning process. Unfortunately, it currently has a low impact although the majority of those involved in the urban planning process are aware of urban area local climate issues and understood that urban climate could be influenced by strategic urban planning (C. Zhao et al. 2011) Some specific aspects of urban microclimate are now investigated showing how existing studies already measured the correlation between one or more metric and performance indicators.

Surface temperature

The green layer can be seen more as a specification or particular feature of the void layer or even, in minor cases like green roofs, of the volume one. It belongs to the performance assessment more than in the understanding of the urban structure. It could address the harsh weather conditions in the regions with rough climate. Green layer hybridization with urban volumes, mitigate the cold wind exposure to the individual buildings, as well as over solar heating prevention during the summer time; moreover, this layer integration with urban voids moderates the negative heat island effect of the neighbourhoods. (Vahabzadeh Manesh 2012). Margalit (2009)underlines the importance of the greater building plots with a garden to achieve a better urban form. According to Zhao et al. (2011), green cover ratio (GCR) is the most significant urban planning indicator affecting the urban thermal environment. Together with building height and building density can explain almost 99% of the variance for time of peak surface temperature.

Solar energy potential

Determining solar access in street canyons, i.e. the ability to receive sunlight without obstruction, is essential for heat mitigation in hot urban areas (X. Li et al. 2016) and to estimate the potential for solar heating and photovoltaic electricity production (Compagnon 2004). Solar access varies by geographic location (latitude and longitude), diurnally, and by day of year, but it also depends on the horizon limitation imposed by the built environment (Middel et al. 2018).

In their study on 16 neighbourhoods in Geneva, Mohajeri et al. (2016) affirm that compactness is inversely correlated to the amount of solar irradiation. The most significant metric for explaining this relation is VAR or VD. Passing from dispersed to compact neighbourhoods there are reduction in Photovoltaics (20% - 3%), Solar Thermal Collectors (STC) (85% - 49%) and passive solar heating (21% - 4%) potential for facades. The solar potential for roofs is much less affected. This is mainly due to the effects of shading from neighbouring buildings. What could be seen as a disadvantage in cold climates, can turn into a positive aspects for hot one.

Ventilation

Urban ventilation efficiency should be taken into account since it affects the dispersion and dilution of pollutant and heat in urban areas (Hu and Yoshie 2013). Stagnant air in outdoor urban spaces worsens outdoor urban thermal comfort and urban air pollution dispersion. In summer, a decrease in wind speed from 1.0 m/s to 0.3 m/s is equal to 1.9 °C temperature increase (Yuan and Ng 2012).

A number of understandings that are significant to urban planning and design can be stated as following:

1) Street grid orientation in grid planning is a significant parameter in urban natural ventilation performance. Main streets should be arranged along the prevailing wind direction.

2) Urban ventilation performance at the ground mostly depends on the pedestrian-level building porosity.

3) On the whole, decreasing the site coverage ratio helps to increase the pedestrian-level natural ventilation performance.

Combining several strategies (urban planning and building design) is recommended because it is usually more efficient than any single strategy. An optimization process can consider further the bio-meteorological needs of air ventilation in different climatic zones (Yuan and Ng 2012).

Pollution

It is widely accepted that traffic is an important source of environmental pollution, both air pollution and noise pollution. Although environmental pollution is just one aspect of a wide range of aspects that determine whether an urban form is 'sustainable' (M. (Michael) Jenks, Burton, and Williams 1996; Wheeler and Beatley 2009), it is certainly an important aspect (Salomons and Berghauser Pont 2012).

The spatial distribution of traffic noise in a city is related to the distributions of traffic volume and urban density, and also to urban form. The physical characteristics of the urban shape, such as the density of construction, the existence of open spaces, and the shape and physical position of the buildings have significant influence on environmental noise (I. C. M. Guedes, Bertoli, & Zannin, 2011; Silva et al., 2014)

The results for idealized urban fabrics show that the shape of buildings blocks has a large effect on the sound level at the least-exposed facade (quiet facade) of a building, and a smaller effect on the sound level at the most-exposed facade. Sound levels at quiet facades are in general lower for closed building blocks than for open blocks such as strips (Salomons and Berghauser Pont 2012).

Environmental noise has serious effects on the health of people. Health effects considered by the World Health Organization include annoyance, sleep disturbance, and cardiovascular disease (World Health Organization. 2002; Silva, Oliveira, and Silva 2014).

The correlation between BCR and average sound level is positive (+ 6dBA for an increase of 8% in BCR) for Silva et al. (2014) and negative for Salomons & Berghauser Pont (2012). Guedes (2005) and Tang & Wang (2007) stated that the urban forms in historical areas with narrow roads, complex road networks and a higher density of intersections lead to lower traffic volumes and thus lower noise pollution

6.3.3 IMM Indicators

Achieving the sustainable city has been the main concern of many planners and designers in recent years. Many efforts have been made with the intention of monitoring the sustainable development. The indicators not only present the performance level of the system, but they would also be key elements to evaluate the intervention and transformation process. Agenda 21 claims that: "Indicators of sustainable development need to be developed to provide solid bases for decision making at all levels and to contribute to a self-regulating sustainability of integrated environment and development systems". According to Nijkamp & Finco' (2009), such indicators would be measurable, comparable, transferable, informative, signalling, and acceptable for policy choices. Ideally, policy choices should be based on realistic information, while the relevant indicator would have to be geared towards urban sustainability policies.

Several indicator systems have been designed by different institutions to provide quantitative and qualitative measures to assess and study the interrelation between social, environmental, economic and institutional development at different territorial levels (T. Ramos and Pires 2013). Over the past two decades the 'indicator industry', as some call the proliferation of indicator systems (Herzi and Hasan 2004), has seen fruitful debates emerging in regard to the roles, achievements, gaps and uses of sustainable development (SD) indicators for cities, regions, countries and at the global level. SD indicators aim to assess and benchmark SD conditions and trends across time and space, monitor progress toward goals and targets, inform planning and decision-making, raise awareness, encourage political and behavioural changes, promote public participation and improve communication on sustainability (Holden 2006).

According to Pintér, Hardi, and Bartelmus (2005), there is a continuous growth in the diversity of SD indicators – with no consensus around methodologies, not even general agreement on the best conceptual frameworks or standardized options to measure SD (Hammond et al. 1995; T. B. Ramos, Caeiro, and de Melo 2004). For example, in urban SD many different approaches have been developed: from international rankings of cities based on different criteria such as quality of life, cost of living, innovation economy, city branding, personal safety or eco-city (Yigitcanlar and Lönnqvist 2013), to compendiums of best practices, the use of future scenarios (Boyko et al. 2012) or self-organizing maps (Arribas-Bel, Kourtit, and Nijkamp 2013). The lack of international consensus produced growing inefficiencies in terms of our ability to develop, monitor and benchmark progress towards goals and objectives (Pintér, Hardi, and Bartelmus 2005; Moreno Pires, Fidélis, and Ramos 2014).

Dahl (1997) questions if standardized indicators are ''capable of covering the full spectrum of interest from the 'super powers' to the small island developing states, from indigenous subsistence to post-industrial communities, and from high-tech to no-tech situations''. Bakkes (1997) argues that indicators must reflect their particular cultural, political and institutional context and Dhakal and Imura (2003) agree that a single set of common indicators that is equally applicable to all cities is not possible.

A possible way to overcome this limits is proposed, and adopted, by this research coherently with IMM methodology approach. Every indicator can be ideally applied to any context. The only limit is data availability. Many indicators measure the same thing using different input data and calculation. This provides more alternative way to assess one performance aspect also in contexts with lacking data. Being obsessed by selecting a finite number of best possible indicators is a waste of time and energy justified only by the will of comparing different cities. This is precisely the original sin of rating systems and sustainability indexes. If we leave this idea and settle for comparing only similar urban systems, subsystems (district) belonging to the same city or different evolutionary stages of the same system, no matter its scale, we immediately make the indicator debate obsolete. In IMM systemic perspective, indicators are an open and possibly endless list, grouped in families and associated with the other elements as KC and Determinants. Every single indicator is so related to, and consequently explained by, one or more complex urban feature, described by a set of metrics. The metric-indicator link is maintained but mediated by the larger framework they are inserted in. The actual list counts 136 indicators grouped first in 12 families (referring to DOP) and then in 5 groups made by the sum of the 3 Determinants plus 2 purely performance aspects as Management and Governance. They have been taken from various list and studies found in literature and no one of them has been invented from scratch. The number is already higher than most common rating systems list (51 criteria in BREEAM Com, 80 in CASBEE UD and 53 in LEED ND).

6.3.4 SDG 11 Specification

The Sustainable Development Goals are the blueprint to achieve a better and more sustainable future for all. They address the global challenges we face, including those related to poverty, inequality, climate, environmental degradation, prosperity, peace and justice. The Goals interconnect and in order to leave no one behind, it's important that we achieve each Goal and target by 2030 (UN.org 2019). This list of 17 goals is the answer to the need of a comprehensive global framework for sustainability (Figure 69).

Figure 69 Sustainable Development Goals (UN.org)

Among them, number 11 is surely the one more closely related to cities, where the research can give a larger contribution. Cities are hubs for ideas, commerce, culture, science, productivity, social development and much more. At their best, cities have enabled people to advance socially and economically. With the number of people living within cities projected to rise to 5 billion people by 2030, it's important that efficient urban planning and management practices are in place to deal with the challenges brought by urbanization (UN.org 2019). The targets of SDG 11 are the following:

11.1 By 2030, ensure access for all to adequate, safe and affordable housing and basic services and upgrade slums

11.2 By 2030, provide access to safe, affordable, accessible and sustainable transport systems for all, improving road safety, notably by expanding public transport, with special attention to the needs of those in vulnerable situations, women, children, persons with disabilities and older persons

11.3 By 2030, enhance inclusive and sustainable urbanization and capacity for participatory, integrated and sustainable human settlement planning and management in all countries

11.4 Strengthen efforts to protect and safeguard the world's cultural and natural heritage

11.5 By 2030, significantly reduce the number of deaths and the number of people affected and substantially decrease the direct economic losses relative to global gross domestic product caused by disasters, including water-related disasters, with a focus on protecting the poor and people in vulnerable situations

11.6 By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management

11.7 By 2030, provide universal access to safe, inclusive and accessible, green and public spaces, in particular for women and children, older persons and persons with disabilities

11.A Support positive economic, social and environmental links between urban, peri-urban and rural areas by strengthening national and regional development planning

11.B By 2020, substantially increase the number of cities and human settlements adopting and implementing integrated policies and plans towards inclusion, resource efficiency, mitigation and adaptation to climate change, resilience to disasters, and develop and implement, in line with the Sendai Framework for Disaster Risk Reduction 2015-2030, holistic disaster risk management at all levels

11.C Support least developed countries, including through financial and technical assistance, in building sustainable and resilient buildings utilizing local materials

Every target has in addition one or more indicator to measure and monitor its achievement progress.

IMM methodology approach provides to designers, local authorities, decision-makers and stakeholders a full understanding on how and why urban systems perform the way they do. It is also a decision support tool for transformation actions aligned to the UN 2030 SDGs. IMM indicators are able to quantify the effects of modifications in the various areas referring to almost all SDG, not only to number 11. If we look at the systemic representation of the SDG we clearly see how the different topics are interrelated in a web structure with different poles of attraction. The entering point of this graph for IMM is SDG number 11, but the indicators affect also additional SDG with lying close to it (Figure 70).

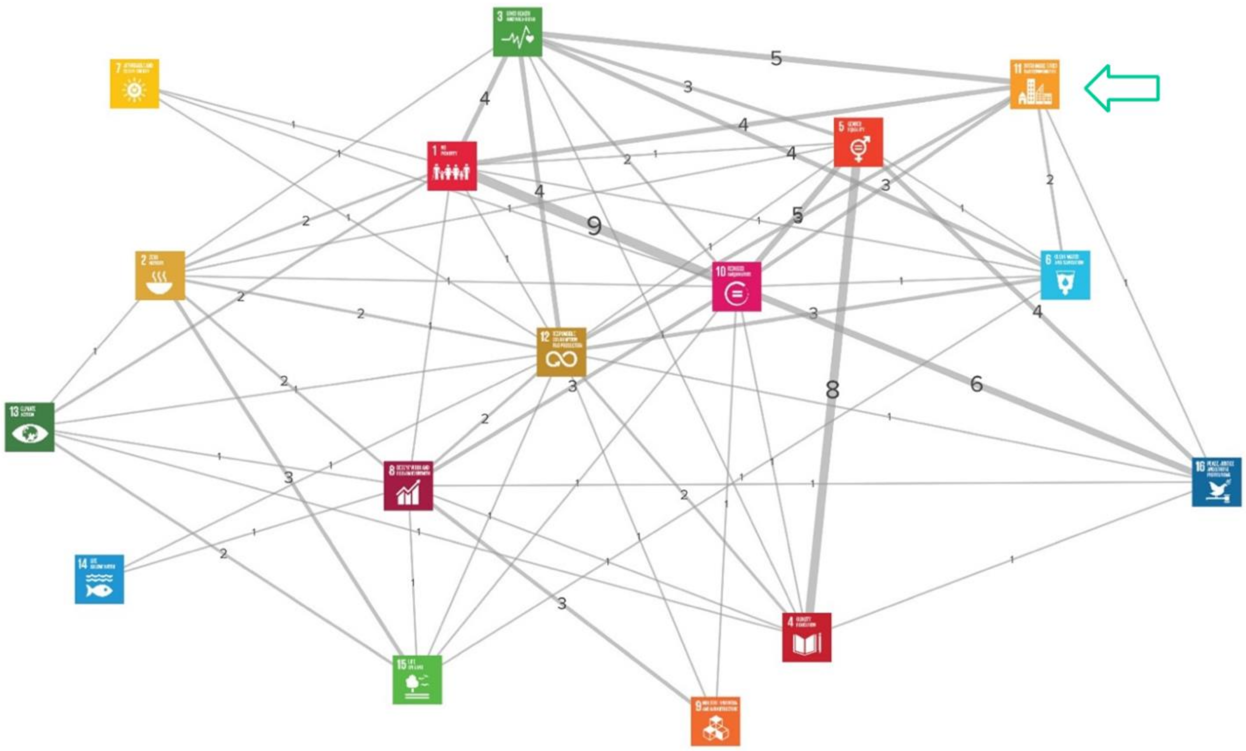


Figure 70 SDGs as a Network. David Le Blanc, UN Department of Economic and Social Affairs. The arrow on the top right represent the entering point for IMM methodology into the SDG system. It means that working on SDG 11 will impact also the remaining one

What allows this interaction are the indicators. Every indicator can be referred to a single SDG or shared among multiple ones. In the second case, the modification of an indicator activates a chain reaction into the system. In order to better explain this theoretical step an example can be helpful. An intervention on an urban system with an environmental focus (addressing SDG 11) will bring to working on targets 11.5 and 11.7 through the modification of the corresponding indicators. These targets affect also the Poverty, Health and Inequity SDGs (1,3,10). Figure 71 displays the full set of SDG related targets and their connections enabling systemic behaviour.

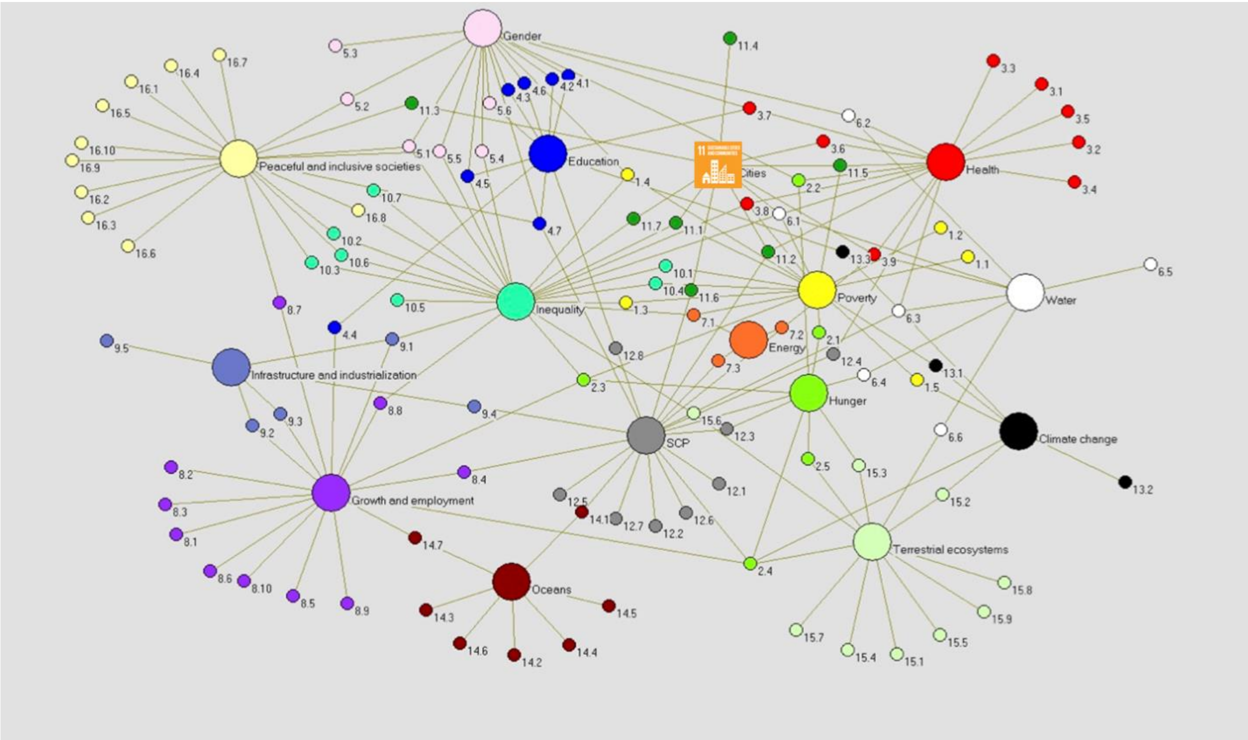


Figure 71 SDGs as a Network. David Le Blanc, UN Department of Economic and Social Affairs. In addition to the previous picture also Indicators are displayed as smaller circles. Some indicators are shared among more SDG making them interact in a systemic way

6.4 Compactness System Determinant

Compactness inside IMM is a system Determinant, the result of the second level of integration. It's a complex emergence coming from the integration of multiple KCs, which are in their turn the result of the integration of Components. It follows that any synthetic representation or measure will contradict the intrinsic complexity of the theoretical framework we are moving in. Moreover, also the efforts put in increasing the modelling complexity will result vain if followed by any attempt of collapsing this huge amount of data and information in a single "magic number". Pure formal compactness measures exist and the debate on that has been rich and various in the last decades. Most of the measures are reviewed by Yoshida & Omae (2005), Bribiesca (2008) and Li et al. (2013) and have been presented here in the previous chapter. By affirming that no synthetic measure is possible I don't want to criticize or underestimate the work of these authors, but declare that compactness as system determinant can't be understood and described as a mere quantitative formal aspect. Cmi (Massam and Goodchild, 1971) and Cndc (Bribiesca, 2008), i.e., are very clear and promising methods for its quantification but can't describe the complexity modelled up to now investigating all the morphological units composing a city.

We can imagine compactness, and the other IMM determinants, as rooms where urban structure and performances meet with a pattern that is specific for every context. They are lenses that allow when looking at city structure and performances, to see the interdependent elements and explore their ligand. Agents are the reason for having always different and context aware correlations. They, as the city they live in, are the result of previous system stages, and their behaviour is affected by cultural, climatic, religious, economic, and social aspects. We must be aware that in addition to porosity and permeability, also other KC like proximity (Jenks, Burton, & Williams, 1996) affects compactness. Considering the need of dealing with Function component it has been voluntarily excluded from the research, but not forgot. The relevance of this aspect is underlined also by the literature about sprawl measurement where not only physical aspects are taken into account (EEA, 2008).

6.4.1 Compactness definition

Compactness can be defined as the quality of being closely packed together or having all the necessary components or features nearly fitted into a small space. This is true for both physical and topological spaces (Encyclopaedia Britannica). Compactness is a tangible and physical dimension as it deals with the Euclidean space. It's materially built on the interaction between Volumes and Voids and deals with the reciprocal position of elements in space, no matter at which scale. The compactness measure of a shape, also known as its shape index, is a numerical quantity representing the degree to which a shape is compact (Gillman 2002). Compactness is acknowledged as one of the most intriguing and important properties of a shape (Angel et al. 2010) and is widely used as a descriptor in a variety of domain tasks (Li, Goodchild, & Church, 2013).

More recently, compactness has become a well-established principle used to guide city planning, evaluate urban settings, and study urban sprawl (Chandra, Chhetri, and Corcoran 2009; W. Li, Goodchild, and Church 2013). A possible way of interpretation of compactness could be land use efficiency, an optimized solution between Volume, Void, and Function layers. The "compact city" is characterized by high densities and relatively shorter distances; it is meant to accommodate urban development while minimizing the use of undeveloped land. The European historical cities are featured by a high density of usage, short travel distances, and a higher quality of life. Conversely, urban sprawl is the large and low density city expansion to the urban suburbs (Thomas, Tannier, & Frankhauser, 2010).

6.4.2 Compactness Optimization

But how compact a city could or should be or which is the optimal level of compactness of a city are still open questions. The reasons why it's so hard, and even impossible, to answer them are mainly two. The first is related to the definition of city form. It seems that the argument for and against the compact city is unnecessarily complicated by the lack of definition of what kind of concepts people have in their mind when discussing city form (Frey, 1999). If we look at the city, it's hard to define which its shape is. As in the problem of the length of the coastline of Britain, that lead to the invention of box counting method to measure the dimension of an object, the shape of the city vary according to the distance you look at it. At the regional level is a patch, at the metropolitan level some undefined patch-looking agglomeration and at city and neighbourhood scale a collection of buildings. Those buildings have their own shape that could be see with increasing level of detail from simple volumes up to ornament. Lead to the extreme, in a provocative way, every brick they are composed by can still be zoomed up to the particle scale using microscopes or other appropriate tools.

We are simply not able to represent and measure the real consistency of any object but we can accept some approximation. Among the different above mentioned scales, there's no one better or more appropriate than others for determining the shape of the system they belong. As it's true that the performance of an urban system is more than the sum of its constituents (buildings), that is valid also for the structure. Can we define compact an area characterized by very compact buildings randomly scattered at large mutual distance? Or, vice versa, highly irregular buildings tightly nestled in a small area? And how can we determine the level of compactness of a system composed by a succession of these two cases? The actual framework shows how every scale has found its own measures and approaches. Studies proposing set of metrics for measuring urban sprawl at the urban patch scale exist and can be seen as the top-down version of our bottom-up approach (EEA, 2008; Huang, Lu, & Sellers, 2007).

These two branches of study contribute in the definition of compactness and, eventually, also future application at intermediate scale could enrich the modelling complexity and improve our understanding, provided that no study expects to be exhaustive on its own.

The other reason appears by looking at the selected (and discarded) spatial metrics in this research. Almost no one of them can be truly optimized in an absolute way. In some cases, maximum and minimum values are often above or below some thresholds that allow to define that object as an urban environment suitable for life. To make a simple example we can consider BCR_G. A value of 1 represents a completely artificial environment with no open space, light, wind or flow permitted. A value of 0 is a totally natural landscape with no possibility to live in it in a civilized way. The same could be said for Compactness metrics. A value of 1 is a full solid circular or spherical mass where there's simply no space for life. Other metrics can meaningfully reach these values but there's no a priori way to determine if is preferable to have a very high, low or intermediate value. For this reason also the diagrams previously showed are a powerful tool to compare different state of the same system, can be used to compare between them different subsystems, but don't allow to display any sort of benchmark or ideal pattern of values. The only possibility to get closer to this goal is to recursively apply the IMM methodology on the same context trying to understand its specific pattern between urban structure and performances, or on extremely different context waiting for the emergence of clear universal correlations.

6.4.3 Compactness investigation

Now that we have defined the theoretical framework and the investigation methods for determining the Compactness of an area and how this affects its environmental performances it's time start applying it in order to collect some results to be interpreted in order to increase our awareness on the topic. Compactness structure and performances have been calculated for all the existing Milanese NIL (Nucleus of Local Identity), a set of 88 neighbourhood-like areas defined by the municipality.

These areas range from an area of 19 to 1371ha (Ronchetto delle Rane, Parco delle Abbazie), a population of 3 to 57'000 inhabitants (Parco Sempione, Buenos Aires) with population density values varying from 6 to 23'000 inhabitants per square kilometre. There historical parts, modern developments, contemporary suburbs, urban parks, agricultural-like areas and brownfield waiting for being redeveloped.

As already mentioned in the Porosity and Permeability sections, a different set of metrics has been used here respect to the one previously tested on the nine case studies (Tadi et al. 2017; Carlo Andrea Biraghi et al. 2019). The reasons for this choice, in the case of permeability are the impossibility to automatize the calculation for Tor, β_N and D metrics on such a large sample, the irrelevance of Top in such a flat city, the need of huge cleaning operation on the datasets for ALL_N, the correlation between SA and with the Street Cover Ratio (SCR) indicator, used among the others to assess performances. For Porosity instead, the results coming from the metrics retrofitting process suggested to substitute some bad performing metrics with others.

Porosity metrics are: BCR_G (Gross Built Coverage Ratio), FAR_N (Net Floor Area Ratio), BBVR (Building Built Volume Ratio), BSR (Building Surface Ratio), BFR10 (Building Buffer 10m Ratio), CTBR (Courts to Building Ratio).

Permeability metrics are: BmbgO (Building minimum bounding geometry Orientation), BLBP (Block Built Perimeter), BLmbgA (Block minimum bounding geometry Area), BLmbgO (Block minimum bounding geometry Orientation), BLmbgC (Block minimum bounding geometry Compactness), VBLPR (Virtual Block Perimeter Ratio).

Performance indicators, divided per family, are:

1 Ground Use – 1 VD (Built Volume Density), 2 BD (Building Density), 3 PD (Population Density)

2 Permeability – 5 SCR (Street Cover Ratio), 8 BLD (Block Density)

3 Multiplicity and Variety – 11 PAcR (Population Activities Ratio), 13 JHR (Job Housing Ratio)

4 Biodiversity – 17 LUsh (Landuse share)

5 Green Spaces – 26 GCRt (Total Green Coverage Ratio), 28 GCRu (Urban Green Coverage Ratio), 29 TD (Tree Density)

6a Cyclability – 31 BikeD (Bicycle path Density), 31b BikeAl (Bicycle path Average Length)

6b Walkability – 41 ND (Number of Crosswalk), 45 AxBLP (Number of Accesses every 100m of Block Perimeter), GFAc (Ground Floor Activity)

7 Flows – 50 PTA (Public Transportation Accessibility), 51 LlPR (Road length per Capita), 41b NDER (Number of Cul de Sac over total nodes)

8 Interchangeability – 67 Modesh (Transportation Mode share), 67b MMsh (Metro line share), 67c StopD (Public Transportation Stop Density), 67d LineD (Public Transportation Line Density)

10 Food Management – 78 GCRa (Agricultural Green Coverage Ratio)

12 Water Management – 86b WAR (Water Area Density)

The results are collected in Appendix C where for every area has been produced a sheet including a planimetry, a radar diagram with the overlapping of Porosity and Permeability pattern, the values of the selected metrics and a set of 25 Compactness-related performance indicators taken from 10 of the 12 existing families referred to the Design Ordering Principles (DOP). On the top right corner of the sheet is indicated in green the position of the area in a ranking based on a synthetic simplified performance evaluation.

DISCUSSION

The above mentioned investigation is a significant sample that allows to make some correlation studies and to discuss the first results. Given that the analysis of the correlation between metrics has already been performed in chapter 5, we can now focus only on the metrics-indicators and indicators-indicators relationship. Most of the results are not surprising but deserve to be mentioned in order to show the clarity of these tools to improve our morphological understanding of an area. In fact, more than learnings on how one or more metric inevitably affect one or more performance aspect, they should be read as descriptors of specific ideas of cities within the same system. This to say that nothing impedes us to imagine an area with values not in accordance with these results, but is somehow harder to find it in the real world, especially in the selected Milanese case study.

We see that nine indicators are pretty highly correlated. They can be roughly grouped in two distinguishing between density and mobility indicators. In the first group we find PD, BD and VD while, on the second Modesh and PTA. BLD, SCR, ND and StopD belong to both families as can be considered mobility oriented density measures. Public transportation requires high PD values in order to be effective and a good accessibility is given by a multi-modal dotation and a great number of stops. Number of different lines seems a minor relevant indicator and not necessarily associated with the one just mentioned (0.47 as average correlation). A high number of blocks means a lower average dimension and a consequent increase in street area and number of crosswalks. This lead to a reduced speed in car traffic according to Schwartz (2008). More interesting is the correlation with the presence of ground floor activities. It has a 0.77 value with PD, taken as reference of the density measures, and 0.68 with PTA, reference on accessibility side. MMsh is also positively correlated with this macro group but in a weaker way as the passage of a metro line is affected by many physical constraints that introduce a degree of randomness to the effectiveness logic.

If we imagine to be looking at an area with high density and accessibility values, like for example Duomo (1), Città Studi (22) or De Angeli – Monte Rosa (58), it will be hard to find large green areas (GCR_t), especially agricultural (GCR_a), water areas (WAR) and cul-de-sacs (NDER). The presence of park-like central areas as Parco Sempione and Giardini Porta Venezia mitigate the relationship with the accessibility value (-0.09). The presence of trees (TD) seems a more independent variable as the only remarkable correlations are with GCR_u and PAcR. While the first is obvious, the second describes some neighbourhoods developed starting from the seventies characterised by large green private areas and big isolated buildings, both residential and public. Another sign in this direction is a slightly positive value of Lush (0.22) paired with a negative GFAc one (-0.35) that confirm the absence of windows shops aligned on the sidewalks, substituted by the presence of malls and public services. NIL as Parco Forlanini – Ortica (24), Gratosoglio – Ticinello (41), Barona (46) and Gallaratese (65) are examples. These areas have a Porosity diagram similar to the pike of a lance with variation on the FAR_N value according to the prevalence of tower or linear building typologies.

These can be considered two ideas of city at the extremes of our sample and all the intermediate values in the different metrics and indicators represent some compromise area on one or more aspects. Every area is unique and even if the metric values allow to catch even the finest differences, from diagrams' pattern shape is possible to classify areas according to some types. Non-urban areas tend to have a vertical line as porosity diagram. This why BBVR is not affected by the number of buildings and BFR10 presents high values when elements are located at great mutual distance, and all the other quantitative based metric present low values. The only exception can be CTBR as it happens is Giardini Porta Venezia (3) and Parco delle Abbazie (85), characterised by a good percentage of monumental court-type buildings. It's interesting to notice that lower BFR10 values are not a prerogative of the city centre (Duomo – 1 – 0.29). In fact they are typical also of the historical settlements previously located outside the city walls that now became part of the continuous city (Affori – 80 – 0.29; Baggio – 55 – 0.32).

Central densely urbanised areas have the highest values of BCR_G, FAR_N and BSR and intermediate values for BBVR (0.75ca, intermediate considering that it ranges here from 0.5 to 1). BFR10 and CTBR may vary according to the prevailing building typology and average street width but always remaining in mid-low values for the first and mid-high values for the second. Area as Duomo (1) and Brera (2) can be taken as examples inside the medieval walls, Guastalla (4) and Magenta – S. Vittore (7) between medieval and Spanish walls with slightly lower FAR_N values. Immediately outside this former limit, on the main axis of expansion of the city, we found areas as Sarpi (69), also known as Chinatown, Buenos Aires (21) and Porta Romana (27) with a similar pattern. On the permeability side, these areas have very high BLBP and VBLPR values due to the alignment of buildings on block sides and the absence of cul-de-sacs. While these two parameters are clearly linked to the NIL construction period, the metric dealing with orientation (BLmbgO) is affected by NIL position within the city. Milan is a monocentric city characterised by a radial expansion on some main axis. This inevitably defines the orientation of blocks and, consequently, of buildings. The area of De Angeli – Monterosa (58) is a clear visual example. Exception to this are those districts built according to modern movement principles of aligning buildings to the helio-thermal axis like some of the blocks in Selinunte (57) or Lodi – Corvetto (35) NIL. The small variation in BLmbgO value shows that this relationship with the orientation is not so strict and that block are often aligned in two opposite directions within the same area mitigating the final average value.

Highest FAR_N value is in Garibaldi Repubblica, the new business district of the city, characterised by skyscrapers with iconic forms (BBVR 0.59) and huge voids for the presence of railway, parks and huge streets (BCR_G 0.29; BFR10 0.46). The presence of high-rise buildings emerge also in Stephenson (75), a marginal area in between railway tracks with a mix of abandoned and new towers with values of VBLPR (0.44) and SA (0.10) among the lowest.

Permeability diagram can be ideally divided horizontally in two. The upper metrics give clear results pretty aligned with the considerations made for Porosity. High values of SA and BLBP can be found in central dense areas like Duomo (1) and Brera (2), but also in Buenos Aires – Venezia (21), Porta Romana (27) and XXII Marzo (26) characterized by a smaller number of streets with a higher width and similar typologies. Areas like Bande Nere (52) and Tre Torri (59) only have peak values in SA, as they host very important arterial roads, while BLBP is average due to the presence of isolated buildings. Sarpi (69) and Ticinese (6) show the opposite trend because of the presence of huge portions of void as the Monumental Cemetery for the first and Navigli system and parks in the second. VBLPR has led clear nuances as half of the NILs present values higher than 0.85 and 88% values higher or equal to 0.70. For this reason we can affirm that cul-de-sacs are not a relevant element for the majority of Milano areas. Top values can be found both in the usual areas (Buenos Aires – Venezia – 21 – 0.98; Magenta – S.Vittore – 7 – 0.95) and in diverse situations as Baggio (55 – 0.98) and Villapizzone (71 – 0.96). Lower metrics describe something that is visible from the maps but that is not necessarily correlated with other morphological features nor allows to make a classification. All three block-box metrics (BLmbgAR-C-O) return ambiguous results in the selected sample. None of them reaches their respective highest values even if they are not only theoretically but also physically possible, differently from other metrics as BCR_G or SA. BLmbgAR could highlight the presence of rectangular-like blocks, common in gridded networks, but it tells nothing about block size or proportion. BLmbgC alone is able to describe the proportions of the bounding boxes but the same box could contain a number of different configurations. For this reason it could be helpful to look at them together and eventually integrate with additional metrics not included in this selection of six as AwaP or BD. Combined highest values can be found in XXII Marzo (26 – 0.85, 0.64), Città Studi (22 – 0.82, 0.52), Bicocca (15 – 0.82, 0.61) and Tibaldi (43 – 0.82, 0.66). The absence of high values of BLmbgC among all these grid-like areas shows that regular square-like grid is not so common in the city of Milan or, as in the case of the former Lazzaretto area included in NIL 21, this morphology is limited in space and the district scale is too large to allow their emergence in the average value. This area is and characterized by nine rectangular blocks with buildings aligned on block perimeter. Four of this nine are almost perfect squares and for them we have values equal to 1 for BLmbgAR, BLmbgC and BLBP metrics. They occupy nearly 2% of NIL area and the remaining blocks are a mix of more elongated rectangles, triangles and trapezoids measuring 0.76 for BLmbgAR, 0.64 for BLmbgC and 0.93 for BLBP.

Another aspect that must be mentioned is a limit of the proposed set of six permeability metrics mainly for the assessment of peri-urban areas or contexts when the concept of block is confused or missing. In fact, while in an urban structure block is a crystal clear concept and morphological unit, the same could not be said for countryside and transition areas among these two extremes. What has been here assumed as block are areas completely bounded by streets containing at least one building. In the investigation sample, i.e., some areas have not any single block because the streets bounding portions of land continues outside the city boundary as in the case of Parco dei Navigli (86) and Parco Agricolo Sud (87), or NIL boundary as for Quintosole (39) and Ronchetto delle Rane (40). The case of Cascina Triulza – EXPO has the same problem but due to the fact that the portion of land that hosts all the pavilions is actually bounded by the railway and not by streets. This problem is not compromising the whole permeability assessment as the measures used in Biraghi et al. (2019) presented before are not affected by this object-oriented issue. Tortuosity value would be almost 0, Constrictivity equal to 1, Directness quite low and ALL_N even higher than 1.

Even if the research refuse any simplistic approach, at this point I found useful to have something that could help understanding a sort of overall district performance as going through all the indicators, not represented in diagrams, could be hard. A very rough synthesis attempt is the map used as cover of Appendix C . It's a graduated representation of all the NILs based on a sum of their ranking in every performance indicator. The choice of using ranking instead of benchmark values comes from the presence of some very extreme high values among the latter that could alter the results. Positive indicators, that should be hopefully maximized, are added while negative ones are subtracted. The lower is the result the better the area is performing. The result shows that most of the best performing areas lie in an intermediate ring going from the former medieval walls to the railway ring. First five positions are occupied by Buenos Aires – Venezia (21), Washington (51), Magenta – S.Vittore (7), Isola (11) and Centrale (10). All these areas are appealing on the real estate market even if not the most expensive ones. It must be noticed that this ranking is based on a selection of IMM indicators considered manageable in terms of number and calculation requirement without any pretention of being the ideal performance assessment method. The weight of the different Indicators' families is unbalanced especially towards mobility aspects and lacks some important issues as the energy and waste management.

7 Porto di Mare Eco-District

This last chapter presents the Porto di Mare (Milan) Eco-District project by the author inside IMMdesignlab, together with the students of Sustainable Multidisciplinary Design Process (SMDP), as a moment of synthesis of the content and the approach presented up to now.

As first step the difference between district and neighbourhood is explained, together with the reasons that encouraged the choice of the first term for the thesis purpose. Contextually, also the most adequate prefix is identified in eco-. The decision to use the district as the intermediate scale for interventions with the goal of activate a global system reaction is supported by a literature review. From the same literature also some good principles of urban design are gathered.

Later, the Eco-District is presented as a performative design approach oriented towards principles of environmental, economic and social sustainability. The idea starts from the need of something more than a collection of high performing individual buildings. Eco-district is a systemic approach to urban design setting ambitious performance targets with the aim of providing high quality of life standards. After exploring some definitions and general guidelines, the impossibility to think about an Eco-District model is demonstrated stressing the important of the context also in terms of its agents, speaking about strategies to increase citizens' consumption awareness in food, housing, mobility, goods and services. Alternative commonly used labels as Near Zero Energy District (NZED) and Smart District are discusses and differentiated. The actors section clarify how this holistic approach need the involvement of citizens, municipalities, private investors and even the need of incubators-like structures in order to facilitate such complex transformation processes. Eco-District projects are classified in the main intervention kind varying from bottom-up incremental processes on consolidated neighbourhoods to the completely new development of an area.

It follows a survey of existing case studies in USA and Europe, with an additional focus on Italian and Milanese framework. A short summary focuses on common feature and exceptional local characters of this large sample of heterogeneous interventions. The positive aspects are balanced with a collection of disregarded expectations, methodological critics and improper use of terms for purely commercial purposes. An additional analysis using IMM DOP as a tool for a systemic reading of five selected projects (Hammarby Stockholm, 22@ Barcelona, Jätkäsaari Helsinki, HafenCity Hamburg, Msheireb Doha) is presented introducing the content of Appendix E, before coming to conclusions.

The context of the case study is then introduced starting from a quick overview of the Milanese contemporary context. Following the IMM phasing, the investigation phase casts the light on Porto di Mare area, dismantled into its Components with the Horizontal Investigation and read through Key Categories lenses with the Vertical Investigation. The diagnostic part is completed by IMM indicators calculation for the state of the art. The genesis of the Eco-District project is retraced exploring the Formulation and Transformation phase as already published by the author (Tadi, Biraghi, and Zadeh 2017, 2019).

The Retrofitting part bring back the attention on Compactness as a comparison between the state of the art (SOA), the Eco-District project (SMDP) and an alternative transformation scenario (AD2Y) is performed using as a tool the same synthetic comparative sheets used for NIL investigation at the end of chapter 6 (Appendix D). This application on different existing or hypothetical stages of the same urban system is seen as a complementary validation to the proposed methodology for Compactness assessment and a further step towards the comprehension of its patterns. The results are discussed focusing on morphology environmental implications.

In conclusion, the dissemination activity related to Eco-District project is presented to prove the consensus for the adopted method not only in the scientific community but also between local actors willing to take care of their city.

7.1 Eco-Districts

7.1.1 District vs Neighbourhood

District and neighbourhood are often as used interchangeable words in the literature. Even if they are synonyms, they represent two slightly different concepts. Districts are areas of county or cities characterized by a particular feature or defined for administrative purposes. It comes from the Medieval Latin 'districtus', that stress the presence of a proper jurisdiction, and classical Latin 'distringere', literally to draw apart, to separate.

Neighbourhood refers to an area or a community within a town or city. It's also used to indicate an area surrounding a particular place, person or object. It implies a sense of closeness without a specific territorial limit. From a mathematical point of view, it can be considered the set of points below a given distance to another target point. The problem is that neither target points nor distances are defined in a clear way in urban studies. It follows that neighbourhood boundaries are blurred and may overlap as they are shaped by individual agents. Neighbourhood is the quality of being a neighbour, of living nearby, next to each-other; district is an administrative division of an area.

The Eco- of Eco-Districts stands for Ecology. Ecology studies the relationships between organisms and their environment. Some of the most pressing problems in human affairs - expanding populations, food scarcities, environmental pollution including global warming, extinctions of plant and animal species, and all the attendant sociological and political problems - are to a great degree ecological (Encyclopaedia Britannica)

For these reasons, district seems the more appropriate term to be used in the process of urban modification. The word jurisdiction sounds very political but can be interpreted as competence. Applying an ecological approach to an area requires the possibility to manage and intervene on all these different aspects. Some of them, as the one related mainly to management like water, energy and waste, need to be thought for a precise area and sized to efficiently support its needs. Neighbourhood is too vague and unstable to be used for energy purposes and infrastructural design and construction. This doesn't mean that district neglect the social dimension as people can be seen as a local resource, as well as the more traditional natural ones, and their behaviour, in the end, is one of the key aspects for the success on any possible initiative.

7.1.2 Why Districts

International precedents show that districts provide the appropriate scale to test integrated sustainability strategies because they concentrate resources and make size and risk more manageable. The district is the optimal scale to accelerate sustainability - small enough to innovate quickly and big enough to have a meaningful impact (EcoDistricts 2014). Mori and Christodoulou (2012) confirm that communities are nowadays considered as a proper scale to assess sustainability of the built environment. Neighbourhoods are laboratories for sustainability innovation. With a holistic viewpoint, district-scale developments are uniquely positioned to be a major driver of the next generation of high-performance buildings and an intelligent electric grid, and to benefit financially from such leadership (L. Campbell and Olgyay 2016).

Considering city as a CAS the benefits of the interventions at the district scale will inevitably affect the whole city. Nevertheless, one should bare it on his mind that the urban sustainability is not achievable solely by sustainable transformation of different neighbourhoods. According to the holistic approach of CAS, the structure which bonds these districts together is more significant rather the individual elements. “The fact that the district is the fundamental compositional unit of the global urban structure does not mean that it is possible to make a sustainable city simply by juxtaposing districts. Districts need to be nested in the metropolis, in a series of coherent scales ordered by limits nodes, and long-range connections” (Salat, Labbé, and Nowacki 2011).

A district is a densely populated, multi-use, and geographically cohesive area (ZEB Resource Hub 2018). Districts are planning unit with a spatially or community-defined geometry. They have a distinct character which provides coherence, allowing the whole to be viewed as a single entity. They may be identifiable by a recognizable morphology, the nature of the architecture of their buildings or by their use (M. (Michael) Jenks, Burton, and Williams 1996). This make easier to investigate the link between the form of the city, its functioning and its performance. As a fundamental building block of the city, neighbourhood is not only the basic space to create a truly sustainable community but also the starting point for the use of low carbon ideas and technologies to address climate change and promote the construction of a low-carbon city (Canosa Zamora and García Carballo 2018)

Their city form is supposed to be: people friendly, efficient, legible and imaginable and to establish sustainable relations with the hinterland (Hildebrand 1999). The presence of recognisable urban elements plays a role in reaching these objectives according to many authors. These are landmarks, static and recognisable objects which can be used to give a sense of location and bearing, paths, major avenues of travel through the environment, nodes, important points of interest along paths and edges, structures or features providing borders to districts or linear obstacles (Ingram, Benford, and Bowers 1960; Lynch 1960). Jenks et al. (1996) believes that the districts should be developed, while they carry their local characteristics, as a part of the whole urban form. On the other hand, Urban Task Force focuses on the point that urban neighbourhoods should be vital, safe as well as beautiful places to live. In fact, this is a matter of economics rather than simply aesthetics. Since cities constantly compete with each other to host increasingly enterprising international companies, their credentials as attractive, vibrant homes are major selling points (Yavuz & Kuloglu, 2017). Therefore, it is considered necessary that greater significance be given to the design and management of public realms in order to provide people necessary opportunities for public interaction and social integration besides the sense of place (Rogers 2005).

7.1.3 Eco-Districts Approach

Eco-Districts represent a different approach towards the territory and aim to achieve higher quality of life standards. “An Eco-District is more than a mere accumulation of buildings boasting ultrahigh-tech specs! By combining together, the concepts of “eco” and “district” mutually enrich one another. It has been clearly demonstrated, such a neologism allows to restore the complexity of the totally overused word “eco.” On the other hand, more profound meaning is restored into the word “district”: neighbourhood, living together, solidarity, closeness, pride, identity, intensity, density...” (*Paris Innovation Review* 2013).

They follow sustainability principles and promote landscape and economic heritage of cities optimizing the use of natural resources, selecting construction materials, developing mobility strategies and fostering social relations. Their main challenges are to create a high quality of life level, to reduce individual transportation, soil sealing and to contrast crisis strengthening local economic fabric (ANCE 2013). An Eco-district is based on a performative design approach and represents the basic unit of the durable city and its goal is the creation of an environmental heritage for future generations. It's not intended to be an island but to participate into an organic strategy for the development of the whole city (Sartoretti 2014).

This label designates an urban planning aiming to integrate objectives of sustainable development and reduce the ecological footprint of the project. This notion insists on the consideration of the whole environmental issues by attributing them ambitious levels of requirements. Eco-Districts commit to self-organizing, setting ambitious sustainability performance goals, implementing projects and tracking the results over time (EcoDistricts 2014).

Defining an Eco-District model is almost impossible as every experience tightly fits to a specific context with sometimes non-exportable solutions. In many cases, more than a sudden large scale operation, the birth of an Eco-District passes through a series of minute interventions, realization of macro-level goals coming, i.e., from the Agenda 21 (Sartoretti 2014). More than sharing features or formal characteristics, Eco-District shares a design strategy based on a systemic approach. This deals with cycles and ecosystems (water, energy, wastes, materials, fluxes) harmonizing environmental, economic and social performance in a participative and multidisciplinary process (Charlot-Valdieu and Outrequin 2007).

More than the 70% of people environmental impact is determined by where they live, how they commute and what they eat (ANCE 2013). Footprintcalculator.org (Ecological Footprint Calculator), a website that allows to estimate our impact on earth, confirm this by using as consumption categories for its estimation food, housing, transportation, goods and services (Figure 72).

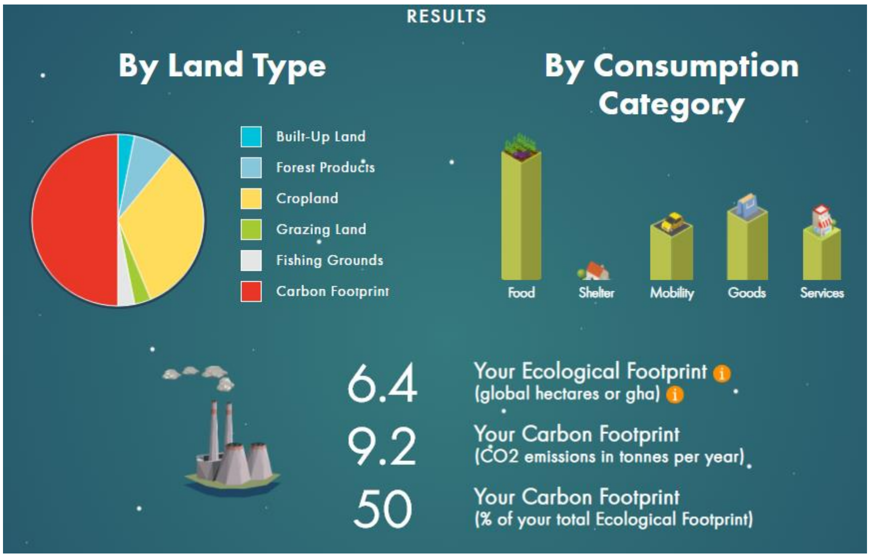


Figure 72 Author's footprint calculated using footprintcalculator.org

Eco-District systemic and bottom up approach tries to act on people making sustainable behaviours much easier than elsewhere, transforming them into more sensible agents (EcoDistricts 2014). In order to achieve this result it is necessary to modify urban environment with a process intended to improve its performances. The so called "eco-density" approach aims to reproduce a compact and green city with a low ecological footprint (Sartoretti 2014). High values of population density are coupled with green spaces and urban parks, elements which contribute to improve the perception of microclimate and acoustic comfort (Lossano and D'Ambrosio 2012).

In the existing literature other two similar concepts has been used to describe comparable initiatives: Zero Energy Districts (ZED) and Smart Districts. The first one seems to particularly stress the energetic aspect taking other qualitative aspect of district planning, as for example the presence of green, bicycle paths and mix use, for granted. Mazzucchelli & Baroni (2017) define “smart districts” as the generic meaning of ZED, and highlight their importance in the optimization of energy efficiency in the construction sector. The principle is to connect single high performing buildings into common district energy strategies.

ZED has the potential to dramatically improve the economic competitiveness, resiliency, environmental quality, and energy independence of communities. Zero energy districts consist of multipurpose, energy-efficient buildings and use a variety of approaches to optimize energy use. For example, aggregating buildings' energy loads and using district-wide heating and cooling strategies that take advantage of waste heat can result in significant reductions in energy. In this sense we can see the definition of “Green Districts” (Bouton, Newsome, and Woetzel 2015) as a first step towards ZED.
Common design principles are energy saving, use of renewable resources, use local and ecological construction materials, water and waste management, ecologic mobility and quality of life. These innovative and respectful interventions, often involving citizens in participative governance activities, want to become economically self-sufficient in short times.

It is curious to notice that among the requirements of an Eco-District ANCE (2013) lists some very basic dotation of any new urban development as sidewalks and green public spaces or seismic safety. Some other requirements are acoustic islands or car free zones, thermal insulation, district heating. District energetic modelling becomes crucial because single buildings' one doesn't allow to correctly visualise and evaluate the overall behaviour (Mazzucchelli and Baroni 2017).

ACTORS

In a survey launched in a neighbourhood in Wuhan, China, results indicate that most respondents concerned the low-carbon impact on their daily lives and expected the government to make differences in low-carbon transition (Peng, Wang, and Guo 2018). Municipalities and regions have the responsibility to stimulate this transition from standard neighbourhoods to Eco-Districts by geographically concentrating innovative operations intercepting a local need. Citizens must be ready and willing to be trained and to adapt to more sustainable new life habits. Moreover economic advantages follow the environmental and social one. Higher initial costs are profitable long term investments thanks to the adoption of technical innovations. The needs of an Eco-District are much lower than a traditional district. Heating energy and CO2 emissions are reduced of more than 60%, electricity is 30% lower and is possible to daily save up to 100l of water per inhabitant. A house inside an Eco-District consolidates and increases its value becoming an interesting investment. These areas often become very popular and representative of the ecological efforts of the whole city. Their construction is also an opportunity to train professionals in the involved sectors, representing an incubator of sustainable enterprise and green work (ANCE 2013).

To support the development and refinement of this new approach, the U.S. Department of Energy (DOE) launched the Zero Energy Districts Accelerator (ZEDA) in late 2016. ZEDA encourages the expansion of zero energy districts by partnering with district developers, planners, owners, and key additional stakeholders to develop the energy master planning documents needed to achieve energy goals during the lifespan of the project (DOE 2016). ZEDA brings together districts, national laboratory researchers, subject matter experts, and national organizations doing related work to explore and address issues facing zero energy districts (Pless, Polly, and Zaleski 2018).

In addition, the Rocky Mountain Institute has developed a business model for developing net zero energy or ultralow energy districts in a way that is attractive to the district developer, parcel developer, and tenants; creates a profitable business for an integrated energy services provider; and benefits the local electric grid and neighbouring community (L. Campbell and Olgyay 2016).

According to several authors there are three main typologies of Eco-District intervention:

- New urban development
- Regeneration of an existing neighbourhood with a coherent intervention on buildings, to improve their efficiency, and public spaces for urban quality.
- Consolidated existing neighbourhoods where the approach focus mostly on sustainable citizens behaviours

(ANCE 2013; Sartoretti 2014; "Example Projects | Urban Green-Blue Grids" n.d.)

These kind of initiatives have a great variety scale, actors and settings so it's hard to find precise criteria to gather them. In addition every different experience, even the smaller ones, may present one particular solution that could be scaled and transferred in other contexts so it can be useful to not exclude them from the analysis.

7.1.4 Case studies

This section makes an overview of Eco-District projects located mainly in Europe and US, trying when possible to compare them according to their structure and technological strategies for implementing environmental performances.

United States

Pless et al. (2018) collect the projects participating in the Better Buildings Zero Energy Districts Accelerator, giving an overview of the American current state of the art. These recent projects share the same principles but differ under many aspects. Site size vary from the 40ha of Sun Valley EcoDistrict, Denver, Colorado (SVED) to the 270ha of Advanced Energy Community, Huntington Beach, California (City of Huntington Beach). Return of investment period range from 5 years in National Western Center, Denver, Colorado (National Western Center) to 20 years of Ford Twin Cities, Saint Paul, Minnesota (Made in St. Paul). The projects have different final land use but they all insist on critical areas as brownfields, former industrial areas or low income neglected residential areas. The only exception is Energize Fresno, California (Local Government Commission), that interest a large area including the business district in a sort of diffused ZED made of punctual disconnected interventions. During a 18-month master planning process, the project leaders identified an "Energy Opportunity Zone" that would comprise a portfolio of commercial and residential projects across a range of building types and residential neighbourhoods, including 13 development sites, two activity centres, two program enhancements, and two electric vehicle charging proposals. It is nice to notice the presence of a No-profit initiative whose final goal is delivering projects with a social return and an economic benefit to community members and the city as a whole (SVED). Another interesting point is to notice than it is possible to combine ZED approach with a doubling of building footprint, usually seen as a negative thing (NWC). From the communication point of view the Western New York Manufacturing Zero Energy District, Buffalo, New York (Better Buildings Initiatives), deserve to be mentioned. The first planned project in the district is designed to be a large, zero energy, light industrial building to serve as a "lighthouse project" to attract more zero energy development. As the first certified zero energy manufacturing facility of its size in New York State, the project will result in a state-of-the-art, dynamic facility to showcase new advances in renewable energy construction. The facility will serve as a valuable hub for construction education and performance testing, energy management, and workforce training for the remaining district build-out and the greater region. Midtown Atlanta EcoDistrict consists in a platform for an existing community to collaborate on initiatives that result in improved environmental and economic performance. The structure of the existing neighbourhood is already favourable to the establishment of an Eco-District having mix use, transit options, green space and existing built pedestrian friendly blocks (Midtown EcoDistrict).

Another sources for similar initiative in the US is the Ecodistricts website (www.Ecodistricts.org) that graphically represents all the projects on a world map and collects 14 initiative in the section “Case Studies: stories from the neighbourhoods”.

Europe

Europe and in particular northern countries are pioneers on these initiatives and the first projects started in the early nineties. The city of Freiburg is a front runner in this field developing the first Eco-District (Stadtteil Vauban) still working and improving, and other two large interventions as Rieselfeld (Siegel 2009) and Weingarten (Stadt Weingarten). Other German projects that deserved to mentioned are Kronsberg in Hannover (Kronsberg Life) and HafenCity in Hamburg (HafenCity Hamburg). Sweden is also particularly active and sensible to the topic. The most relevant and famous projects are Hammarby Sjöstad in Stockholm (Hammarby Sjöstad 2.0) and Bo01 in Malmo (Urban green-blue grids). Not far from them, Ørestad in Copenhagen, Denmark (byoghavn.dk) and Jätkäsaari in Helsinki, Finland (Uutta Helsinkiä) complete the Scandinavian picture. Remaining on prevalent cold climates we found UK projects as Bedzed (ZEDfactory) and Greenwich Millennium Village (GMV) (Greenwich Millennium Village) in London, Solar City in Linz, Austria (Castelli) and EVA Lanxmeer in Culemborg, Netherlands (EVA-Lanxmeer.NL). Mediterranean countries followed the success of their neighbours sometimes even applying these initiatives on a broader scale, as in the case of France, with more than 200 built or programmed interventions spread on the whole country. Four case will be presented here: De bonne in Grenoble (Graie.org 2004), Ginko in Bordeaux (Eco Quartier Ginko), Euroméditerranée in Marseille (Euroméditerranée.Fr) and the Docks de saint-ouen-sur-seine (Les Docks de Saint-Ouen). Also Spain have some examples but mainly concentrated around the two main cities, Madrid, Puente de Vallecas (Canosa Zamora and García Carballo 2018) and Barcelona, 22@ District (barcelona.cat) and Trinitat nova (Barcelona accions per l’habitage 2008). I decided to include in this collection also Msheireb project in Doha, Qatar (Msheireb Properties) for its resemblance with a European urban fabric and for a lack of similar initiatives in the African or Arabic context that would make necessary to dedicate them a specific section.

Some authors made a work of selection and comparison among some of the above mentioned projects, helpful for more detailed information on the specific case studies. Among them need to be mentioned the research of Lossano & D’Ambrosio (2012) on the Scandinavian countries, the analysis of Flurin (2017) selecting four cases according to their initiator (private, public, residents) and construction period, the investigation made by Williams (2016) on the impact of first realizations on the city development regime and the thesis of Favaro (2015), from Padova University, comparing Eco-District according to architectural, urban planning and energetic parameters. Another thesis developed in Politecnico di Milano (Mauri, Mazzucchelli, and Sala 2018) under IMMdesignlab supervision treated the topic as a preliminary research for the development of a building inside an Eco-District. These last two works produced very interesting synoptic representations that have been inserted in a specific appendix of the present research (Appendix

E). It follows now a synthetic summary of common and exceptional features of the above mentioned projects under the different aspects.

All the interventions deal with many sustainability issues defining integrated strategies to reduce the environmental impact of the neighbourhood. They range from the 82 apartments of Bedzed to the 6000 of Kronsberg. They are usually processes more than simple projects (Marseille Eco-District started in 1995 with an extension of 310ha and has been implemented with other additional 170ha in 2007 for a total project budget of 7 billion) and citizens are often involved. The principle of learning while planning, introduced in Vauban, allows to increase citizens' sense of responsibility and environmental awareness. Also Trinitat Nova project organized workshops with multi-disciplinary actors made of both technicians and citizens to define a common vision and six priorities for the area. Eva-Lanxmeer housing development is a model for participative aspects as the entire neighbourhood, except for the masterplan, has been designed and conducted by representatives of the future residents. These activities show to the people the importance of being active for their community and foster the creation of committees or working groups to keep the neighbourhood alive. The body constituted for the development of the project, usually called Forum, coordinates these groups as in the case of Weingarten ("Live together", "Active for Weingarten", "Social Well-being"). Always in Barcelona, i.e., some years later the birth of the Eco-District educational and cultural programs were launched to fight school failure and increase sustainability awareness. Social mix is encouraged with housing policies and a control on housing prices as well as functional mix to promote local employment and entrepreneurship. In Docks-de-Saint-Ouen, where all buildings have green roofs and parking spaces and structures are pooled, 40% of residential spaces is dedicated to affordable housing. The proximity or the accessibility to the city centre is also important. De Bonne slogan for example is "to allow everyone to live within the city". New districts are designed as homogenous parts of the city in which there are relevant service functions (universities, research centres, cultural districts, centres of entertainment, sport, shopping malls, conference or exhibition centres). The challenge starts from the demonstration to create a "city environment effect" in non-central areas, aimed to avoid any loss of relevance in relationship to the historic city. Bo01 in Malmo is a relevant example as in addition to common shops and services introduces a new metropolitan function as a university.

To reduce mobility impact, private cars are limited or forbidden and public transportation, walkable and cyclable paths and shared electric vehicles are proposed as alternatives. The presence of multi-modal alternatives is an important factor to make public transportation competitive with the private one. Ginko and Hammarby projects have four different alternatives thanks to the presence of navigable water canals.

Eco-districts are not a mere collection of technological implementation. They propose a new kind of urban form considered more efficient. It takes the density and the heights of the city centre but with bigger distances among buildings, filled with green and blue areas. Ginko project in Bordeaux introduces innovative landscaping to manage storm water mixing Green and Water city models. The suburb model of single family house with private garden is rejected and compacted into multi-family buildings surrounded by public spaces. Going into detail we notice that the attention focuses on different architectural aspects. In Rieselfeld an attempt to optimise the compactness of the volumes generated a building typology composed by a cube of 16m side containing apartments distributed on 5 storeys. In Bedzed the orientation towards south was adopted to maximize solar gain and photovoltaic potential.

Always in Bedzed construction materials were gathered and fabricated within a radius of 35km from the site. The principle of self-sufficiency and Km0 involve also food and energy supply. The use of renewable energy is a constant and sometimes it covers the full consumptions of the area as in Malmo. The most common sources are photovoltaic and geothermal, often integrated with passive heating or cooling systems as greenhouses or winter gardens. In Hammarby heating is provided on one half by non-recyclable wastes, and on the other by the combustion of biological-oil and dark waters. Ginko and Jätkäsaari uses also wind turbines while Euroméditerranée uses the first geothermal marine power plant for houses heating and cooling. Where not strictly necessary, cooling is even forbidden.

Another important aspect is monitoring the impact of the adopted solutions. This allows to communicate the achievements not only between the residents but also to the outside increasing the appeal of the area. Each of these districts is measuring a set of important sustainability indicators as local greenhouse gas emissions, vehicle miles travelled, transportation mode splits, storm water quality, access to healthy local food, utility savings, job creation and access to services, among others, to keep performances under control (EcoDistricts 2014). It is common to find web pages that collect performance indicators that prove the efficiency of the district. “Vauban in numbers” is probably the clearest example of it.
Eco-Districts, as all other real estate development, need also to be sold to new potential citizens. Beside the performances, also communication is a crucial aspect to increase the attractiveness of the new living solution. Bo01 was launched in 2001, in order to candidate for European housing Expo, and its abbreviation, resembling the number 2001, in Swedish means “Habitat 2001”. To increase the recognisability of the project an iconic building was also constructed: the “Turning Torso” by Santiago Calatrava. The same happened in Ørestad with the “8 house” by BIG and in Marseille with the “CMA-CGM tower”, 150m tall.

Italy

The Italian framework is quite different from the European one. An initial phase of discussion and promotion of such initiatives, started decades later than the neighbouring countries, produced almost no results both in terms of movement and built projects. In 2011 has been launched a project called “Ecoquartieri in Italia: un patto per la rigenerazione urbana”, promoted by Audis, GBC Italia and Legambiente, organizations dealing with both urban and environmental issues (AUDIS, GBC ITALIA, and LEGAMBIENTE 2011). The results of this initiative are not so clear as emerge by exploring the actors’ websites. The dedicated website created in 2011 has never been updated in the following years (Ecoquartieri.org 2011). The same could be said for the website Ecoquartieriperlitalia.it, born and dead in 2012 presenting as a case study the only area of San Salvario near Turin despite the national echo of the name (Ecoquartieriperlitalia.it 2012). In order to track down the development of these issues I looked at the partners involved in the project.

AUDIS is an independent public-private association born in 1995 to support operators in the urban regeneration sector. It’s composed by public administrations, organizations and research centres, companies and professionals in order to integrate the different competences and knowledge in the process encouraging the communication between them. Nearly every two years they publish a report on related topics as “The Circular Soil” (2019), “Regenerate urban regeneration” (2017), “Matrix of Urban Quality” (2017) and the “Chart of urban regeneration” (2015).

Green Building Council Italy (GBC) is an institution providing sustainability certifications. Their activity is still mostly focused on the buildings and the only registered district project is Uptown Milan (UPTOWN Milano) in the area of Cascina Merlata that will be better explained in the next paragraph. It deserves to be mentioned their sheet for the evaluation of districts according to sustainability criteria (GBC Ecoquartieri 2015).

Legambiente is a no-profit association of citizens based on scientific environmentalism. They born almost 40 years ago and pursue different fights against pollution, illegality, inequity and for the safeguard of landscape and life quality. They are still very active on environmental issues but no specific reference to eco-districts is present on their agenda (Progetti ⋆ Legambiente 2019).

It's symptomatic that in the next "Ecomondo" in November 2019, an exhibition of eco-products and services, there's no trace of eco-districts. All the different aspects that should be integrated in a comprehensive proposal are still treated separately and divided in sectors as wastes, water, resources, circular economy, decontamination and hydrogeological risk mitigation ("Ecomondo: The Green Technology Expo" 2019)

Even if the debate is barely alive and some reports have been produced, there's a lack of built projects that give consistency to the initial agreements. If on one side there are few eco-district-like initiatives in Italy, on the other there is a problem of uniform labelling and communication. The word eco- is often substituted by smart- probably for the vagueness of this last in comparison to the first. Under the broad umbrella of "Smart City" even in Italy there are plenty of initiatives and projects. The website Smartcityweb.net gathers projects, grouped by city, on very different aspects and topics. Some of these initiatives could be integrated and coordinated in a comprehensive eco-district perspective as seeds for a deeper transformation but unfortunately, it seems that there's no interest in that (Smartcityweb | Il Portale Delle Smartcity Italiane). One of the main problems seems to convince investors to associate a physical output to the ongoing immaterial services and initiatives for environmental, social and economic sustainability.

The word eco- has been substituted with bio- to describe interventions focusing more on agriculture and food chain at a scale larger than the district one on non-urbanized contexts. Biodistretto.net is a portal managed by the International Network of Eco Regions (IN.N.E.R.) that collects initiatives and reports in a very clear and exhaustive way (Pugliese, Zanasi, and Basile 2015).

A more recent project that deserves to be mentioned is CITYFied, financed by European union, that aims to develop a replicable, systemic and integrated strategy to adapt existing cities to the smart future ideal one (Mazzucchelli and Baroni 2017). The results will be published after the completion of this research so we can only hope that some positive and tangible deliverables will be produced.

By the way some projects actually exist even if there's not any platform to collect them. For this reason, except the most popular and recognisable ones, the research of eco-district-like initiatives is particularly hard and fragmented. The most important project is surely "Le Albere" in Trento, an area of 11ha half devoted to public park. It has been designed by Renzo Piano Building Workshop on the former industrial Michelin Area inside a PRUSST program (Plan of urban regeneration and sustainable development of the territory). All the residences achieved a level B CasaClima classification for energy efficiency and the MUSE, the main building of the area, a LEED gold certification. These buildings were part of a district heating network powered by PV and geothermal plants (SPECIAL 2013). Other projects are presented by ANCE (2013). Monterotondo in Rome invested on soft and sustainable mobility with electric vehicles and bicycle paths, public green areas, PV panels on public buildings, social and economic support for fragile people and enterprises. In addition two public buildings were constructed: one museum of sustainability and tradition and one civic tower gathering community spaces and services. Villorba near Treviso is a small intervention made by only 8 houses in a common park with a vegetable garden and a common house for meetings and events. Sartoretti (2014) mentions the San Rocco area in Faenza. This project for a "Mediterranean eco-district" is a residential development close to the highway and quite far from the city centre. The attention of the developers is on the participative process and some micro-scale interventions. The project is deeply explained by (Nonni and Laghi 2008) in a dedicated book.

Milan

In Milan there isn't yet any built project comparable to the previously mentioned European Eco-Districts. However, in 2013 an interesting project, result of a competition, has been realized on the west border of the city, not far from San Siro Stadium. The intervention, called "Cenni di Cambiamento" (signs of change) covers only 17'000mq and is totally constructed in wood using x-lam technology. Its main focus is the creation of a social mix community through typological housing variety. It inserts in a mono-functional area adding public green spaces for building relationships in continuity with a renewed historical farmstead used for cultural events and entertainment. The project has been successful also from the participative point of view and has contributed to slightly revitalize a critical area. It could be considered an "Eco-Block" for its limited dimensions that avoided it to focus on larger scale aspects as mobility.

More recent residential developments of a certain dimension in the city of Milan call themselves "SmartDistrict". There are 4 projects with similar characteristics that could at least be confused with an Eco-District in different sectors of the city. Uptown in the area of Cascina Merlata, close to the Expo 2015 site (UPTOWN Milano) and EcoDistrict, near Cimitero Maggiore (EcoDistrict - Palladium Italia), both on the NW axis, Symbiosis (Symbiosis) close to the Porta Romana rail yard and Fondazione Prada in SE part of the city already interested by the Sharing Cities project "Sharing Cities Milano) , and Milano4you in Segrate on the east side of the city not far from Linate Airport (Milano4You – The Smart District Concept).

It's not so simple to evaluate these projects and truly understand if they satisfy all the requirements of an Eco-District for many reasons. First of all the websites mainly tries to sell already available apartments in areas where the expected services are not yet built. Moreover they highlight as unique and exclusive something that one century ago was considered a minimum standard requirement for a population increment as schools, shops and green areas. From the energetic point of view all buildings are declared to be A+ class (probably and hopefully true) but there is no attention at all to the employed construction materials. The dependency by car risks to be very high because of the lack of facilities in the surrounding areas and due to the mono-functional residential buildings that are already in place. All the areas declare a high level of accessibility but mostly referring to the proximity to highways and private transportation infrastructures. The "key areas" where they arise are in reality peripheral and mono-functional zones. In the case of EcoDistrict, declared as close to the new citadel of science, linear distance from this possible future development is 1,5km but no walkable pathway shorter than 4km exists or is foreseen. Moreover some of them have been built on former urban agricultural active land tremendously increasing soil consumption in already strongly sealed areas.

Eco-District critic

After showing all the potential of Eco-Districts it's correct to mention also some minor cases where the not every initial goal was satisfied. It's the case of De Bonne Project, that according to Sartoretti (2014) disregarded initial goals, of Docks-de-Saint-Ouen where community involvement played an irrelevant role and of Ginko where even after achieving a HQE certification, was hard to convince people to move in (Flurin 2017). Direct observations return a daily life that does not correspond to the conditions launched and promoted by real estate marketing. The feeling of isolation, anonymity, a few common experiences and low social inclusion, but also the occasional persistence of a peripheralized perception, counterbalance other positive aspects. The development of an inclusive sociality still has shadows (Lossano and D'Ambrosio

2012). In the case of “incomplete” districts – including Ørestad and Malmö – neighbourly relations and the use of space cannot restore a sense of community. Ordered and well-kept spaces, or even sparse and undefined spaces, are compared with an organization of daily life with low permeability degree for new activities, too conditioned by the existence or absence of social routines (Trkulja 2011). (Canosa Zamora et al. (2018) dedicate an entire study to the failure of Eco-District projects in the city of Madrid analysing six different areas. According to them, the main reasons for the failure can be found in a scarce integration with the existing planning, few municipality commitment, disregarded promises and a limited participation. Someone critics also part of the assumptions of this approach. For Antonio Da Cunha, director of the Institute of Geography and of Observatory of the city and Urban Development in Lausanne, Switzerland, social mixing is by no means ensured by residential diversity: “Classical sociological studies show that neither social homogeneity nor social heterogeneity guarantee that individuals will actually socialize.” (*Paris Innovation Review* 2013). Some of these problems may be due to confused communication. This is a very important problem for our era and in particular the abuse of labels applied to “sell” a specific product, project or policy. The terms “sustainable”, “bio”, “eco”, and similar words are often employed one after the other in current language without any concern for providing a more profound meaning (Forlani 2015). The Milanese cases are a clear example of that.

7.1.5 Discussion

We are asked to decrease the climate impact of cities while we make our cities more liveable, social inclusive and able to create new economic opportunities. A climate neutral urban district uses an integrated and innovative strategy based on the main ambition to achieve both environmental and social sustainability in its development. This model must be based on a full integration of several infrastructural systems in the designing from the very beginning: technical infrastructure, mobility and communication infrastructure, building infrastructure and to some extent green-blue infrastructure, as well as the physical flows of energy, water and waste in order to reduce its carbon footprint.

Eco-districts, as emerges from the case studies, seems the most promising approach to urban design projects to achieve these ambitious goals. IMM methodology with its holistic approach is naturally compatible with the Eco-district one. The DOP can be seen as a sort of guide to promote the transformation of an existing district into a better performing one with the goal of becoming an Eco-district. From this perspective, DOP, can be used as a tool to investigate existing projects in a systemic and organized way.

System mapping

Few case studies from different climatic and cultural context have been selected for their, size, urban character, variety of solutions and success. Studying these examples and comparing each other, can help to understand concepts, ideas, and how best practice has been developed around Europe (and Arabic Peninsula). An analytic reading of these projects can be of great benefit for the design process. The selected case studies are:

22@ Barcelona District, Barcelona (Spain), HafenCity Hamburg (Germany), Hammarby Sjöstad (Sweden), Jätkäsaari Helsinki (Finland), Msheireb Doha (Qatar).

The research activity has been performed with the support of the students of the Sustainable Multidisciplinary Design Process (SMDP) course with the aim of highlight common and unique features. Due to their dimension, the sheets for every case study are collected in Appendix E, while here is reported a short summary of this work findings.

The main shared principles are: architecture and location; walkability, cyclability and public transportation; recycling and reducing need of maintenance; mix use, especially at the ground floor; intermodality, to reduce the use of private cars (which increase the total pollution).

Jätkäsaari area in Helsinki uses tower buildings to increase density preserving green areas. Ecological construction materials and passive strategies are employed. Is the only area using wind energy, in addition to PV. Grey water is recycled for irrigation and gardening uses, supporting among others, local food production. An underground pipe system collects wastes. The sea border as in many Scandinavian cities, is a huge walkable area well integrated with the rest of the network.

HafenCity in Hamburg, covers an area of 1,6 million sqm and represent an expansion of 40% of the existing city area. As a former harbour, water plays a key role and is an attraction element of the district. It's also used for producing energy, together with solar energy and bio-fuels. Soft mobility is encouraged with different solutions. The ratio between cycle pathways and normal car's way is two to one and all parking is concentrated in the underground level.

Doha recognizes the cultural and historic value of the area and reinterprets old form into a contemporary city. Urban morphology is very compact in order to provide shade and increase wind flow to fight the high temperature during all year. Open spaces are connected by roof covered walkway. The use of bicycle, almost impossible due to temperature, is replaced by local tram ring line. Materials of facades and pavements are white or with light colours. Recycled water, a scarce and precious resource in that region, is used for irrigation. Buildings are made sustainable with the use of passive strategies and renewable energies.

Hammarby Sjöstad in Stockholm is a project of sanitary redevelopment of brownfields into attractive residential areas with parks and public spaces. The 25% of space is devoted to green layer. Among this amount, vast forested area with footpath and cycle routes are created, there are green roofs and old trees are preserved. Thanks to the adopted solutions, 60% of water consumption and 40% of waste production are saved. There is a district heating system powered by wastewater. Looking at transport layer, all the subway stations have more than four different options (subway, bicycle, street cars and buses). Metro, tram, bus and boat provide a high intermodality level.

Barcelona has iconic high technology buildings producing the minimum energy they need while having the possible facilities, like air conditioner or outside lights. The concept of superblock is typical and is of particular interesting for walkability, giving pedestrians a key role in the city. This is connected to the mixed used spaces. Every corner has to be a social space, achieving 50% of public area and 50% of private in the entire area. They create a transportation system that goes from the mountains to the sea providing a high connectivity level. The waste collection is automatic and uses smart bins.

7.1.6 Conclusions

In highly urbanized contexts, physical constraints to locally produce renewable energy could inhibit the transformation of existing buildings into nZEB according to the existing regulations, while better technical solutions and a higher economic return could be found at the district level (Mazzucchelli and Baroni 2017).

Eco-districts might be able to activate a circular metabolism integrating under "a circular model" what normally used to be separated by topics. Mobility, energy use reduction, waste management, water use, opens spaces definition, urban morphology and energy production, are all connected to meet economic, environmental and social goals.

It is also worth to consider if an intermediate scale between building and district can be found. Given the importance, as shown by this research, of blocks as key urban elements it could be interesting to test if they could be a profitable compromise scale for the application of these strategies. The main advantage is that land ownership can often be totally private, even if divided among different actors, and that mobility issues could be ignored, except for the potential development of internal walkable paths. Probably not all blocks would be big enough to ensure some advantages respect to the plot or building scale but actually there are no studies about it.

7.2 Porto di Mare Case study

7.2.1 Milano

The city of Milan, with about 1,4 million inhabitants, lies on 182 square kilometres.

It's characterised by an uneven radial growth, faster in the northern part and limited in the south because of geological properties of the soil and the activities that consequently developed. The area of what is now called "Parco Agricolo Sud" has one of the most productive soil and always had an agricultural potential that gave birth to a strong rural ecosystem (De Finetti et al. 2002).

This make peripheral areas in the south closer to the city centre and to the countryside at the same time, defining a precarious boundary pushed and threated by urban development pressure. This condition allows to have an sudden passage from a productive and natural countryside and a strongly developed urban area instead of a more common smoother fading of one into the other. Milan is rapidly gaining more and more importance in the international panorama attracting people and investments. In the next 10 years an amount of nearly 10 billion of euro is expected to land on the few remaining available area for their redevelopment (Dezza 2019). The question, apparently, is so not if ATU (Urban Transformation Areas) will be developed or not, but only how this process will happen.

This proposal is a practice to apply morphological based modifications to start a low-carbon transformation in an urban context. The area of Porto di Mare (ATU15) is an important and underdeveloped zone in the south east of Milan, characterized by an unexpressed potential. This study is an inquiry into possible ways in which a local modification could trigger global transformations. The attempt of this study is to demonstrate how Porto di Mare - as a segregated area - has the potential of transforming into an eco-district with high quality urban performances. This study draws a new perspective for this area in which nearly all the social and environmental aspects are systemically interconnected into an integrated design methodology and proposal.

7.2.2 Porto di Mare Introduction

The area of Porto di Mare has a recent but complex history, full of ambitious projects always stopped by economic constraints or changing of needs over time. Is a piece of land where all this projects started leaving a sign that, the project abandoned, become something different, sometimes being reabsorbed by natural landscape. The interest for this area is explained by its strategic position according to transportation networks, starting from waterways taking advantage of natural confluence, to arrive to railway system, with the Hub of Rogoredo Station, and cars with the gate for A1 highway.

The first result of searching "Porto di Mare Milano" on the internet is a picture of the underground exit of the yellow line (M3). This is quite representative of the absence on meaning of this area, combined by the absence of almost every feature usually characterising an urban area. This exit connects two parts separated by the beginning of the highway and so the neighbourhood is intrinsically divided in two. If we exclude Mazzini quarter, that may be associated with Corvetto stop, the left area have almost nothing but barracks, so not more than dozens inhabitants. Just some sport facility, a park, a discotheque and some traditional agricultural buildings with the related fields are the official existing activities on the left side of the stop. The right side shows just two lines of blocks with large buildings before ending against the railway infrastructure. This area mainly presents office and productive buildings with some residential and commercial activities.

Highest quality and potential of the area has always been its proximity to the countryside and the consequent landscape quality. In the last decades this spontaneous relationship between city and countryside has been interrupted in Porto di Mare area by abusive settlements, both productive and "residential" (D'Amico 2016) that literally create a barrier isolating the two ecosystem. Pathways to reach natural areas became longer, unpleasant and often unsafe, excluding those areas from citizens itineraries.

Milano municipality is now owner of the majority of the area and has finally the opportunity to focus there its efforts and use this area as a pilot one. In fact many other areas along the urbanized perimeter show the same characteristics, even if with some specific differences due to cities evolutionary paths along other rays of growth. It represents the opportunity to contrast urban expansion to the countryside with landscape seepage into built areas, in order to obtain a more integrated system, giving consistency to the "Raggi Verdi" (green rays) project (AIM 2007).

7.3 IMM Diagnostic

It is intended to examine how Porto di Mare can affect and mitigate the city's marginal growth as a whole. In the other words, the main point of interest is to scrutinize how Porto di Mare acts as an intermediate scale agent to eventually affect the transformation of the entire CAS (i.e., the city of Milan). IMM consist of four main phases, Observation and Investigation, Formulation and Hypothesis, Intervention and Design and finally Retrofitting and Optimization. They will be presented here following the right order recalling some of the contents and images already published by the author in (Tadi, Biraghi, and Zadeh 2017, 2019)

7.3.1 Investigation Phase

HORIZONTAL INVESTIGATION – COMPONENTS

Volume

A map with buildings varying from black to light grey following a gradient related to their heights, show main line of urbanization and places where the city inherit properties from the adjacent more central areas. We arrive from a compact city with blocks closed by buildings aligned long the perimeter and smaller volumes to fill the inner space. This is particularly evident on the axis of Corso Lodi down to Piazzale Corvetto, from that point on, the continuity of façades reduce and leave place to a more uncontrolled urbanization on the right side, and to a modernist district with isolated linear building with solar alignment on the left. Volume decrease and void loose shape and coherence entering the last part of barracks and abusive settlements before reaching the countryside. The small isolated agglomeration of buildings in the very southern part is the hamlet of Chiaravalle, a historical village developed around the Abbey.

Void

Void component has a great extension and variety in the area. Void are not just roads, squares and sidewalks, but also parks, private open spaces, rail yards and highways, and finally fields of the productive countryside. A void can be a room for people and so a focal point or, on the contrary, just be a place subtracted to the city if closed, fenced, unsafe or unused. There are a lot of green spaces and interesting landscape features, but unfortunately they are often private and separated. Here, despite the consistency and variety of void spaces, it's hard to speak of void system as they are all disconnected and not participating into a coherent green infrastructure for the area.

Function

As volumes also functions fade from NW to SE. Modernist district was intended to be the last development of the area, almost a dormitory neighbourhood, and so all the functions are concentrated in its upper portion where it meets the older part (1920ca) in Piazza Gabriele Rosa. Right part is the opposite with a low percentage of residential and a lot of offices and working activities. Services for these people not living in the area are reduced to the minimum. Some "excellences" are Sky TV headquarters at Santa Giulia, Nosedo Water treatment plant and Chiaravalle Abbey.

Network

Transportation network at the global scale is one of the strengths of the area and try to supply the local problems with a fast and simple connection with other areas. The presence of both train and metro line makes easily accessible both urban and regional/metropolitan functions/amenities. Rogoredo is the third transportation hub of Milan and its importance will even increase with new Metro 4 line reaching Linate airport. Only Chiaravalle hamlet is not well connected to the rest of the city (only a bus line) but is quite normal considering its size, population and the fact that it became just recently part of the city.

Figure 73 collects the graphical representations of the above described Components.

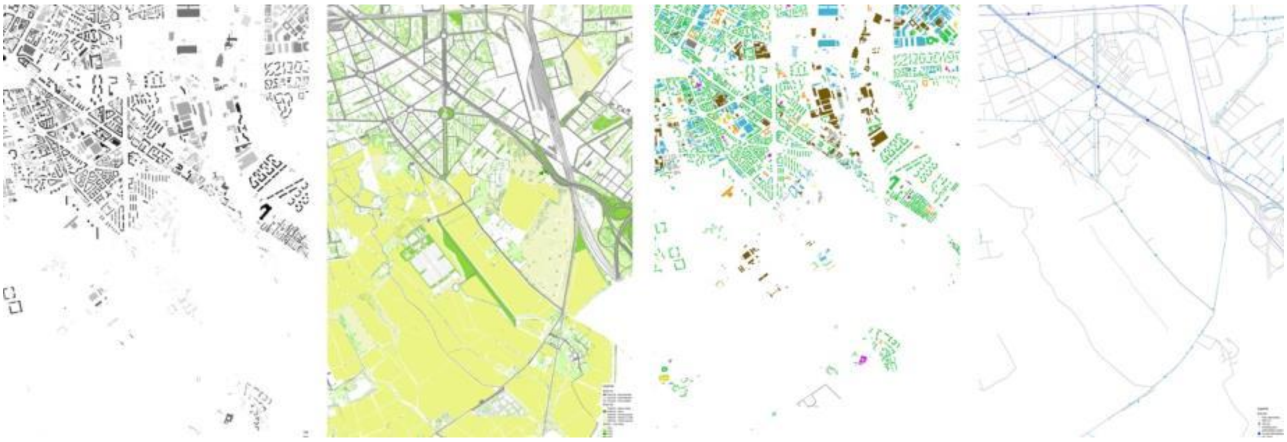


Figure 73 Components representations: Volume, Void, Function, Network (Tadi, Biraghi, Zadeh 2017)

VERTICAL INVESTIGATION – KEY CATEGORIES

Porosity

Investigating the porosity of a urban fabric is not just about quantifying volumes and voids, but more precisely describe the relationship among this two component and how this affect the space qualitatively. The same amount of volume may be arranged in completely different ways shaping or not the void. Here voids are huge both for the presence of the countryside and of large empty areas under a process of transformation that will hopefully integrate them into the city in next decades. So a part of Corso Lodi's blocks and upper part of Mazzini neighbourhood, characterised by quasi closed courtyards with regular shape, the rest of the area present regular, often rationalist, buildings and blurring voids.

Permeability

To understand the permeability of an area we can imagine it as a property of the void space that will be naturally really high or total but can be limited by some built elements. When all voids are connected and crossable the permeability is high. In this area the presence of a large street connecting to the highway is an obstacle that divides the city in two parts. The choice of making an overpass partially overcome this problem and so the node of Piazzale Corvetto becomes a real gate to reconnect separated parts of the city. The right part is also limited by the railway infrastructure and can be so considered a sort of semi-cul-de-sac zone. Left part is slightly better even if all private voids between buildings are fenced and have really few accesses. These areas are so excluded by walkable areas but are easier to be reconnected to the void system, ensuring a high potential. Chiaravalle village is surrounded by fields and connected to the two parts by one street each, this makes it a minor crossing point, due to longer distances, in addition to Corvetto.

Proximity

It can be described as the easiness of accessing to urban key functions by means of walking, and it's so mainly affected by function and link layers. Highest values are in the upper and older part of Mazzini neighbourhood because of a higher concentration of key functions and a finer block grain. Another reason for its success is the role of joint played by Piazza Gabriele Rosa between other areas including Corvetto. The same could be said for old Rogoredo district and northern limit of the area, closer to the city centre. Large fenced blocks and lack of activities made the modernist part, as well as the abusive one working bad under this point of view.

Diversity

This KC describes how function location and fruition affect the use and so the conformation on public space around or in between them. It is a qualitative more than quantitative measure and the multicolour gradient try to give information of concentration and mix use showing also differences of mono functional areas. The system made by Piazzale Corvetto, Piazza Gabriele Rosa and Viale Enrico Martini connecting them shows the highest diversity and consequently street layout has a good quality and variety. The strength of this axe involves also the first part of Viale Omero. Other mixed use areas are the historical neighbourhood of Rogoredo on right side of the railway, and the upper part of the selection area approaching the city centre.

Interface

It evaluates the transportation links in the network. It gives the precise information regarding the urban flow and is assessed by the calculation of the mean depth for each individual link. This analysis has to be performed at the global scale because cutting the selection area and focusing just on it is equal to disconnect it from the rest of the network, and so altering the meaning of the results. Results from Interface in Milan may look obvious for people knowing the past and the present of the city thanks to their potential of revealing the evolutionary path and connections between different urban developments. Red colour of the city centre fades to lighter orange passing the Spanish walls, and turns into yellow after the railway belt. When it meets a rail yard as the one of Porta Romana in the South-East quarter, the passage from one rank (and relative colour) and a lower one is more abrupt. Mazzini Neighbourhood is yellow in his contact point with inner “rings” and turns to green and blue on its back in the direction of Chiaravalle.

Accessibility

Accessibility is the number of jobs of key functions area reachable within 20 minutes using different public transportation methods. Current location of functions is well served by public transportation, whose catchment is even larger and shows the possibility of introducing new activities in the area. That is particularly valid for Porto di Mare metro station on both sides and for other areas under development, now completely residential, that could become more mix used. Some minor improvements may be required to improve connection at the local and intermediate scale

Effectiveness

It defines the capability of the transportation to cover built volumes around it and simultaneously also the potential development within the intermediate scale. The presence of an underused metro station creates a high potential area in the left part while other transportation stops are already located close to some volumes concentration. This potential could not be completely used because of the limit for constructions defined by municipality.

Figure 74 shows the maps related to all the KCs as from Tadi et al. (2017). Porosity and Permeability map have been merged as their representation is not in conflict.

INDICATORS OF PERFORMANCE

In order to complete the diagnostic phase, once done with system structure, its performance has been investigated through the comprehension of the correlation of the basic urban element. To evaluate the energy and environmental performances at the scale of the design area, several sustainable indicators have been used. The Indicators are used again in different phases of the IMM process or CAS Retrofitting Process to compare the neighbourhood performance before and after alternative transformation process.

Zooming down to the intervention area shows interesting results. 49% of the almost 500kg of solid waste produced per capita per year is currently recycled. Among these, 110Kg is just individual food waste, a part of the 12Kg of food-needed daily. Considering the relevance of agricultural land in the area the food issue is of a particular interest.

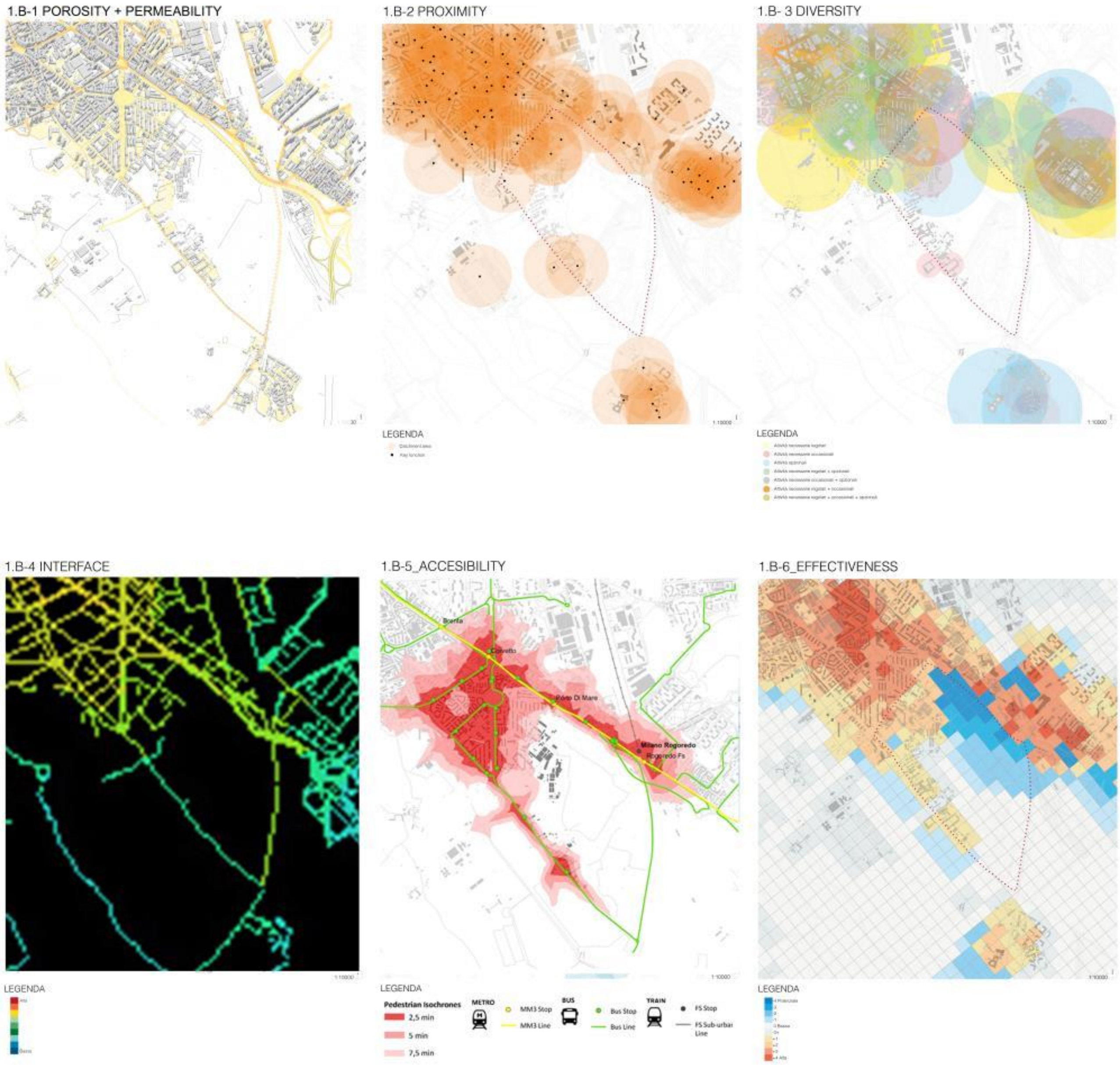


Figure 74 Key Categories representation. Porosity+Permeability (top left), Proximity (top centre), Diversity (top right), Interface (bottom left), Accessibility (bottom centre) and Effectiveness (bottom right)

7.3.2 Formulation Phase

While the investigation phase can be considered neutral, so common to any possible future design proposal, formulation is the first step towards design. It is essentially dedicated for establishing a Supposition/Hypothesis, like a viable way for structural modification of the CAS to improve its performances. The main goal of this phase is to identify the transformation catalyst with respect to the analysis of Key Categories and the indicators associated with them. The Horizontal Catalyst, is the basic component with more potential to initiate the system's reaction, and the Vertical Catalyst will be one of the Key Categories with the same characteristics.

The following contents refer to what will be called "Masterplan 1 (SMDP)", result of the IMMdesignlab research activity together with Sustainable Multidisciplinary Design Process students (Master in Building and Architectural Engineering) and the contribution of two international workshops with Cincinnati and Wageningen University and Research (WUR).

In this study, the Investigation Phase reveals that the major malfunction is related to those features dealing with the Voids layer, Permeability, Porosity and Interface. 91% of Porto di Mare area is Void. This surely represents an immense potential for the area and leaves room for future transformation. Inside this percentage there is the highway dividing from Rogoredo and Santa Giulia, vast abandoned areas and a lot of residual green private spaces adjacent to buildings. Void is so actually redundant, shapeless and limiting connectivity. With little interventions to the existing network a continuous cycle corridor could be created connecting the agricultural landscape and relative heritage (Valle e Cammino dei Monaci) in the south of Milan to the city centre. The cycle path will encourage a connected system of green areas, which comprehensively promotes urban bio-diversity. In addition, the Void layer plays a significant role in neighbourhood's densification process. It traces a clear image to how new volumes should be in terms of position, orientation and the densification level. Rehabilitation of urban voids and its integration with functional nodes, not only, improves the Diversity of the area, but also, will improve the morphological Complexity and Compactness of the neighbourhood simultaneously. The existing transportation network will so become more effective and citizens will have more direct access to it. Interface has been selected as the transformation's vertical catalyst. Interface has a direct relationship to movability inside the urban morphological cavities and the building blocks; it increases the morphological complexity of the system by increasing the number of possible Links to connect two nodes. Main reason for a low level of Interface is the presence of large not-permeable blocks in the lower part of Mazzini neighbourhood and the vast number of dead ends along via Fabio Massimo and via San Dionigi, fading in an undefined green area. In a transformation process of the CAS, activated by one or more catalysts, a Reactant is a member of a system that undergoes the modification course. The election of Interface as Catalyst will activate a reaction in all the others KC.

7.3.3 Transformation Phase

Ordering the DOPs in consideration of the local condition and the elected Catalyst is part of the IMM transformation phase and it allows focusing design on most urgent issues weighting the impact of benefits from transformation. Here the suggested DOPs' list ranked for Porto di Mare:

1. Promote Walkability, Cycling and Reinforce their integration with public transportation. The design concept for a car free neighbourhood in Porto di Mare area is based on walkability and a full integration with public transportation system at local and larger scale. A new bio methane bus will cover 9 new stops inside the new Eco-district and Mazzini quarter, integrated with bike-sharing, electric car-sharing stations and the new mobility interchange hub which integrates parking spaces, the MM3 stop and light mobility system supporting the car free neighbourhood (Figure 75).

2. Balance the ground use with a systemic approach integrating the physical flows of energy, water and waste. New volumes are arranged in coherent balanced layout taking care of shading, distances and soil consumption (Figure 76).

3. Fostering the local energy production. Building as component of Smart Energy Community: a transformation of such a large area is a fantastic opportunity to profitable establishes smart grid and local energy production strategies. Renewables will play a key role, at the building scale making them energy producers by integrated Photovoltaic systems and, at the district scale, taking advantage of Nosedo Purifier and waste management system that is going to feed the whole Eco-district with heat water and electric energy coming from the water treatment and their integration with heat-pumps (Figure 77).

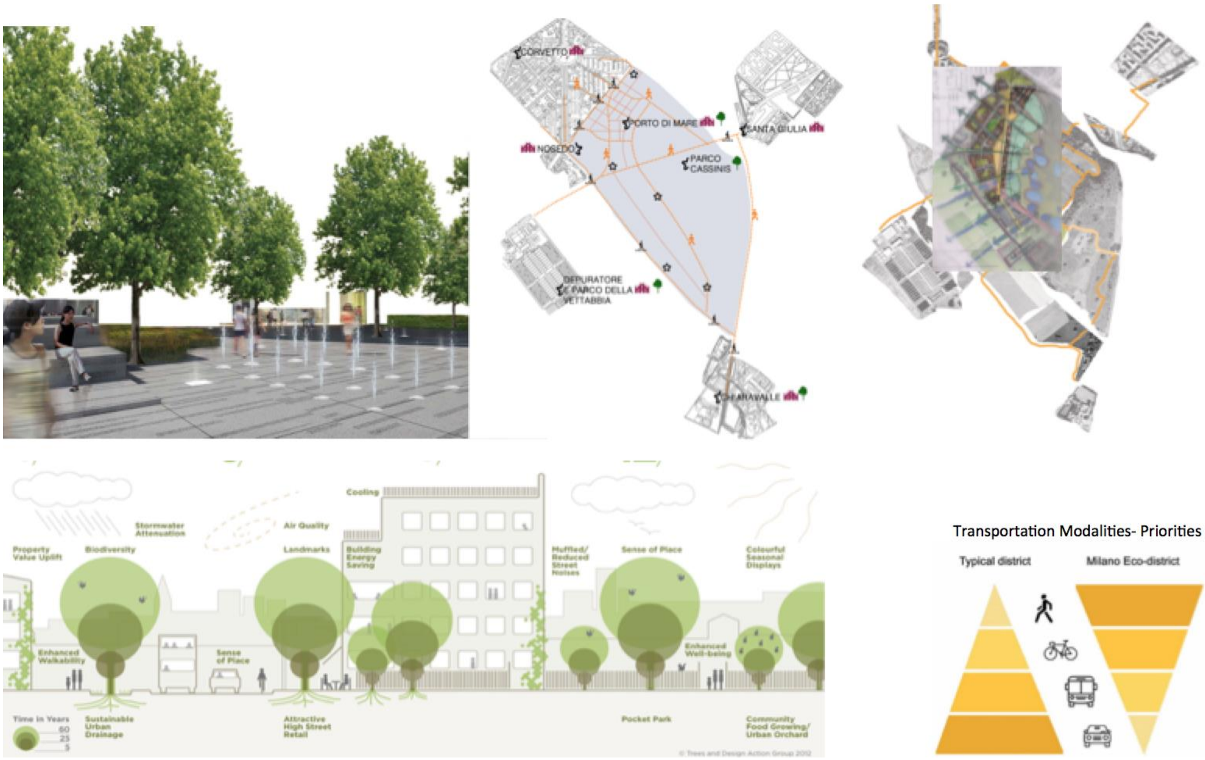


Figure 75 DOP #1 Promote Walkability, Cycling and Reinforce their integration with public transportation

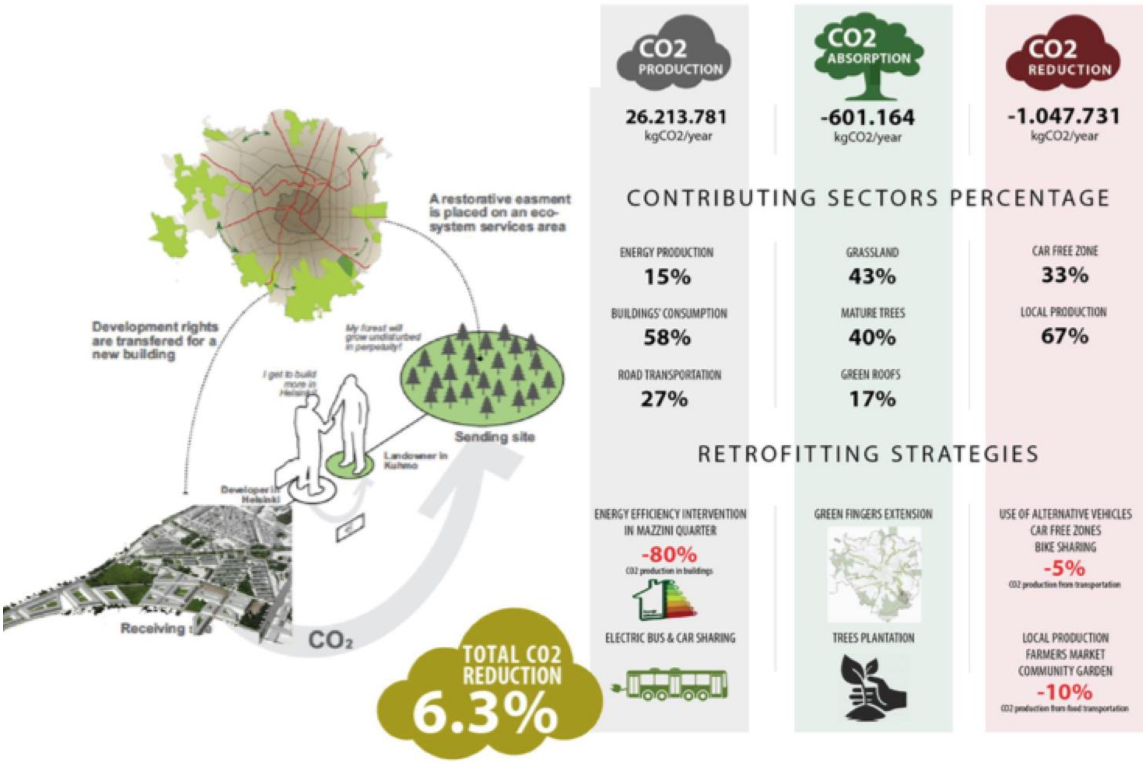


Figure 76 DOP #2 Balance the ground use with a systemic approach integrating the physical flows of energy, water and waste

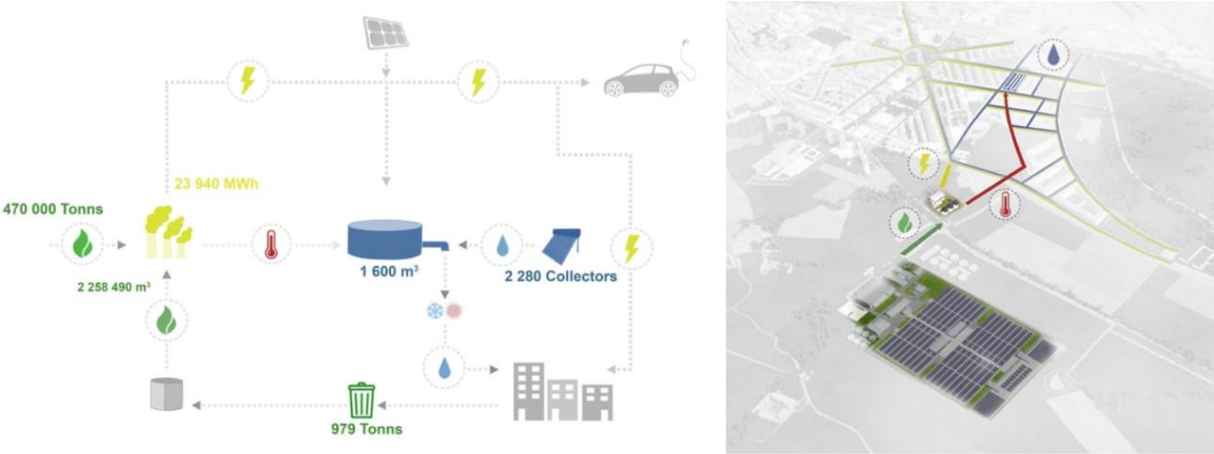


Figure 77 DOP #3 Fostering the local energy production. Building as component of Smart Energy Community

4. Prevent the negative impact of waste: turn an informal junkyard into a pilot intervention for waste management will have a benefit at global scale. An innovative automated waste collection system (AWCS) with optical sorting technology is applied for the first time in Milan with the goal to reduce heavy waste transportation in the area as well as carbon dioxide emissions (Figure 78).

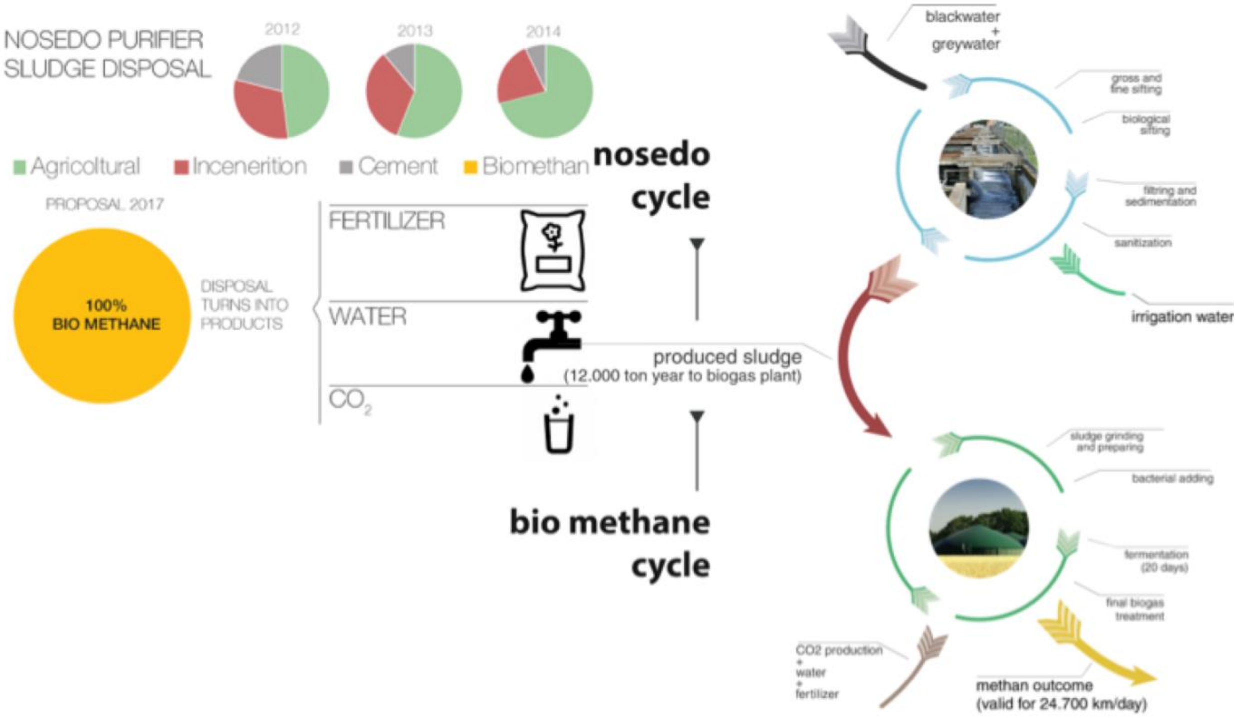
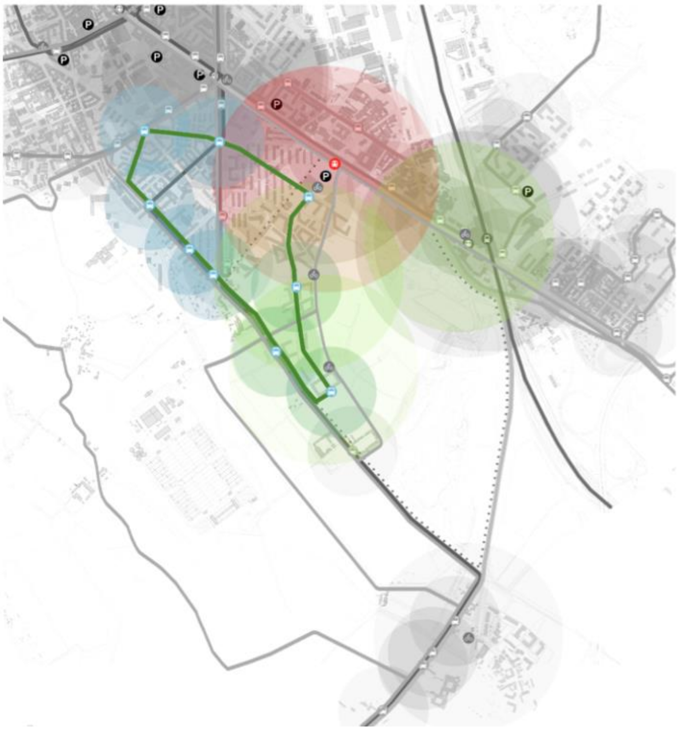


Figure 78 DOP #4 Prevent the negative impact of waste

5. Balancing the public transportation potential through creating a mobility network that offers more choices that ultimately reduces the travel distances. A new local eco-bus line is introduced in order to reach those areas that are too far from metro stations and to encourage the use of sustainable means of transportation even for small displacements in the area (Figure 79).



Features Line

- Length: 3669m
- Stops: 9
- Range: 400m

Features Bus

- Dimensions: (LxWxH) 11.980mx2.500mx 3140m
- Weight: 12500kg
- Capacity: 72 people, 27 seats, 1 space for a wheelchair
- Drive motor: 120/240kW, 1100/3600Nm
- Consumption: 1.1kWh/Km
- Range: 300km/day
- Motor lifetime: 6 years (2500 recharging)

Figure 79 DOP #5 Balancing the public transportation potential

6. Makes Biodiversity an important part of urban life: let nature from countryside enter urban area to build a more pleasant environment. Green corridors cutting the former abusive settlements reconnect the larger natural ecosystem of Parco Agricolo Sud to the smaller urban spots encouraging a deeper penetration of animal species (Figure 80).

Figure 80 DOP #6 Makes Biodiversity an important part of urban life

7. Convert the city in a food producer: agriculture is in the past and in the present of this area. Productivity may improve thanks to technological implementation and expanding arable land. The project aims to work on the Integration of the area with the surrounding countryside as part of a wider city Food strategy. Statistics are calculated for the production of food at the Parco Agricolo Sud Milano, where the production is assumed to be the approximate suggested by the World Bank survey, which is 5709 kg per hectare. The food consumption values are based on the nutrition survey of how much food is required per capita, per annum (Figure 81).

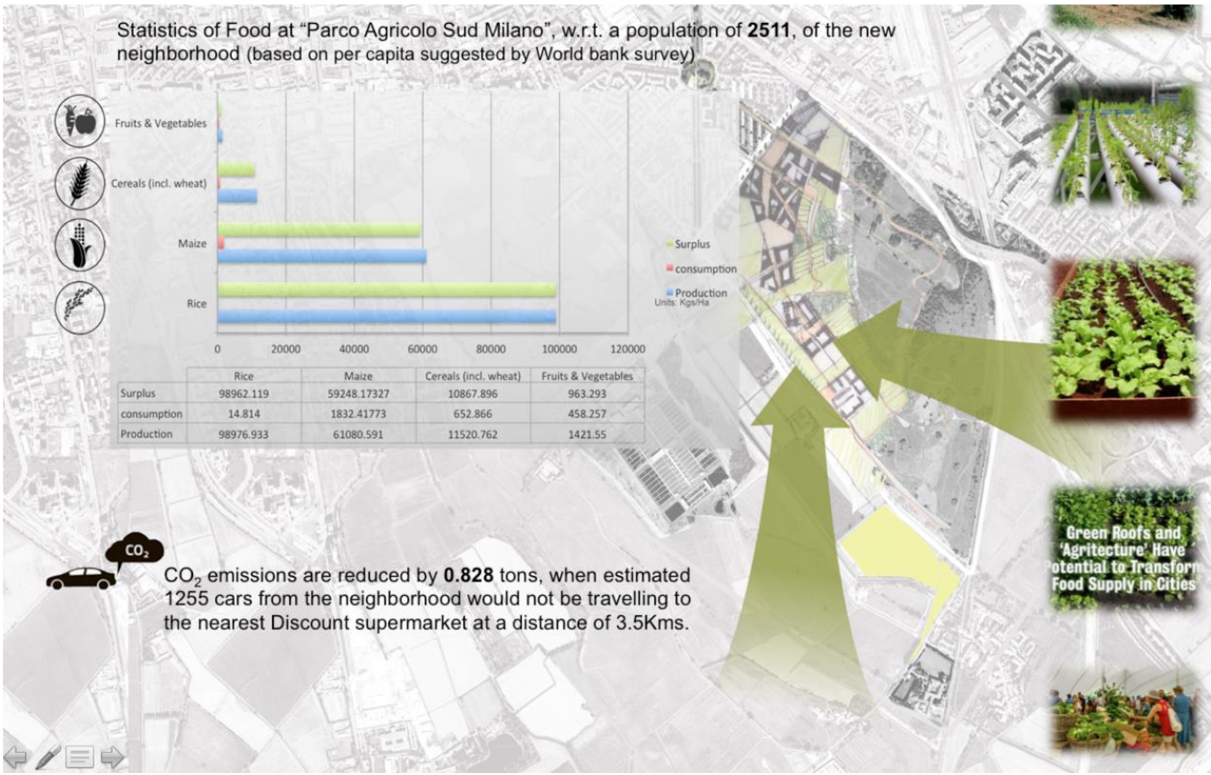


Figure 81 DOP #7 Convert the city in a food producer

8. Balance the distribution of functions and developing multifunctional urban spaces: The project distributes the functions inside the district wi.th public spaces in ground floors and close to the main streets, in order to activate safe and pleasant connections with the consolidated city, encouraging non-motorized mobility (Figure 82)

9. Create connected open space system, activate urban metabolism: voids must turn from unsafe empties to a variety of shaped spaces full of meaning and activities connected in a pedestrian network enclosed by volumes. A network of parks, green spaces and walkways runs through the district to provide a counterbalance to the dense urban landscape. Green surfaces and trees have been planted also to help collecting rainwater locally instead of having it drain into the sewage system. The vegetation will also filter the pollutants from this storm water runoff and ensure cleaner air (Figure 83).

Figure 82 DOP #8 Balance the distribution of functions and developing multifunctional urban spaces

Figure 83 DOP#9 Create connected open space system, activate urban metabolism

10. Change from multi-modality to inter-modality concept: Rogoredo Hub already works properly in an inter-modal perspective at the city scale, local buses and bus lines are also implemented. A new Intermodal Hub will provide parking spaces, electric cars sharing, bicycles sharing, supporting both the car-free zone and limited traffic zones (Figure 84).

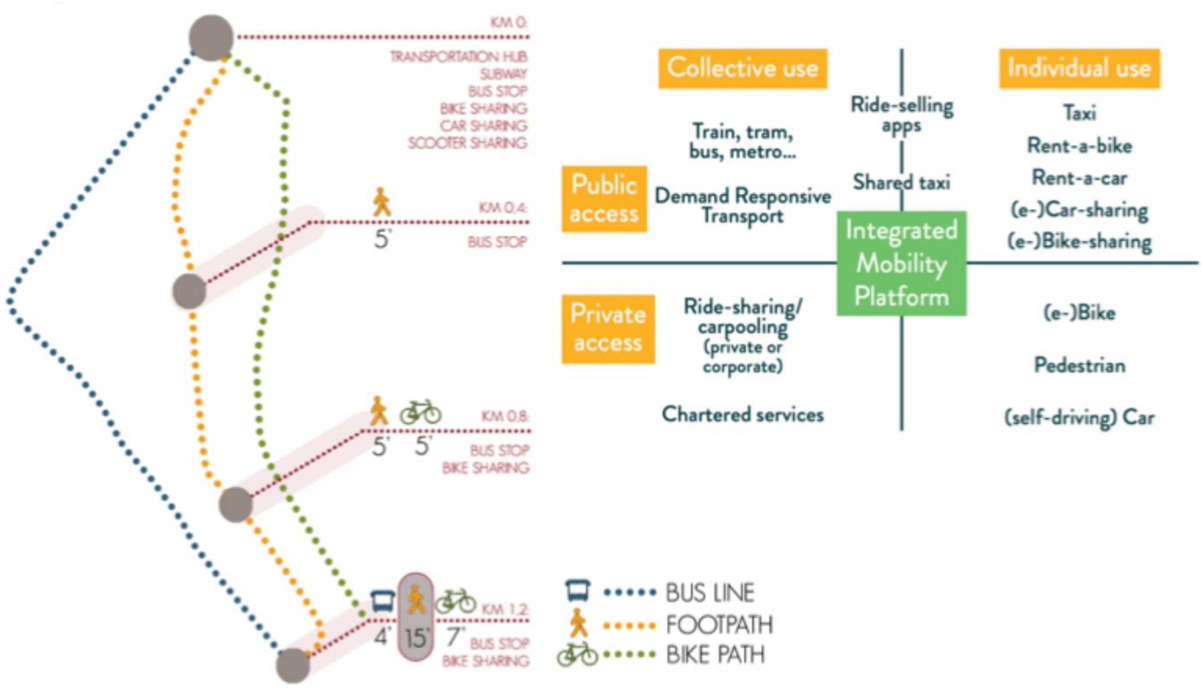
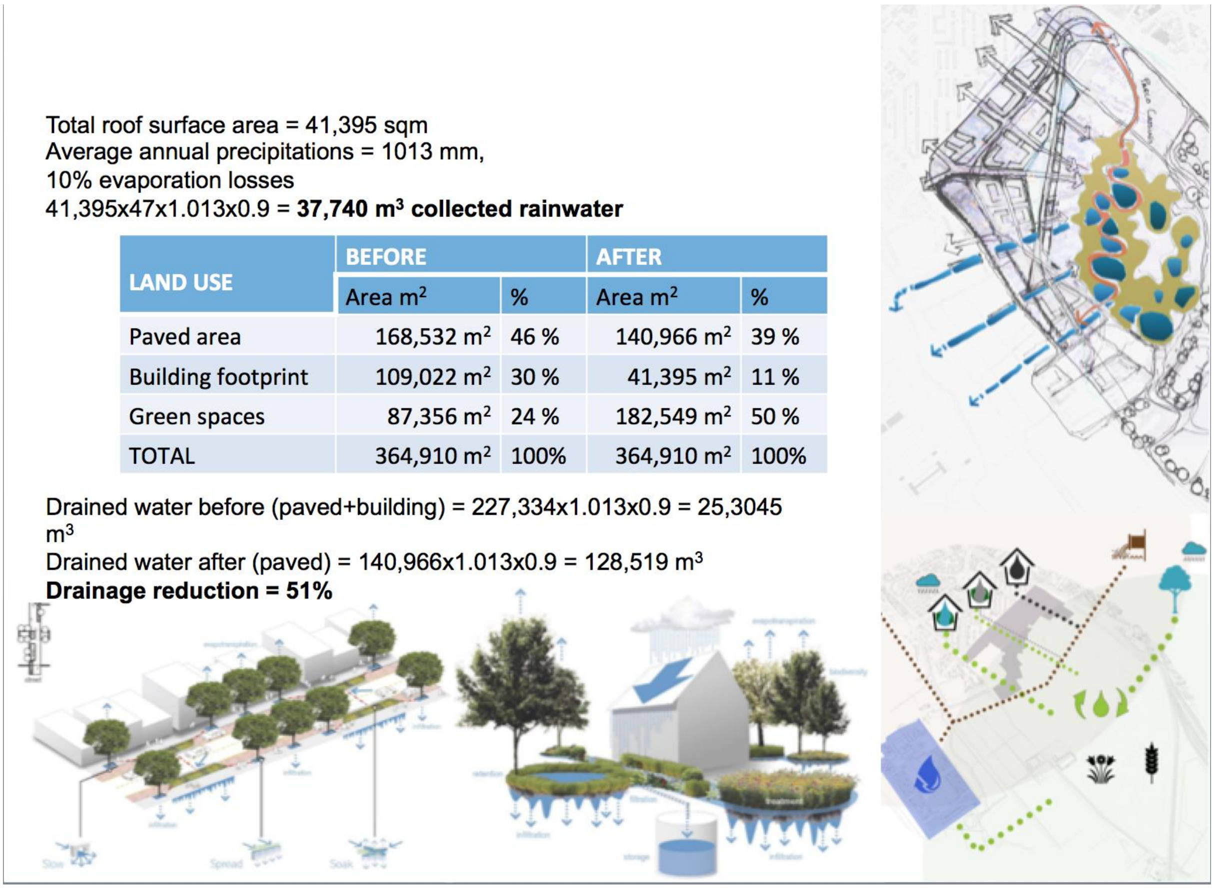


Figure 84 DOP#10 Change from multi-modality to inter-modality concept

11. Implement Permeability to facilitate urban flows and adopt a locally based strategy: the area, even after the transformation, will remain a boundary with no further development allowed on both south and west side. Urban flows won't so become so relevant except for reaching the countryside. The already planned transformation of Highway overpass will increase the pedestrian permeability on the East side towards Rogoredo area (Figure 85).

Figure 85 DOP #11 Implement Permeability to facilitate urban flows and adopt a locally based strategy

12. Implement water management: this is one of the strength of the area thanks to the presence of Nosedo Water treatment plant so few further precautions at building scale may be adopted. Actually the project aims to takes advantage from the sludge cycle already existing there (Figure 86).



Total roof surface area = 41,395 sqm
Average annual precipitations = 1013 mm,
10% evaporation losses
41,395x47x1.013x0.9 = **37,740 m^3 collected rainwater**

LAND USE	BEFORE		AFTER	
	Area m^2	%	Area m^2	%
Paved area	168,532 m^2	46 %	140,966 m^2	39 %
Building footprint	109,022 m^2	30 %	41,395 m^2	11 %
Green spaces	87,356 m^2	24 %	182,549 m^2	50 %
TOTAL	364,910 m^2	100%	364,910 m^2	100%

Drained water before (paved+building) = 227,334x1.013x0.9 = 25,3045 m^3
Drained water after (paved) = 140,966x1.013x0.9 = 128,519 m^3
Drainage reduction = 51%

Figure 86 DOP #12 Implement water management

Eventually, by the integrated modification of the systems' elements and through the course of the time, a system with improved performance and different structural configuration will emerge.

7.3.4 Retrofitting

The retrofitting phase is in charge to size and evaluate the impact of the transformation phase in terms of the environmental performances of the area. Contextually, when possible, is the chance to visually and structurally compare alternative transformation scenarios. In this case, three different layouts are going to be compared passing below the IMM hand lens:

- State of the Art, nearly abandoned and illegal area
- Porto di Mare Eco-District (SMDP), result of the IMMdesignlab research activity together with Sustainable Multidisciplinary Design Process students (Master in Building and Architectural Engineering) and the contribution of two international workshops with Cincinnati and Wageningen University, presented above
- Alternative Transformation Scenario (AD2Y), result of the author's research activity together with the students of Architectural Design Studio 2 (Bachelor in Architecture)

The choice of comparing two projects developed according to different principles and approaches has been done to highlight the possible application of IMM methodology, and of the specific compactness tool, in the evaluation of the results of competitions by, i.e., a municipality or an investor.

The three stages of the system are presented graphically in Appendix D using the same sheet format used for Milan NIL diagnostic activity summarizing the visual, structural and performance point of view. Here a synthetic comparison among them is provided both at NIL 35 (intermediate) and ATU 15 (local) scale presenting both Porosity and Permeability diagram.

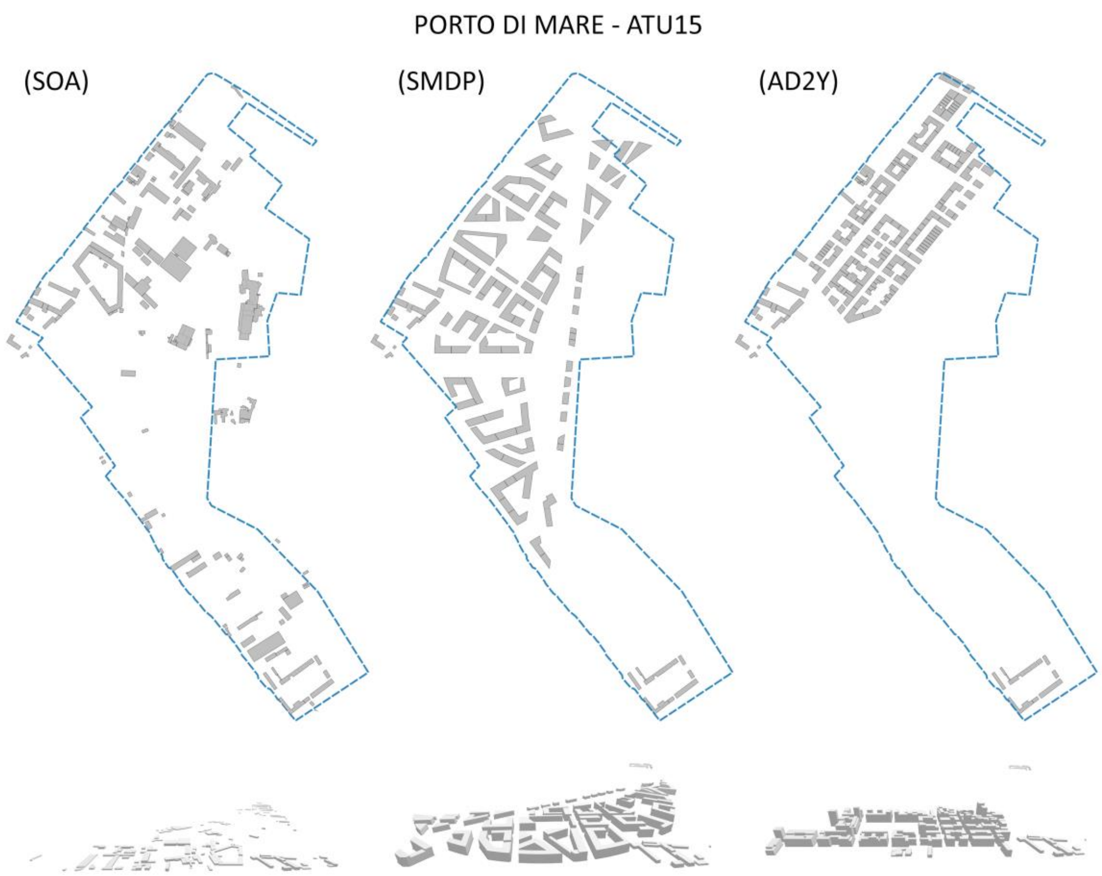


Figure 87 ATU 15 Porto di Mare plan and view of the three compared system stages: SOA, SMDP and AD2Y

Comparing the Porosity and Permeability diagrams of the State of the Art (SOA) and of the two alternative transformation scenarios (SMDP and AD2Y) at both ATU and NIL scale allows to make some considerations. What is immediately visible is that local scale (ATU) diagrams (Figure 89-90) are strongly affected by the proposed modifications compared to the intermediate ones (NIL, Figure 87-88). This is pretty obvious and is due to the fact that the ATU represent only a small part of the NIL and for this reason the modification impact is somehow mitigated or soften by the remaining unchanged volumes and voids. A project modifying transportation network, i.e., could have a more visible impact at the intermediate scale respectively on the Accessibility and Effectiveness KCs diagrams. Local scale seems the most appropriate to assess the impact of transformations mainly affecting Volume and Void Components. The most visible changes are on FAR_N and BSR metric, due to the dense urbanization of a brownfield-like area with buildings much higher than the existing ones, VBLPR and BLBP for the dismantling of a huge irregular block into a coherent street pattern with buildings facing and shaping the new streets and void space system. BBVR increase is instead mainly due to the inevitable lower level of detail used to model the new transformation scenarios.

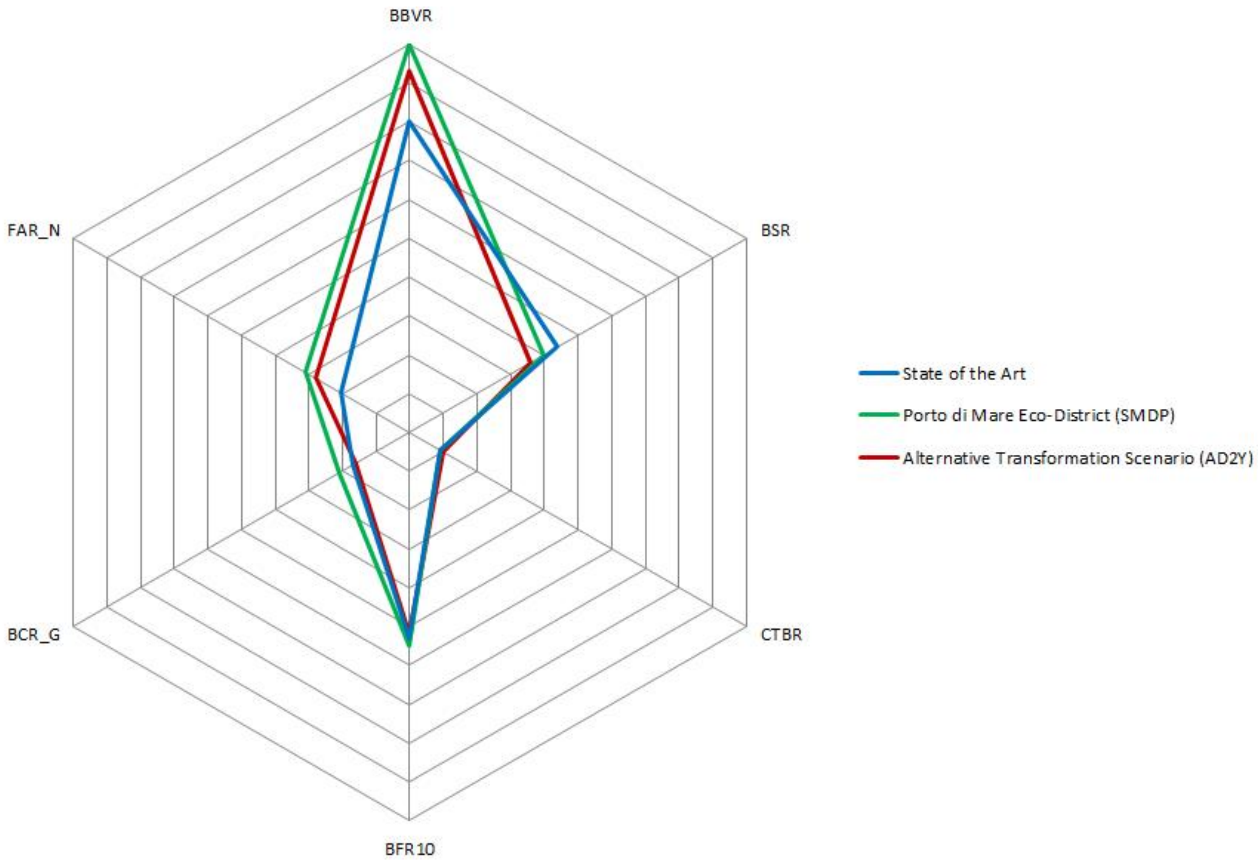


Figure 88 NIL 35 Lodi - Corvetto Porosity retrofitting diagram

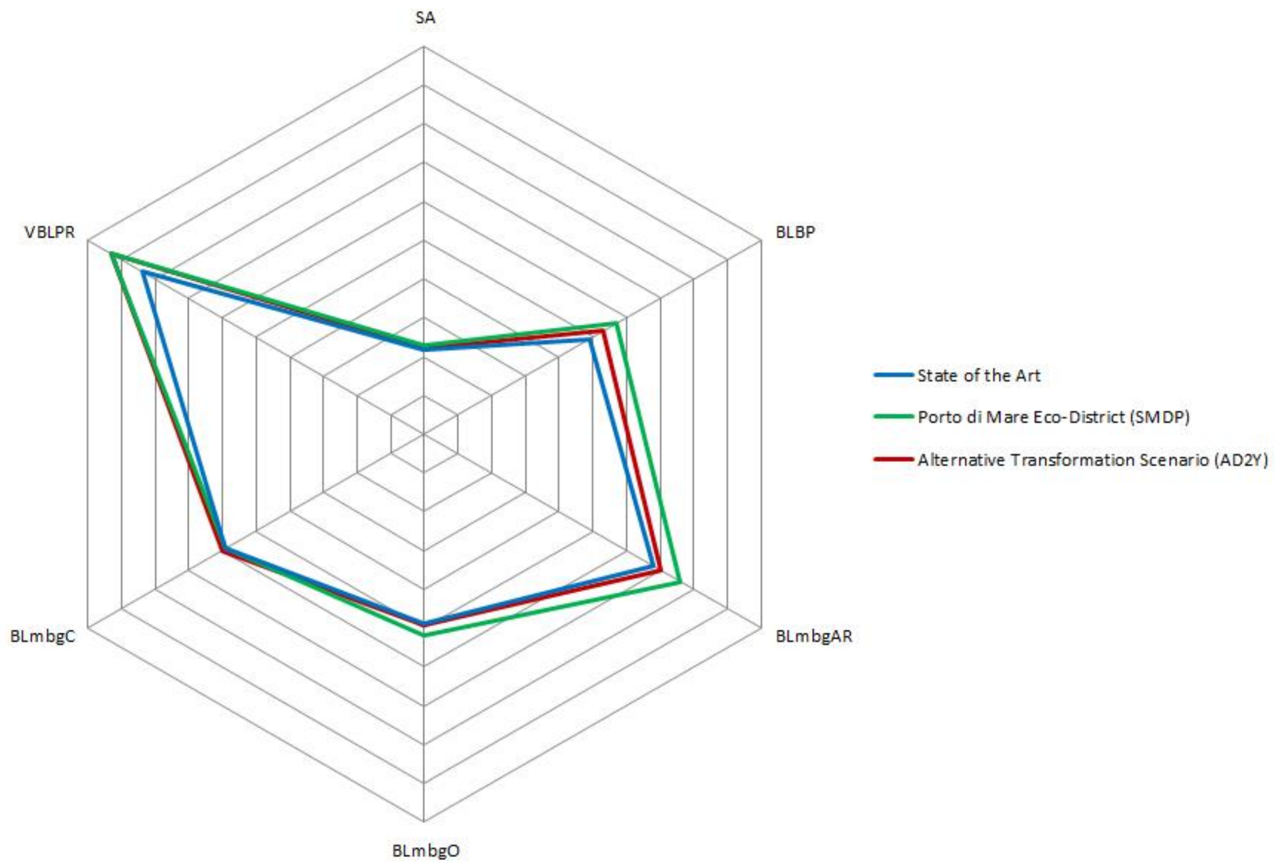


Figure 89 NIL 35 Lodi - Corvetto Permeability retrofitting diagram

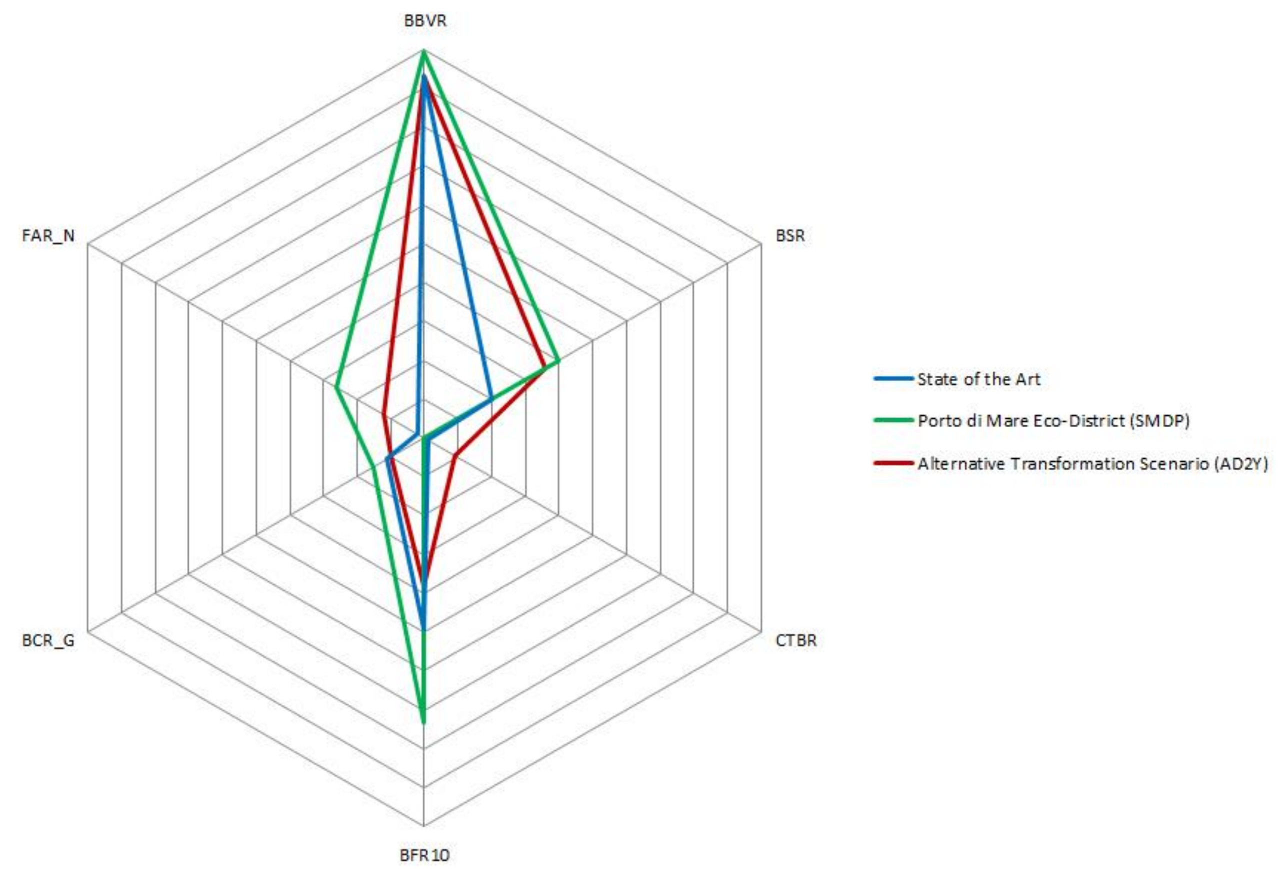


Figure 90 ATU 15 Porto di Mare Porosity retrofitting diagram

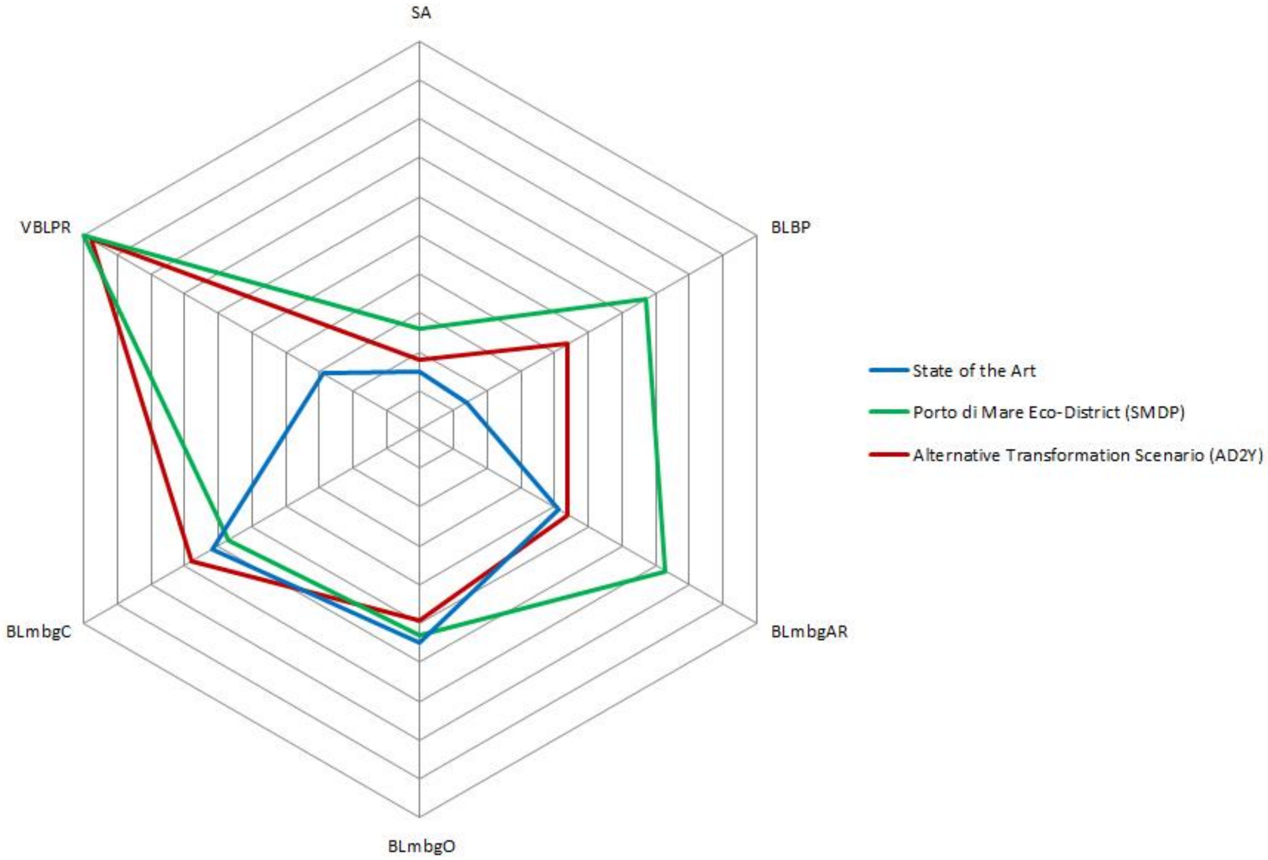


Figure 91 ATU 15 Porto di Mare Permeability retrofitting diagram

It's interesting to notice how even small variation of the selected metrics could generate an impressive impact on performances even at the NIL scale. Both the transformation scenarios in fact contributed to upgrade the NIL performance ranking of more than 20 positions (SOA #45 - SMDP #26 - AD2Y #22) thanks to an increase in performance, with different percentages, for more than 80% of the analysed indicators.

Even the ATU itself, especially for the Porosity diagram, shows little variation due to the specific context characteristic of having huge void spaces occupying almost 90% of the area. SOA porosity diagram is very similar to the non-urban areas analysed among NILs. The area is not planned and characterised by few detached abusive buildings floating inside a huge (BCR_G 0.11; FAR_N 0.02) irregular (BLmbgA 0.41) and elongated (BLmbgC 0.62) block with many cul-de-sacs (VBLPR 0.61). A number of minor volumes contribute to mitigate BFR10 value (0.49) even if the underdeveloped street network system doesn't allow to perceive them as belonging to a small number of clusters.

Both Porosity transformation diagrams are more "open", mainly due to the increase in FA, but with some differences. The most visible one is the BFR10 value, increasing in SMDP (0.73) and decreasing in AD2Y (0.38). This reflects the differences in building and block spacing in the two masterplans and how they occupy the whole transformation area. AD2Y adopts the minimum distances according to Italian regulation (10m between two facing buildings with windows) except for two slightly larger streets (15m and 20m). Streets width is minimum considering that almost only private traffic is allowed in the area. It concentrates all the volumes in the northern part of the area almost in continuity with the existing city to benefit of the existing transportation infrastructure. SMDP has higher FA but not higher buildings (max height 22m vs 60m for AD2Y) and this turns into higher BCR_G value (0.15 vs 0.10). Closed courts, rare in SOA, disappear in SMDP while AD2Y counts nine courts shared by multiple buildings. Future implementation extending court mapping also to nearly closed one will surely provide more interesting results. In fact, as it's visible from the maps, all scenarios show more court-looking spaces than the ones officially counted in the metric. A BBVR value is pretty high for all the cases but a closer look at the volume arrangement shows some nuances. SMDP (0.99) has buildings characterised by uniform height and a small number of volumetric units so the only void elements within the building boxes are ground floor passages. AD2Y (0.93) have more typological mix including towers attached to lower parts and terrace buildings in addition to the ground floor connections. It must be said that both scenarios have been modelled in a way that is necessarily simplified respect to SOA and that is mainly due to the level of detail required by the project. For this reason SOA value (0.93) in somehow hard to be compared as the grain of small auxiliary volumes is much finer.

Coming to permeability, the most evident changes are in BLBP and VBLPR. Both masterplans have buildings mainly aligned with blocks' perimeter. SMDP jumps from 0.14 of SOA to 0.67. AD2Y value (0.44) is lower for two reasons: the presence of a very large mostly unbuilt block in the lower part and the presence of a linear green space in the upper blocks occupying half of their perimeter. This two aspects reduce a value that otherwise could be very close to 1 due to the continuity of building façades. The first aspect explain also the relatively non-high value in BLmbgA (0.44) as all the planned blocks have very regular and concave shapes. SMDP in fact has a higher value of 0.73 thanks to the fragmentation of this large bottom block into smaller ones. VBLPR is almost 1 in both cases as all the cul-de-sacs have been removed. BLmbgC is slightly higher in AD2Y (0.68) respect to SMDP (0.57) because the blocks of the first are almost square-like while the ones of the second have more diverse proportions including elongated ones.

From the performance point of view is clear than both masterplans represent an improvement respect to the state of the art. SMDP is performing better than AD2Y on almost 80% of the indicators. This is mainly due to the systemic approach adopted for the Eco-District project, including aspects related to mobility as the introduction of a new bus line, to landscape integration as the presence of wetlands and to a deeper study on the optimal FA amount to be displaced (Mauri, Mazzucchelli, and Sala 2018), more than to benefits coming from the morphological arrangement. In fact, as it will be better explained in the conclusions (Chapter 8), the adopted indicators are more appropriate to understand the existing trends between morphology and performance than to understand the real advantages of one arrangement respect to another in terms of Volumes.

7.4 Dissemination

Porto di Mare Eco-District is not only the case study of this PhD thesis, a test field for compactness understanding, but an integrated proposal that has been developed with public and private partners and presented in different contexts, both scientific and not scientific. The idea of an Eco-District is stronger than any possible layout but has been presented in the form of the SMDP Masterplan by IMMdesignlab. The partners that supported and helped to develop this proposal are:

- Milano Depur S.p.a. – Depuratore Milano Nosedo
- REsilienceLAB
- Gruppo Ecologisti Est Milano – GREEM
- Associazione Piccole e Medie Industrie di Milano – API Milano
- Wageningen University and Research – WUR

This initiative have raised consensus and interest every time has been presented and so, the work on this area will continue even after this thesis. The initiative has been first presented at Triennale Milano and published with a paper titled "Urban transition, a new Pilot Eco-district in Porto di Mare area (Milan) via

IMM methodology" has been first published on "Urbanpromo 2017: a reliable future for city". The following year has been included into 2018 Resilience Practices Forum at Fondazione Feltrinelli, considered as a best practice for urban large scale interventions. At the beginning of 2019, together with the partners, have been submitted for the 2030 PGT Milan Call for Ideas. After being selected, has been presented again at Triennale Milano in front of urban planning municipality assessor. In the following months, hosted by water purifiers' festival organized by Nosedo purifier and Greem, the project has been shared with local citizens and other actor proposing complementary interventions on the area. This local meeting has been very profitable for getting in touch with Italia Nostra, in charge of taking care of the landscape below the urbanized area, currently occupied by illegal and unsafe activities related to drugs. In June 2019, as a consequence of applying to Transformative Cities initiative, Porto di Mare Eco-District has been introduced in the Atlas of Utopia 2019. Another paper titled "urban low carbon energy transition. The new Porto di Mare Eco-District in Milan based on IMM methodology" has been published on the number 160 of the journal Urbanistica. The hope is that raising interest and consensus around this initiative the probability of attracting municipality's interest will increase.

8 Conclusions

The research objective was to develop and implement a multi-scalar and multi-metrics methodology capable of objectively representing some morphological properties of the city considered as a Complex Adaptive System, investigating in particular Porosity and Permeability, how they concur in the definition of the Compactness of an area and their environmental implications. For doing that it tried to answer already debated questions like:

- How to characterize urban morphology?
- How to demonstrate the relationship between urban form and environmental performance?

The first one has been answered in a very exhaustive way on many different levels. The first achievement is the consolidation of the multi-metrics approach, integrated with the radar diagram visualization for a complex reading of urban structure. What has been done here for morphology (Volume and Void) can be easily transferred to the remaining city Components, the KCs result of their integration and the remaining Determinants following the IMM logical structure.
The process of how metrics can be created has also been enlightened reconceptualising the IMM Components and identifying a finite set of input layers for their investigation. It has been given a name and a role to every step of this process in order to better understand the modelling possibilities and encourage the creation of new metrics. The importance of form has been recognized and there has been an attempt to articulate its complexity in a set of attributes and metrics with the use of ancillary layers.
New metrics have been introduced, explained and tested on a proper real sample in order to validate them and understand their contribution in the morphological assessment of an area at different scales. Exploiting the advantages of the metric-pool approach, also measures outside of the main research goal were developed (UBR and UVBR i.e.) and shared with the scientific community for the assessment of other urban issues. Among them, a satisfying number has resulted to be high quality metrics able to qualitative describe certain aspects of urban morphology at all the different investigation scales. Finally, the above mentioned achievements, puts the basis for a metric-based classification of morphological units as buildings, blocks and courts, already handled in an object-oriented perspective.
The definition of protocols for the creation of metric-based maps (Permeability Directness, Tortuosity, Equivalent grid for ALL_N and SA) completes this framework associating visual outputs to the metrics' values for a clearer quantitative and qualitative understanding.
Some of the topics treated open to interesting and promising future development. Among them, the definition of a method to identify and objectify also semi-closed courts and the individuation of new metrics based on the continuous function of building spacing (BFRn). In addition, the comparison of metrics applied to different scales' representations, including urban patches and fractal dimension, could allow the emergence of further spatial correlations.

The work presented in chapter 5.2, unexpected before the research start, cast light on a problem of urban disciplines and tries to overcome the existing limits. Without any pretension of unmistakability, the terms elected as the most appropriate and the method proposed for metrics naming can be considered at least a first step towards a reorganization of the disciplinary vocabulary. Here starts also the understanding on the ambiguous use of the word Indicator and the consequences on environmental performance studies.

In fact, the indicators used also in this performance assessment result to be pretty correlated with the morphological aspects. For this reason, they also effectively work as descriptors of different urban configuration. This means that they are able to describe some performance implications of different existing morphologies. Some of them, in fact, are currently used as metrics inside other researches.

Most of the employed performance indicators aren't based on features exclusively referring to Void and especially Volume Components and the related Key Categories. While TD and GCRs, i.e., are based on what could be called the "green layer", a qualitative specification of the Void one, others like PTA, StopD, Modesh and Bikelane refer to transportation Network. BD and VD are highly correlated with other quantitative metrics used to describe Porosity Key Category as FAR_N as demonstrated in Appendix A, when they are considered metrics as found in the literature. Also PD, theoretically independent, uses to be strongly affected by these latter. This means that given the same building arrangement, we can ideally find very diverse configuration of the other Components and, consequently, values of the related indicators. The different Components affect each other but they are not inevitably correlated. They are independent variables in theory, which shows some pattern of dependencies when it comes to reality and practice. Some combination of metrics and indicators, not found in the sample, could be found in different contexts or are at least ideally possible. This means that not all the possible kind of cities have been created yet.
Eco-District approach can be seen as a promising strategy to overcome the existing dichotomies between centre and periphery in terms of density, green, accessibility and type of uses. They wonder if is possible to combine one structure and its well performing aspects with the advantages usually related to another. An example of synthetizing this approach is the term eco-density as cited by Sartoretti (2014). The morphology of the intermediate areas, as the one developed in the first half of XXth century, seems the most promising in this sense as they are already mostly compliant with current building regulations and present a good balance between Volumes and Voids.

A possible improvement of this study would be the analysis of the correlation between the proposed metrics and diagrams, considered a huge achievement for the discipline, with more complex performance indicators, result of simulations (wind, sun, temperature) whose inputs are within the input used for the morphological analysis. A smaller number of more synthetic indicators, unequivocally optimisable, could help understanding how volumes arrangement affects performances, like for example, urban micro-climate. The minimum ingredients for those simulations are volumes, trees, context based climatic files and eventually surface materials. For example, Best Energy software, an Energy+-based SketchUp plug-in developed at Politecnico di Milano, could be used to compute average indoor free floating temperature, given fixed construction parameters, to size simultaneously the benefits and disadvantages of sun, shading, wind and attached surfaces and how they vary from context to context. BSR metric, or even a new one expressing the percentage of free vertical surface on the total one, together with BFR at low distances, could be a very good measure to investigate the advantages of attaching buildings or not to find the right balance between dispersion and ventilation. Also outdoor temperature can similarly be computed confronting how the proposed transformation affects the percentage of comfort hours on total one. This to overcome some limits coming from others indicators, as façade PV potential (Mohajeri et al.,2014), that are not necessarily a value that must be maximised. In fact, the advantages related to the production of energy from renewable sources (only potential as the real advantage takes place if these resources are exploited), could be counterbalanced by a stronger negative impact on outdoor comfort temperature in hot climates. This has not been done inside this research mainly due to computational limits. In fact, this tool as many others are thought to work at the building scale and cannot manage the number of objects contained in areas as the one analysed in this study.

The thesis of Mauri et al. (2018) partially goes in this direction by computing shading a solar potential for increasing FA values and different kind of roof geometries on a portion of Porto di Mare Eco-District project. The smaller amount of objects (buildings) involved in the simulation made the computation considerably more manageable. Some metrics, as BCR_G, BFR10 and CTBR and all the permeability ones, are not affected by these modifications while BSR and FAR_N vary by increasing FA and BBVR by playing with roof geometry. The elements the base of these correlations are only the configuration of Volume Component and the climatic profile of the analysed context. The application of the proposed methodology on a great number of heterogeneous morphologies and climates, including very extreme one, could progressively help to understand the profound relationship between urban structure and environmental performances.

The adoption of a parametric design approach, enriched by the level of complexity provided by thesis morphological achievements, could represent a promising strategy for the optimization of urban fabrics. All this aspects actually exist but separated in different software environment. This make even more evident the need of a new generation of software thought to handle districts and city portions with part of the detail currently used for buildings. Technology may help also in deepening the studies on complex correlations thanks to data mining tools and techniques.

But technology alone can’t do anything. We develop tools and software that no matter how clever o smart could be, need to be run by a human user. Respecting the initial goal presented in the preface, this research wants to be a learning tool, a support for students, professionals and non-expert users to better understand urban form, its dynamics and implications. Victor Hugo (1831) considered architecture as a way to transmit history through the ages. If a building is a stone book, city is a library that contains and tells, among others, also its own story. Thesis approach can be seen a translator from and unknown language to mathematics, the alphabet in which God as written the universe (Galilei 1623).

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9.2 Picture Index